JOHN W. CAMPBELL

THE ATOMIC STORY

HENRY HOLT AND COMPANY · NEW YORK

PRINTED IN THE UNITED STATES OF AMERICA

BY H. WOLFF, NEW YORK

CONTENTS

PART ONE: THE QUEST FOR ATOMIC KNOWLEDGE

1. *OFF TO A SLOW START* 3
2. *FIRST APPROACHES TO THE ELECTRON* 14
3. *ATOMIC ENERGY IS RECOGNIZED* 34
4. *DISCOVERY OF THE NUCLEUS* 52
5. *THEORY RIPENS—THE ATOM SPLITS* 72
6. *FROM MAN-MADE RADIOACTIVES TO URANIUM FISSION* 89
7. *URANIUM—CHAIN REACTION?* 104

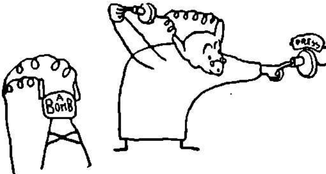
PART TWO: MAKING THE ATOMIC BOMB

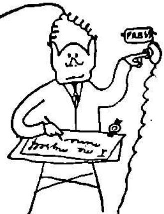
8. *THEORY OF THE URANIUM PILE* 117
9. *CONSTRUCTING THE PILE* 133
10. *ATOMIC FIRE IS KINDLED—December 2, 1942* 150
11. *PLUTONIUM PRODUCTION* 160
12. *SEPARATION OF U-235* 175

13. *ELECTROMAGNETIC SEPARATION* 187
14. *FINISHING THE JOB* 200
15. *TRYING OUT THE PRODUCT* 213

PART THREE: THE ATOMIC FUTURE

16. *POINTERS FROM HIROSHIMA AND NAGASAKI* 231
17. *ATOMIC STRATEGY AND TACTICS* 243
18. *NEW POWER FOR PEACE* 261
19. *THE HUMAN X IN ATOMIC POLITICS* 280





CAST OF CHARACTERS

MASS, a heroic figure, equivalent to energy.

Not just the same as "weight." Far out in space, away from pull of gravity, weight fades out, but mass remains.

ELECTRON, a lightweight, the ultimate unit of negative electricity.

In mob scenes electrons make up currents of electricity as they flow from one point to another. Can be regarded as having no mass.

PROTON, a plump, positive fellow, fundamental unit of mass.

Actually, nucleus of hydrogen atom, simplest of all atoms. Nearly 2,000 times more massive than the electron. Positive-charge-with-mass.

NEUTRON, a neutral character.

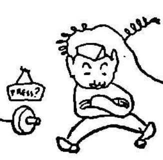
Has same mass as proton, but not electric charge. Unit-mass-without-charge.

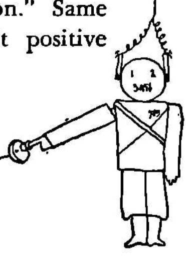
NUCLEON, family name of nuclear particles.

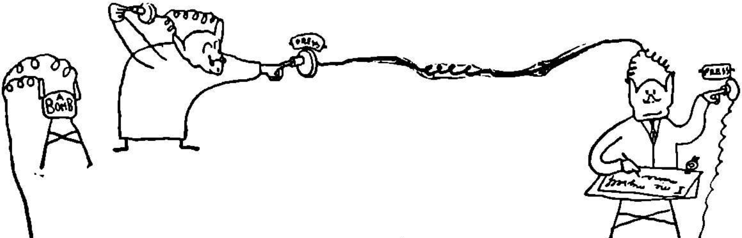
May be either proton or neutron. Not a newcomer, only a new name. Related to "proton" and "neutron" as "cattle" is to "bull" and "cow."

POSITRON, the electron's opposite number.

Sometimes called a "positive electron." Same slight mass as an electron, but unit positive charge. Positive-charge-without-mass.







ALPHA PARTICLE, really a family group.

Actually, nucleus of helium atom, encountered as radioactive discharge from heavy elements.

BETA PARTICLE, just an electron.

Given a special name because not recognized at first when encountered around radioactive atoms.

GAMMA RAY, villain of the piece, radiant energy.

Highly penetrative and changeable. To atomic reactions what light is to fire; related to light waves as light waves to radio waves. May convert directly into an electron and a positron, material atomic particles.

NUCLEUS, the heart of the atom.

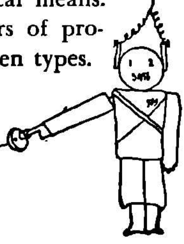
Made up of protons and neutrons. Carries all positive charge of atom and practically all mass. Center about which everything in atom revolves; storehouse of nearly all its energy.

ELEMENT, a chemically pure substance.

Cannot be broken down into component fractions by any chemical means.

ISOTOPE, type of atom of element.

Cannot be distinguished from other types of atoms of the same element by chemical means. Difference consists in varying numbers of protons and neutrons in nucleus as between types.



PART ONE

THE QUEST FOR ATOMIC KNOWLEDGE


C. VROMAN

1. *OFF TO A SLOW START*

OUR CHILDREN will speak the language of atomics rather easily, but for many of us it is still a very strange tongue. Its principles are simple, however. We need to fix a few of its grammatical rules in our minds, and we can do so by running over the development of atomic knowledge—that's the first part of this book, about the atomic past. The second part of the atomic story, about the bomb, is the tale of a present that is already slipping away into history. The grand climax, yet to unfold, is the atomic future that threatens consummate evil and yet will eventually bring us peaceful marvels such as we now can scarcely conceive.

The harnessing of the atom is the inevitable result of mankind's constant effort to explore the world. The earliest men apparently answered the whys and wherefores of the cosmos with myths about gods and devils and spirits; it took at least 200,000 years to move on from the use of fire, flint, and caves to the building of the Pyramids, and centuries still had to elapse before history reached Homer and the ancient Greeks. Yet modern science really started only two and a half centuries ago. Why, if mankind was capable of making the enormous progress of the last 250 years, should 250,000 years or more have been spent in savagery?

Largely, the answer is in the trite old saying that "it's easy when you know how." The atomic story, like the whole story of science, is transparent when it has once been told, but before men could tell any story of science, certain things had to be discovered—things so basic to our knowledge today that we can't see them as tremendous intellectual triumphs, though that is what they were originally. The first of these triumphs was by far the hardest. Before any progress could be made, men had to realize that progress was possible, that humanity *can* learn the nature of the Universe. The greatest contribution of the Greeks is probably the concept that the nature of things is not a special, private, forbidden knowledge accessible only to gods. The next great triumph was the development of scientific method—the combination of experiment and reason in proper proportions.

After this the speed of human progress accelerated to a degree that is almost impossible for us to appreciate. Julius Caesar would have fitted into George Washington's America with only a slight change of costume and a minor change of weapons—smooth-bore cannon instead of catapults, rifles instead of bows and arrows. Even the earliest Pharaohs of Egypt would have managed pretty well in the America of 1776. But George Washington would be completely bewildered by the America of only 170 years later. It is as though mankind had been laboriously pushing a balky automobile and progressing at a snail's pace, and then suddenly, about 1700, the engine started. In the next 250 years the rate of progress was that of a fast car.

Before the atom could be harnessed, these discoveries had to be made:

First, of course, that there are such things as atoms.

Second, that the atom has an internal structure.

Third, that there are tools and apparatus for manipulating and exploring atoms.

Fourth, that the things we now call protons, neutrons, and positrons exist.

Fifth (the most intangible of the great discoveries), that energy and matter are simply two different aspects of the same thing, as much the same as a lump of ice and the steam in a boiler.

These discoveries were immensely difficult, because until they were made, no one could guess that they *could* be made. Usually the ideal tools for making a discovery, for demonstrating any fact that is to be proved, involve a use of the fact itself. A mechanical equivalent of the problem of these basic discoveries would be the job of making the first metal-planing machine. A metal-planing machine has to have a flat bedplate on which the metal to be planed can be fixed. Such a bedplate is easily produced by planing it on a finished machine, but you can't do that when you're making the world's first machine of the sort. The first one has to be made the hard way—by hand, with files, chisels, and emery paper. The first chapters of the atomic story recount the ways in which men discovered the facts they had to have. If we see how the puzzle was fitted together, the logical pattern of atomic physics will be far clearer.

Most of the basic ideas of science can be traced back to the Greeks, because the Greeks were the first people to accept as a matter of course the concept that men could know all things. This assumption set their minds free to roam with imagination, controlled and guided only by logic, and when several thousand keen minds discuss and think freely over several centuries, they can hardly help hitting on most of the simpler basic ideas.

Essentially, all of our modern sciences are atomic sciences—all of them are based on characteristic behavior of some part of the atom. Chemistry is the study of the behavior of the outer fringes of atoms and of the ways in which the outer fringes of different kinds of atoms interact on each other. Electronics is the study of how the electrons—the outer fringes of atoms—behave in vacuum tubes or in near-vacuum tubes. Electrical engineering, too, studies the behavior of electrons, but in electrical engineering the electrons are confined to metal wires and bars instead of being released in vacuum tubes.

The newest and most modern atomic science—the science that has released the energy bound in the atom—involves a study of the very innermost structure of the atom, the *nucleus.* The specialists working in this field have named their new science "nucleonics"—the study of the particles of the nucleus. The great difference between nuclear energies—the energies studied by nucleonics—and the chemical and electrical energies that men have worked with in the past is simply one of magnitude.

Once upon a time men used catapults to hurl missiles. A catapult works by compressing a springy piece of material—wood, metal, or twisted rope—and then suddenly releasing the stored energy. Later, men used gunpowder, which has its energy "compressed" in the very bindings between the atoms by the manner in which the powder itself is made; gunpowder releases far more energy than any catapult and releases it far more violently. Similarly, nuclear energy is the energy stored not in the bindings *between atoms,* but in the energy bindings *in the heart of the atom itself*—and this energy is even more violent.

The science of chemistry is much more complex and harder to grasp than nucleonics. Chemistry considers some 2,000,000 chemical compounds, which have been analyzed to reveal only 92 elements. When these elements were discovered, the nature of things seemed much simpler than before—the differences between all the things in the world were more the differences between the different hands of bridge that can be dealt from one pack of cards than fundamental differences in nature. Whatever a substance appeared to be, it was actually only a reshuffling of the same 92 cards. The chemist was able to make the universe seem a lot less hopelessly confused. But the nuclear physicist goes still further. Just as the 52 cards of a deck are made up of only 4 suits, so the 92 elements turn out to be made up of only 4 different units: the proton, neutron, electron, and positron. The complexity of things is reduced to a still lower common denominator.

Nuclear physics, so far as its general rules and concepts go, is quite simple. Like any other specialty, it is enormously complicated at the stage of working with precise details, converting general rules into practical engineering figures. Before such detailed work can be handled, a man must put in ten or fifteen years of study. A good certified public accountant needs about the same amount of study and practice; yet almost anybody is enough of an accountant to add a restaurant check or figure how much a dozen apples cost at 6¢ apiece. Similarly, most people can understand the general logic of nuclear physics even though they are not capable of managing the Hanford transmutation plant.

The atomic story starts with a free-thinking Greek, Democritus, who, some 2,300 years ago, proposed the atomic theory of matter and gave us our word "atom," derived from Greek words meaning "not cuttable." He believed that if water, sand, or any other homogeneous substance were divided in halves, then halved again, and again, and so on, there would eventually come a point at which further halving would be impossible. The smallest particle of the substance would then have been reached, and this particle was an uncuttable, indestructible bit of matter. For Democritus this was a purely philosophical theory, not open to experimental proof.

From the time of Democritus to the eighteenth century no elaborations or developments of the theory were made. Many men in the intervening centuries believed in it, but the idea remained unprovable by experiment. During the 1700's post-Renaissance man added a new dimension to his interests, and the great scientific societies began to form; the atomic story, which had not moved for almost two millenniums, was about to get started again.

Chemistry was a novelty then. Customers bought chemicals by weight, not by grade, in the 1700's. Gunpowder, soap, painters' pigments—all were sold by the pound. But gunpowder had to be made by weight, too; it had to be properly compounded of materials that were just right, or it wouldn't work. Any weight of the product was worthless if it didn't measure up to a certain grade, and everybody knew it. Gunpowder is nothing but a mixture of niter, sulphur, and charcoal; if the niter you use isn't clean—and it does not occur clean in natural form; for example, in the manure piles that were a common source in the early days—then your gunpowder will just fizzle loudly, foul up the barrel of the gun, and drop the bullet gently at your feet. Niter used for gunpowder imposed on men for practically the first time in history the necessity of working with a chemically purified compound. Compounding gunpowder accurately by weight, with carefully prepared, chemically pure materials, introduced process control. This technique, which is basic in our present civilization, gave the impetus to the development of analytical chemistry, which in turn led to chemical engineering.

Up to 1750 few laboratory chemists used the weight of chemicals as a major means of investigation. As early at A.D. 770, however, an Arab chemist had conducted a few minor experiments by weighing lead, then heating it, and weighing it again. The heating had turned the lead into calx, a powder that mysteriously weighed more than the lead from which it was made. What had happened was that the lead had been oxidized; oxygen from the air had combined with it. The puzzle was not solved till somebody thought of heating the metal in the air of a sealed vessel and found there was now no change of weight, though when the seal was broken, the powder again proved to be heavier than the metal originally sealed in. Air is rich in oxygen, which combined with the metal to make the powder heavier and what was left of the "air" lighter. The left-over air proved to have several peculiar properties. Air left after copper had been heated seemed to put out candles that were introduced into it; mice could not live in it. The scientists had no name for this new sort of air until Jan van Helmont, about 1660, persuaded them to call it "gas"—a nonsense syllable that had previously had no more meaning than a made-up word like "mup" has today.

The chemists also found that when carbon was calcined—heated or burned in air—two different kinds of gas could be obtained. One was odorless, mixed with air easily, and had a pair of nasty habits. When mixed with air, it was explosive, and it was also deadly poisonous. The other kind of gas had a rather sharp odor; it was not particularly poisonous, though it would kill a mouse if the mouse were put in the pure gas; it would put out a flame, and it could be poured invisibly, because it was noticeably heavier than air. They found that 3 pounds of carbon, burned with 4 pounds of oxygen, produced the poisonous, explosive gas. But 3 pounds of carbon, burned with 8 pounds of oxygen, yielded the nonpoisonous gas—which was also found in human exhalations. Iron, dissolved in muriatic acid, yielded two different compounds, with different quantities of muriatic acid required to form the different compounds. Sulphur, burned in air, produced a poisonous, evil-smelling gas that made a weak acid when dissolved in water. But sulphur could be made to burn further and produce a powerful substance that, when dissolved in water, was sulphuric acid.

Sometimes, evidently, two elements could be combined in more than one way, if different proportions of the two substances were used. The most interesting fact that was turned up was this: *Whenever two elements formed more than one combination, the ratio of the weights of the elements could invariably be expressed as small whole numbers.* Thus, carbon and oxygen combined in two compounds, one of which had just *twice* as much oxygen as the other. The lead oxides (combinations of lead and oxygen) had ratios of 2:2, 2:3, and 2:4. The compounds of iron and muriatic acid had the ratios 1:2 and 1:3.

An English chemist, John Dalton, in the first decade of the 1800's concluded that when one substance unites with another in more than one proportion, these different proportions bear a simple ratio to each other. He was now ready to make a great step forward.

When ratios of measurements of natural phenomena come out as small whole numbers, it means something. It doesn't just happen by coincidence. So many ratios in nature are extremely complex or even completely incommensurable that there must be a reason for it when the answers are small, simple whole numbers.* Through 1802 and 1804, Dalton published a series of commentaries on the simple ratio he had observed. Another series of observations, added to data on simple ratios, gave Dalton the final necessary clue. If 100 parts of iron are to be combined with oxygen, 30 parts of oxygen, no more and no less, are required. The same amount of oxygen will combine with 230 parts of copper or 58 parts of sulphur. But—100 parts of iron or 230 parts of copper will also combine with exactly 58 parts of sulphur. Putting it another way, 30 weight units—whether grams, pounds, tons, or ounces—of oxygen have the same chemical combining power as 100 weight units of iron, 230 of copper, or 58 of sulphur.

This suggested strongly to Dalton that there was some kind of unit in chemical elements that was not a weight unit, but an actual chemical unit. The units of different elements might have different *weights*, but they had the same chemical combining "size." It looked as if Democritus had been right! There actually were uncuttable units of every element. There were such things as atoms. Dalton's atomic theory was a useful tool. It explained a great deal. Nitrogen and oxygen united in proportions of 1:0.57, 1:1.14, 1:1.72, etc., in terms of parts by weight. But the proportions indicated ratios of 1:1, 1:2, 1:3, 1:4, and 1:5 in terms of *atoms*. With that one clue a seemingly hopeless jumble began to fall into place, like an intricate Chinese puzzle once the system has been discovered.

Dalton visualized his atoms as incredibly minute, hard, indestructible balls. We can get some idea of the atom as Dalton conceived it if we imagine ourselves looking through a microscope so powerful that the atoms appear to be as large as ping-pong balls.

* For instance, the ratio of the diameter to the circumference of a circle or sphere is 3.14159 . . . ad infinitum. The ratio of almost any set of natural measurements picked at random will be—random. If there is a mathematical pattern, it almost certainly means that there is a *reason* for that mathematical pattern—that it is an expression of a *deeper* pattern.

The balls are all the same size—but they have very different weights. Hydrogen is the lightest atom, a true ping-pong ball atom. Oxygen is the same size, but much heavier, more like a golf ball. Iron atoms are still heavier, and copper atoms heavier still. Each, however, is the same size.

These different atoms—these little balls—have "handles" on them by which they can unite with one another; some have more handles than others. Some of the handles on a particular atom are easier to take hold of than others. Imagine an atom as a small ball with some small tentacles reaching out, forever trying to get hold of something else. This illustration is not to be taken literally, but is only for the sake of understanding a mysterious attraction that some atoms have for other atoms. Some, like oxygen, have *very* active little tentacles. Others, like gold and platinum, have listless tentacles that prefer to curl up on the atom and not take hold of other atoms.

Some kinds of atom have only one tentacle; hydrogen is like that. Others have two—or three, four, five, six, seven, or as many as eight. Oxygen has two; chlorine has seven; the rare metal osmium has eight, nitrogen five, carbon four. Carbon monoxide, the early chemists discovered, consists simply of one carbon atom using two of its four tentacles to hold the two tentacles of an oxygen atom. In carbon dioxide another oxygen atom is held by the carbon atom's other two tentacles.* Similarly, the various nitrogen oxides are due to more and more of the nitrogen atom's five tentacles, going into action. Chlorine forms a series of seven different combinations with oxygen, by a similar process.

Not all of this was clear to Dalton and his contemporaries, but the theory was readily accepted for a number of good reasons.

First, it did explain why the ratios of weights in a series of compounds were small whole numbers. Obviously, if uncuttable atoms existed, you could have a 1:1 or a 1:2 or a 1:3 ratio of atoms, but you couldn't possibly have a fractional ratio. The atom was indivisible; so a 1:1½ arrangement would be impossible.

* The proper term for these tentacles is *valences*—which are no more like tentacles than an atom is like an octopus. Actually, the valence attractions seem to be mainly electronic and electrostatic in nature. The exact nature of these attractions is not yet known.

Second, the assumption that different kinds of atoms had different weights explained the way iron, copper, sulphur, and oxygen reacted. Evidently, 100 weight units of iron represented a number of iron atoms equivalent to the oxygen atoms in 30 weight units of oxygen, while the equivalent number of copper atoms weighed 230 units.

Third—and almost equally important to explain the immediate welcome given to Dalton's ideas—the theory suggested a practical way of writing down a chemical reaction. It was useful. Before 1810, chemists had had a most laborious system for indicating a chemical reaction. Their methods were as confusing as multiplying MCDXLIX by MDCCCXXXVII. Dalton's atomic theory made the whole thing easier. It made simple and obvious symbols possible. The symbol "O" could now stand for oxygen and could mean a great deal. It could mean "one atom of the element oxygen," but it could also specify a certain *weight* of oxygen, because each atom of every element has a definite weight. The atom of oxygen, for instance, proved to be about 16 times as heavy as a hydrogen atom, half as heavy as a sulphur atom, and 0.4 times as heavy as a calcium atom.

Water was found to consist of hydrogen and oxygen atoms combined in a 2:1 ratio; the fact could be stated simply by the symbol for hydrogen, H, a numeral indicating the number of atoms of that kind, and the symbol for oxygen, O, as the familiar H_2O, meaning two hydrogens combined with one oxygen. Further, since it had been found that oxygen atoms were about 16 times as heavy as hydrogen atoms, the formula told the chemist that, roughly, 2 weight units of hydrogen combined with 16 weight units of oxygen—whether the weight units were grams, ounces, pounds, or tons.

The next great problem for the chemists was to determine the relative weights of the different kinds of atoms. They didn't know how to weigh *one* atom of hydrogen or *one* atom of oxygen—but that didn't bother anyone. If they knew the *relative* weights, their chemical calculations would work nicely, and that was all they needed. By careful weighings of various compounds the relative weights of all the kinds of atoms could be determined, and since only *relative* weights were involved, any arbitrary unit could be chosen. The chemists started off by making the atomic weight of hydrogen 1.000, simply because hydrogen is the lightest of all elements. If it were made the unit, there could be no fractional atomic weights—less than 1.000—whereas if oxygen were made 1.000, hydrogen would have to be made about $1/16$.

As accurate determinations were made, though, the chemists found a certain unexpected inconvenience—a minor nuisance, it seemed at the time, and of no real consequence. With hydrogen 1.000, the ratios worked out so that oxygen was 15.85, carbon was 11.9, and calcium was 39.96. But if oxygen were arbitrarily made 16.000, hydrogen's atomic weight became 1.008, while carbon, calcium, and many other elements came out with even-number weights. Since the whole thing was simply an arbitrary scale of ratios, the chemists, to save themselves trouble, shifted to the "oxygen = 16.000" system to make the arithmetic of chemistry simpler.*

That hydrogen's relative weight was 1.008 instead of 1.000 seemed unimportant. At that point the chemists had accidentally stumbled onto one of the most important facts in all nuclear physics—then an undreamed-of-science. When oxygen is 16.000, helium's atomic weight is 4.002. Four times 1.008 is 4.032, or .03 units higher than the atomic weight of helium. It is the enormous energy that that tiny mass of .03 weight units represents that keeps the sun shining and lights all the stars in the heavens. A star like our sun is an immense engine that burns hydrogen into helium—but that discovery was beyond the abilities of chemistry. Chemistry can touch only the outer fringes of the atoms.

In the mid-1800's the chemists thought of atoms just about as Democritus had some 2,200 years before: little balls that bounced and reacted, but were as featureless and structureless as so many ball bearings. It was to be a great many years before chemists were able to measure just how tiny the atom was; the methods they used

* It also made chemistry itself simpler. If "hydrogen = 1.000" is used as the standard, all elements must be compared with hydrogen. But hydrogen does not combine with all elements, so that iron, for instance, must be compared with oxygen, with which it does combine, and then oxygen must be compared with hydrogen. Oxygen, however, combines with all elements that form any chemical compounds at all, and so it may be directly compared with all elements.

were ingenious and exceedingly involved, and they don't directly affect our interests. Even the figure obtained is meaningless; it is too far out of the range of normal experience to have any understandable relationship to ordinary things. The best way to understand how infinitesimal a single atom is—and what inconceivable numbers of individual atoms there are in even the most minute grain of dust—is by a step-wise approach.

A mosquito is a tiny and pestiferous thing. It is also dangerous because, tiny as it is, it may carry in its minute salivary glands malarial parasites that are still tinier. Not just one or two, but thousands of these minute animalcules can reside happily in one salivary gland of one mosquito. Yet these tiny death bearers are very readily visible under an ordinary microscope—even a microscope of only moderate power. The syphilis spirochete is so much smaller that no optical microscope will allow us to see into it; only with the invention of the electron microscope was it possible to fill in our picture of the syphilis organism. Since these electron-microscope pictures have become available, it has been discovered that the spirochete of syphilis has a complex structure of parts, organs, cell walls, and cavities. These syphilis spirochetes are—well, *small,* but the parts of the tiny organisms are made up of organic chemical compounds, extremely complex molecules, each molecule containing hundreds of thousands of atoms arranged in a rigidly fixed pattern of carbon, oxygen, hydrogen, nitrogen, sulphur, and so on.

The infinitesimal spirochete is huge by comparison with those atoms. Yet long before the electron microscope made it possible to detect the existence of such minute structures, human imagination, ingenuity, and experiment had combined to discover, measure, and weigh the individual atom. The hydrogen atom weighs $\frac{167}{100{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000}$ gram. The diameter of the nucleus or core of the atom is about $\frac{1}{1{,}000{,}000{,}000{,}000}$ of a centimeter. Needless to say, the atom was not weighed on a pan balance nor measured with calipers!

The early stages of the atomic story established that atoms existed and that they had certain relationships with each other. No one had yet used imagination to look inside the atom.

2. *FIRST APPROACHES TO THE ELECTRON*

BEFORE the true significance of atoms could be understood, science had to discover that they had structure. Chemistry had gone about as far as it could toward helping along the atomic story. Now the discovery of greater forces, more subtle and penetrative powers, was needed in order to get at and explore the unknown interior of the atom. Again we shall have to go back to the time of the early Greeks to understand the forces that ultimately revealed the inner secrets of the atom.

Amber is a very ancient gem material. The Greeks were familiar with it, admired it, and knew that if a bit of amber was rubbed with a piece of wool, the amber acquired a strange new property. It would attract to it bits of lint or dust. The Greek word for amber was *elektron;* in later centuries a whole class of phenomena became associated with that peculiar property of the substance the Greeks called *elektron,* and the strange attractive force became known as *electric force.**

If some genius about the year 100 B.C. had invented central heating and installed a good system in some north European country, the science of electricity might have developed faster. In our modern steam-heated houses the dry air makes it easy to generate static electricity. When you walk over a deep-pile carpet and touch a door knob or some other person, a tiny flash of static electricity bites you. When a woman pulls her wool dress across her silk slip, the crackle and snap of static electricity makes itself evident, and the highly charged silk slip molds itself tightly against her body. Cat's fur snaps and crackles vigorously when it is brushed. Fine human hair,

* To avoid confusion we should remark that the modern word "electron" is not related to the Greek *elektron* save in form. Amber has nothing more to do with electrons than bakelite, hard rubber, or glass.

when brushed, stands on end and follows the movements of the comb. Static electricity is very obvious and demands attention in the air of a steam-heated modern house.

In the moist Mediterranean air and in the damp climate farther north in Europe these things weren't obvious. The great castles and palaces of Europe in the Middle Ages were wonderful places, but the average winter temperature of a drawing room in a royal palace was in the neighborhood of 40 to 50° Fahrenheit. Little items like that can do a lot to influence the course of science. The Arabs, working on the fringes of the Sahara Desert, had a better chance to observe static electrical phenomena, but they didn't accomplish much in that line either. The air wasn't dry enough, and silk, glass rods, amber, and similar materials that readily generate static electricity weren't very common.

The Greeks knew about the attractive powers of rubbed amber as early as 600 B.C. Two thousand years later the same knowledge was being faithfully passed along from one writer to another—with nothing more accomplished. Experimental work on the subject did not begin until the seventeenth century. It was Queen Elizabeth's court physician, Sir William Gilbert, who introduced the terms "electrified" and "electric." He found that many substances besides amber could be made to show the same sort of phenomena—could, in his new term, be *electrified.*

We know now that friction always produces electrification—a building up of the attractive forces. Only in the substances that prevent such electrification from leaking away, however—in the *insulators*—is the effect readily detectable. Amber is an extremely poor conductor of electricity; when electricity once gets on a piece of amber, it has a hard time getting off again. Therefore, when amber is rubbed and friction produces electricity on it, the electricity has to stay there. Rubbing a piece of copper with wool or cat's fur produces electricity in the copper, too—but copper is an excellent conductor of electricity, and the effect is not at all obvious, because the electricity leaks away instantly.

Recently another term has been invented: *electrostatic.* "Static" means nothing more than "standing still." The term "static" used in connection with the angry-animal noises your radio set produces during a thunderstorm is short for "electrostatic." But forget that meaning temporarily; static electricity is simply electricity that, like the electricity on a piece of amber, has been trapped and can't get away.

The simplest demonstration of static electricity is the familiar stunt of rubbing a fountain pen or pocket comb with a piece of flannel or wool, then holding it near an ash tray; bits of cigarette ash will leap up and cling to the pen. The Greeks didn't have fountain pens, but their amber did as well, and wood ashes work the same as cigarette ashes. Men have been performing that simple experiment for 2,500 years—and only in the last 300 have they gone any farther down the road that the results of the experiment point out. If you rub a glass rod with flannel or wool, it too will attract bits of ash. The early scientific experimenters probably found ashes rather dirty to work with; their favorite subject was a pith ball suspended on a very fine silk thread. If you want to try the same trick, a tissue-paper ball will do nicely.

The experimenters found that, although rubbing glass rods and rubbing pitch or hard rubber rods produced the same electrical effects, there was one curious difference. If a hard rubber or plastic rod is rubbed and suspended from a silk thread, a pith ball similarly suspended will be attracted to it. But if a second rod of the same material is rubbed and brought near the suspended rod, the suspended rod is *repelled,* not attracted. If a glass rod is rubbed and brought near, the suspended rod is very strongly attracted! On the other hand, if a glass rod is rubbed and suspended and a second glass rod rubbed and brought close, there is strong repulsion.

The early scientists seem to have been hard on the local cats; nearly all the classical experiments of the early days involved the use of cat's fur. Some sort of standard material was required, and the electrification of cat's fur had long been observed; so they chose that. Not long after the discovery of the fact that rubbed pitch rods repel each other, that rubbed glass rods repel each other, but that rubbed glass attracts rubbed pitch, someone noticed that the cat's fur with which a pitch rod was rubbed was attracted to the pitch, but repelled from a rubbed glass rod.

The business was now getting complicated and a bit hard to keep track of. There seemed to be two different kinds of electrification—

the rubbed pitch kind and the rubbed glass kind. The experimenters needed names to identify the two reactions. A further fact that had been determined led to the final choice of names. If a rubbed pitch or rubbed rubber rod was touched to another rubbed rod of the same kind, despite their repulsion for each other, things were not changed when they were allowed to separate; they repelled each other as before and attracted bits of fluff as before. But if a rubbed glass rod was touched to a rubbed pitch or rubber rod, the effect was quite different. They attracted each other, of course—until they had made good contact. Then, abruptly, they simply ceased to be interested in each other at all. They no longer attracted each other and no longer attracted bits of fluff. Apparently the two kinds of electricity were opposite in nature, so that when they did get together they canceled out.

Benjamin Franklin finally gave the two kinds of electricity their names. He suggested that the rubbed glass kind be called "positive electricity" and the rubbed pitch kind "negative electricity." He chose the terms "positive" and "negative" for only one reason. If you add $+1$ and -1, you get zero. If you add a positive charge of electricity and a negative charge of electricity—you get no electricity at all.

Like Arabic numerals and John Dalton's atomic symbols in chemistry, Franklin's names for charges of electricity were quickly adopted. The rules for electrical behavior could now be expressed simply. Instead of saying, "Two rubbed glass rods repel each other, but a rubbed glass rod attracts a rubbed pitch rod," scientists could say: "Similar electric charges repel, and unlike electric charges attract. Positive charges attract negative charges and repel positive charges; negative charges repel negative charges."

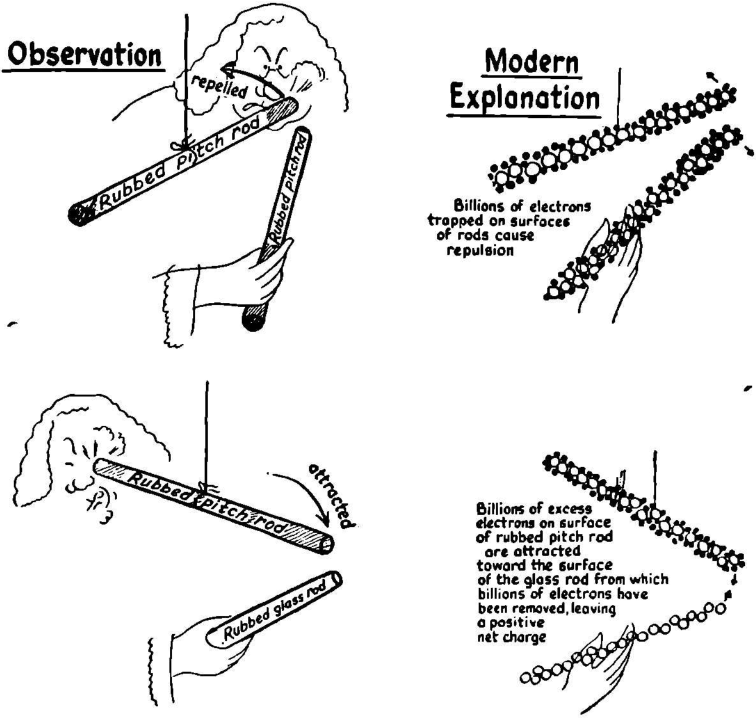
Franklin had a theory about electricity. He thought that all matter normally contained a certain amount of "electric fire" or "electric fluid" and that rubbing one material against another rubbed some of this electric fire off one piece and onto the other. The displaced electric fluid had a natural tendency to return—to level out so that there were no excesses at some points and deficiencies at others. He spoke of "electric fire" because he believed he could see the stuff returning in the visible sparks that accompany discharges of what today we call static electricity. Franklin's theory was remarkably close to being correct. The electron was not to be discovered till nearly a century later, but the true explanation of static electric phenomena is worth comparing with Franklin's ideas.

The electron is the unit of negative electricity—you might say it is the atom of negative electricity. The proton is the unit of positive electricity, and protons reside very firmly fixed in the centers of atoms; they can't move in solid materials. Electrons can move around freely in metals—which is why metals conduct electricity. They can't move very well, however, in insulators like glass, amber, and hard rubber, nor in hair, wool, or silk. But electrons can be broken off, so to speak, from the surface atoms of a mass of glass, hard rubber, wool, or the like. When hard rubber is rubbed with wool, the friction succeeds in breaking off some of the surface electrons of the hairs of cat's fur, wool, or flannel, and these electrons become trapped on the surface of the rubber.

The rubber rod, as a result, has an excess of electrons or negative-charge units. Like charges do repel each other; these electrons repel each other, and they also repel any other electrons that come near. Thus, if another rubbed rubber rod is brought near, the excess of electrons on each rod repels the excess of electrons on the other. If the two rods are forced into contact, the very strong repulsion simply chases all excess electrons away from that point, and both rods remain negatively charged.

Glass is different; when glass is rubbed with cat's fur, the electrons are "broken off" the surface atoms of the glass and picked up by the hairs of the fur. This leaves the glass with a deficiency of electrons. Since it has too few electrons, the protons—unit positive charges present in the atoms that were not dislodged—are now in excess. There is a net positive charge. Positive charges attract negative charges; the rubbed glass rod with an excess of positive charges attracts the rubbed rubber rod with its excess of negative charges or electrons.

Moreover, since in ordinary uncharged matter there are electrons in numbers just equal to protons, the glass rod will attract bits of ordinary matter because it attracts their electrons. Similarly, the rubbed rubber rod will attract ordinary uncharged matter to it because the excess electrons on the rubber attract the positive-charge protons present in ordinary matter. But if the excess-electron rubber rod is allowed to make contact with the electron-deficient rubbed glass rod, the excess charge of electrons on the rubber neutralizes the deficiency on the glass—the negative electrons satisfy the demand of the positive protons, and the electric charge apparently vanishes. The electrons and protons are still



Electronics—A.D. 1700.

there; there is just as much positive and just as much negative electricity as there was before. But because they balance, neither is detectable.

Here is a mechanical analogy for the seeming disappearance of electric charge. Suppose you have two gas-tight tanks, each fitted with a valve that is normally open, so that each tank has a normal amount of air in it. You attach a pump to one of the tanks, pump in a considerable amount of air, and then close the valve. After putting a pressure gauge on it, you will read, let us say, 10 pounds pressure. Next you attach the pump to the other tank, but this time you pump air *out* of the tank, until your gauge, when attached, reads 10 pounds again—but this time it is 10 pounds *less* pressure inside than outside the tank. The gauge you are using simply says "10 pounds," without qualification. If you connect one tank to the other with a hose and open both valves, there will be a brief hissing and then quiet. Now the gauge, when attached to either tank, will report "0 pounds." What's happened to all that air? We had 20 pounds of air pressure; yet when we put them together, why, we didn't have any! The answer is easy. We merely shifted the air from one tank to another, then allowed it to shift back.

Electric charge works the same way. You cannot charge one object without at the same time producing an equal and opposite amount of charge somewhere else; you can pump electricity around, but you can't get rid of it. Even when it appears to have vanished completely, it's still there—but so balanced that it's no longer noticeable. In the mid-1700's scientists didn't know about electrons or protons, nor had they guessed why electricity worked or what the accumulation of electric charge was. They were really looking for the electron, but they were working under the severe handicap of not knowing what it was they were seeking!

Rubbing rods with cat's fur wasn't a very satisfactory way of pumping electrical charges around. Various contraptions were designed and built to perform the mechanical equivalent of rubbing rods. These apparatus didn't actually use cat's fur or mechanical friction, but they did develop electricity and were thus the first electric generators. They were usually made of one or more large discs of plate glass rotated by cranking a handle, and there were various devices for picking up the static electricity generated. Small-boy laboratory assistants were the usual sources of power for these machines. The great scientist tried to figure out just *what* was going on when the boy turned the handle. These electrostatic generators were, actually, a wrong answer to the puzzle of electricity. But in science wrong-answer experiments aren't fruitless; in threading a maze it is necessary to know which paths *don't* lead to the goal. Sometimes the negative answer can be extremely informative.

The discovery of uranium fission itself, as we shall see later, was the immediate result of a negative experiment, an experiment that proved conclusively that the original idea of the experimenters was definitely, unequivocally *wrong.*

These earliest generators, however, could not teach much that the rod-rubbing technique didn't teach, and no matter how hard the little boys cranked, they couldn't get a useful amount of power out of them. Some of the whirling glass discs were as much as 6 feet in diameter and generated almost enough electricity to light a small flashlight bulb, if any such device as a flashlight had been available at that time. Though the machines generated very little power, they did generate an astonishing amount of voltage. Voltage is the electrical equivalent of pressure; it is a measure of how powerfully a negative charge is attracted toward a positive charge, or vice versa. Static electric voltages can mount to phenomenal figures. The electrical pressure, or voltage, of a flashlight battery cell is 1.5 volts. The ordinary household power line carries a pressure of 110 volts. The sort of spark you get after walking across a deep-pile rug on a dry day may represent 20,000 volts. Some of those early glass-disc static generators could build up 200,000 volts!

The trouble with the old high-pressure electric generators was that they couldn't generate any *quantity* of electricity at that pressure. One of the little metal gadgets some people use to fill a home-filled soda-water siphon contains about a teaspoonful of carbon dioxide, but it's under a pressure of nearly 750 pounds per square inch—lots of pressure, but not much quantity. An automobile tire contains air at approximately 30 pounds pressure—but there's a lot of air in the tire, enough to run a little compressed-air motor for quite a while. Finally, one of the familiar tanks of oxygen used by welders contains gas at a pressure of 2,000 pounds per square inch—and a remarkably large quantity of it can be crammed into one of the tanks under that pressure. The soda-water siphon charge is somewhat like the old electrostatic devices—lots of pressure, but not much quantity. The automobile tire is more like a household power line—moderate pressure, but considerable quantity. The welder's gas tank is more like a modern power-plant generator; the pressure is high, and there's a great quantity available.

Electrical experimenters in the early days didn't have voltmeters to measure voltages, but they did have one way of measuring. If you put two metal balls a quarter of an inch apart in the air and push more and more electrical pressure into them, the attraction of the individual charges on one ball for the charges on the other becomes greater and greater. The nonconducting air keeps them apart, but as the pressure grows higher and higher, the strain on the wall of air gets greater—and finally breaks through with a snap and a crack. The thicker the air, the more electric pressure it will stand before breaking down, just as a thick steel wall will stand more gas pressure than a thin wall. The old experimenters could rate the abilities of their electrostatic generators—and the enthusiasm of the small boys engaged in cranking them—by the number of inches of air gap that could be penetrated by the spark.

The experimenters had only these electrostatic generators to work with up to about 1800, and they had gone about as far as they could on the road of discovery with such tools. The next set of phenomena to be investigated required a source of strong currents of electricity rather than the high voltages they had used in the past. Their electrostatic generators were like bicycle tire pumps delivering little squirts of air under considerable pressure; what they needed now—though they couldn't know it!—was something more like an electric fan, something that would push a great volume of electricity at low pressure.

About this time Alessandro Volta, for whom the unit of electric pressure, the *volt,* was later to be named, was following up some strange observations made by Galvani, an Italian biologist. Galvani had been startled to see some dead frogs' legs kick when a piece of copper wire and a piece of iron touched them. Volta discovered another interesting fact. If he touched a gold and a silver coin to his tongue, there was no noticeable taste until the coins *also touched each other.* Then he was conscious of a strong bitter taste.

His experiments were many and involved, and eventually they led to a device known as the voltaic pile. It's a simple arrangement: a sandwich made of a zinc disc, a flannel disc wet with salt water, and a copper disc. When a series of these little packets is piled one on top of another and put in a frame to hold them, an appreciable voltage can be obtained. A later version consisted of a series of cups filled with dilute acid, into each of which one zinc and one copper plate dipped. The zinc plate of one was wired to the copper plate of the next, and so on. The net result was quite an appreciable voltage, plus a useful output of current.

These were in essence small wet cells; from them developed the modern dry cell and the modern storage cell. A *cell* is a single system of two plates and a solution of acid or salt; a *battery* is simply two or more cells. The storage battery in your car consists of three cells, each usually containing 10 plates of metallic lead and 11 plates of lead dioxide supported in a lead meshwork. It can generate only about 6.8 volts of electric pressure, but can deliver a river of current. On a cold day the motor of the car may draw as much as 400 amperes. By comparison a 100-watt electric light bulb draws only 1 ampere from the 110-volt line, and a flashlight bulb draws only 0.3 ampere. The *ampere* is a unit of rate of electric current flow—it's like gallons-per-minute in the rate of water flow.

Your radio B battery, incidentally, is a modern voltaic pile. Zinc and graphite plates are used, and there are other modern improvements, but the essential idea remains the same. There is no better source of power for many delicate electronic devices than the good old-fashioned B battery.

The invention of the battery had a tremendous effect on the whole field of science. Chemistry benefited immediately. The battery became available about 1805; in the next two or three years Sir Humphry Davy, an English chemist, was able to isolate nearly a dozen chemical elements no one had been able to isolate before. The new powers of electricity in motion, instead of electricity standing still, precipitated great chemical activity. When the current passed through water, the water broke down into bubbles of hydrogen and oxygen. When it passed through fused soda lye, the soda lye broke down into a hitherto unknown metal, sodium, and hydrogen and oxygen. Element after element was isolated.

In 1820, Hans Christian Oersted, a Danish scientist, accidentally made a long-sought discovery. The Greeks had discovered amber's powers of attraction; they had also discovered that the lodestone would attract bits of iron. In the Renaissance period, when long-range shipping became important, the magnetic compass was discovered, and magnets were studied with great interest. Somehow it seemed that there must be a connection between the mysterious power of a lodestone—or a bit of steel magnetized by rubbing with a lodestone—to attract bits of iron and the power of glass rubbed with cat's fur to attract bits of almost any sort of matter. Just because man happened to think it was logical did not by any means make it true; nevertheless, it was a good guess, for there is a connection. But no matter how men manipulated their static electricity, they never could find any interaction between magnets and electric gadgets. Oersted did—while trying to prove there was *no* connection between the two!

Oersted had been lecturing on electricity and magnetism, and part of his lecture called for a demonstration that electricity had no effect on magnets. He put a wire carrying current from a battery across a compass, with the wire running at right angles to the needle. The needle was not deflected. After the lecture several students came up to the table and he placed the wire *parallel* to the needle; when he closed the switch, the needle swung! Oersted's mistake—and the mistake everyone else had been making—was to believe that if the wire had any magnetic properties at all, it would act like a bar magnet. A bar magnet will make a compass needle move only if it is placed at right angles to the needle; if the magnet and the compass needle are parallel, there will be no noticeable effect, since that is the position the compass needle would naturally seek. The magnetic force exerted by a current in a wire is not *along* the wire, but at right angles to it; hence the wire had to be parallel to the needle for things to happen. As a demonstration of the nonexistence of magnetic effects of an electric current, Oersted's was one of the most spectacularly successful failures on record. His discovery was something the whole science of electricity had been waiting for. It was a new beachhead for invading unknown electrical territory. And Oersted's name has been immortalized thereby, for the *oersted* is a unit of electromagnetism.

The scientific world immediately started looking for the corollary: If an electric current would generate a magnet, how could a magnet be made to generate an electric current? The right answer was very simple. A magnet, when moved in a coil of wire, will generate a current in that coil of wire. This can be demonstrated very readily by any small boy who may be interested. A coil of wire from the local dime store—the usual 10¢ coil of bell wire will do—

and a magnet from the same source of supply, plus a secondhand meter from the local radio store, costing perhaps $2.00—or even an old automobile dashboard ammeter costing as little as 75¢—can be made to do. Thrust one end of the magnet into the coil of wire, and the current generated will make the meter needle kick over; draw the magnet out again sharply, and the needle will jump the other way.

Michael Faraday in 1821 began to look for the secret of making a magnet generate a current. He was working in England's Royal Institute physics laboratory with the finest equipment the world of that time could produce. Ten years later he finally discovered that the magnet had to move through the coil. In the meantime his many experiments had produced the electric motor, the electric transformer, and the induction coil. But it took *ten years* for this first-rank scientist, one of the world's greatest experimental physicists, to discover what any modern youngster could discover in an afternoon's play with magnets, wire, and a small meter. Why?

The youngster will be playing with a magnet of enormous power, relatively speaking. In Faraday's time most magnets were produced by stroking steel bars with a lodestone. Lodestone is just barely magnetic, and the magnets were very weak. The alloy steels used in modern magnets are the product of a tremendous industrial civilization. When we make a child's toy magnet, it has a power and stability that would have astonished Faraday. The 10¢ coil of wire the boy picks up has been produced from hard-drawn copper refined to an amazing purity by special electrical processes; the insulation has been applied by a special machine, perfected by decades of designing and redesigning. And, finally, the $2.00 meter from the radio store is the result of a century of research and engineering development—and it works partly by reason of some of those supermagnetic cobalt-steel alloys. The boy, in other words, has tools that can easily do the necessary job of fundamental research. But they have been made possible only because Faraday first did the job with crude, hand-insulated wire and very weak magnets. The boy's wire, magnet, and meter couldn't be invented until Faraday had done his work!

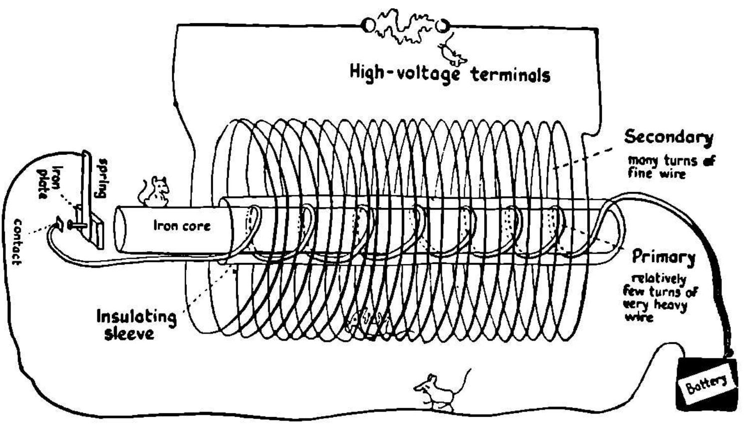
Time after time atomic science has been stopped for lack of the right tool for the next discovery. The right tool can't be invented until that next step has somehow been taken, because no one can know what that right tool is until the insoluble problem has been solved. Each time someone, somewhere, somehow has managed to get around, or under, or over the difficulty. Sometimes it has taken ten years, as with Faraday; sometimes it has taken half a century. Occasionally the right tool has been at hand, but in the wrong place. The discovery of the electron was waiting for tools, but now the tools were building. Vacuum pumps had to be invented, then improved. Faraday had discovered the transformer, though it still had to be developed into something that would give strong high-voltage currents from the low voltages available in batteries.

The transformer is one of the most remarkable machines in the world. It is a device that works without mechanical movement, is more than 99.9 per cent efficient, and consists of only three non-moving parts—two coils of wire and a hunk of iron. The transformer is simply a machine that pushes a magnet into a coil of wire and yanks it out again. When a magnet is driven into a coil of wire, the magnetic force of the magnet causes the electrons in the wire to move—although this was not, and could not be, discovered until the electron was found, many years after Faraday's time. When the magnet is jerked out of the coil of wire, the same magnetic force makes the electrons move the opposite way. The stronger the magnet used, the harder the electrons are pushed and the higher the electric pressure, or voltage, developed. Also, the faster the magnet moves, the stronger the push and the higher the pressure. And, finally, the more turns of wire there are in the coil, the more voltage will be generated. To get a very high voltage, we need to move a very strong magnet rapidly into and out of a coil with a great number of turns. In the 1840's and '50's there were no very strong magnets and no devices capable of moving them rapidly. Manufacturers, moreover, weren't turning out enamel-insulated 32-gauge copper wire from which to wind 10,000-turn coils.

Suppose we make a small coil of fairly heavy wire and put it across a battery. Oersted had discovered that when current flows through a wire, it generates magnetic force. In the coil each of the turns will add some magnetic force, so that with a number of turns and a strong current we can get a very powerful magnet. Now let's turn on the current and build up the magnetic force in the coil—

then very suddenly open the switch so that the current stops flowing. The instant the current stops, the magnetic force is gone. *It is as though a very strong magnet had been jerked away at an enormous speed.* The diagram below shows the general mechanism of an induction coil, the device that makes use of this simple trick.

Around an iron core, usually made of thin, flat strips of soft iron, which best concentrates the magnetic force, a layer of heavy wire is wound. An insulating sleeve fits over this, and then many turns



Induction coils make big volts out of little ones.

of fine wire are wound. At one end of the iron core a buzzer arrangement very like that of a doorbell buzzer is set up. When a battery is connected, the spring is holding the contacts together, and current flows through them into the *primary* coil, the heavy-wire coil. This generates a magnetic force so that the iron core becomes a powerful magnet, and that, in turn, attracts the iron plate on the contact. The contact opens—and it is as though a very powerful magnet were suddenly yanked out of the big, finely wound *secondary* coil. All the energy that the electric current in the primary coil spent in building up that magnetic force suddenly rushes out through the high-voltage secondary coil and generates a powerful high-voltage current flow. Simultaneously the magnetic force of the iron core vanishes, and the spring pulls the iron plate away, so that the contact closes once more and another strong surge of current is sent from the battery into the primary coil. The energy of the current from the battery flows *into* the primary and *out* of the secondary. When a low voltage and a large current flow into the primary, a very high voltage and a correspondingly small current flow out of the secondary.

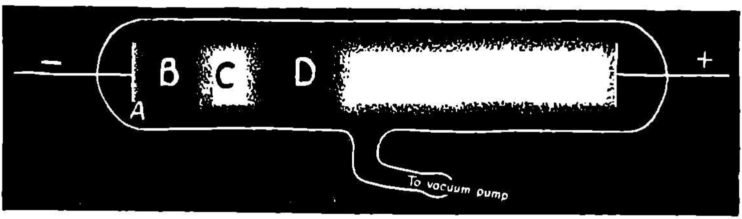
Faraday's induction coil is the great-grandfather of the ignition coil that supplies the spark to keep the engine of your automobile running. It is also the direct ancestor of the "vibrator" in your automobile radio set, which takes the 6-volt battery current and turns it into the 300 volts your radio tubes need. The induction coil can supply voltages up to 250,000, but such coils are usually designed to give about 20,000 volts. This is the reason why spark plugs on your automobile engine can reach out and bite your knuckles the way they sometimes do when you're tinkering under the hood. Fortunately the current is very low; so no damage is done. Anyway, Faraday's induction coil, plus the vacuum pumps the chemists had been developing, were the tools that were needed for the next step forward.

In Paris in 1853, Masson sent the first electric spark from a high-voltage induction coil through a partially evacuated glass vessel. The instant the current leaped through his partially evacuated globe there was no familiar thin spark, but instead the whole globe lit up with a brilliant glow—and Masson didn't know what to do with the "neon" lamp after he had invented it! In 1853 he had in his hands the principle of the modern neon sign and of the ultra-modern cold-cathode fluorescent lighting tube. He also had the key to half a dozen types of electronic tubes used in the most modern equipment—one of the most important aids to spectroscopy and the study of chemistry—and a hundred other immensely important devices.

Standard physics texts refer to Masson as "an obscure French scientist." He made one great invention, one great discovery, but he didn't know what to do with it. Masson did so little with it, in fact, that his name has never even been associated with the neon sign. In the days before neon tubes became standard advertising devices they were known in the laboratories of the world as "Geissler tubes," because a clever German glass blower in Tübingen heard of Masson's discovery and developed the idea commercially.

He made tubes in assorted shapes, sizes, and colors—fantastically complex, with knobs and loops and spirals, and of almost every color except the orange-red now so commonplace in the neon sign. He couldn't make that, because neon gas hadn't yet been discovered. Geissler's tubes became familiar in the laboratories and lecture halls of the Continent, and they spread the interest in high-voltage discharges over the scientific world. Although they were only scientific novelties, their unusual beauty and strangeness attracted attention where attention could be most fruitfully put to work. The strange behavior of electric currents in partially evacuated glass tubes became a fascinating subject for study.

The direction of the next step on the way toward the electron was obvious. What happens when the tube is more completely



The "defective fluorescent light" was a great discovery.

evacuated? That is an easy question, but getting the answer was difficult. The vacuum pumps of the nineteenth century weren't neat little electric motor-driven mechanical types and by no means the superpumps of the modern laboratory, which use mercury vapor diffusion systems. Leather washers were still popular in the mid-nineteenth century. To investigate the problem of the vacuum tube, scientists first had to take a few years to invent a vacuum pump that would work. The result of their efforts was a pump of great efficiency. Then they settled down to further investigations. What they found is shown above.

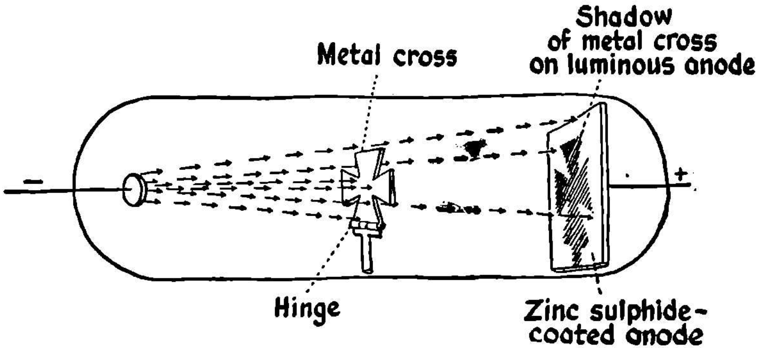
When the pressure in the tube dropped to $1/750$ of normal atmospheric pressure, alternate dark and light bands appeared. These bands were named for their discoverers. The reason they were discovered separately was that each band makes its appearance at a different pressure. Each man who built a better vacuum pump discovered a new dark space and had his name attached to it. At *A* there is a thin layer of faint glow; at *B*, a sharply defined dark space, followed by another luminous region at *C*, followed by another dark space at *D*, which is followed, in turn, by a column of luminosity extending to the positive electrode. The dark space at *D* is called Faraday's dark space. The dark space at *B* is Crookes' dark space. Sir William Crookes' vacuum pump was a little better than Faraday's; his dark space appears last, and it expands steadily, as still more air is pumped out, until eventually it fills the entire tube. The 'scope tube in modern radar and every modern vacuum tube is filled with Crookes' dark space.

When Crookes and his contemporaries first succeeded in getting their tubes evacuated enough to make Crookes' dark space fill the tube and end all gas-discharge glow, they found that the tube still glowed mysteriously with a pale greenish color in the region of the positive electrode. But there was a very important difference about this new glow; it was not a glow *in* the tube—it was a glow *of* the tube. The solid glass of the tube itself was glowing faintly—and further evacuation of the tubes made no difference, except that the glow seemed to vary slightly with different tubes. Some would glow green, some blue-green, and a few almost pure blue.

The cause of the glow was then unknown. For the first time men had observed electrons in action—electrons alone and unaccompanied, unmasked by the presence of atoms. You can frequently see the same phenomenon in a modern radio power tube. A faint bluish glow is often visible on the sides of the tube near the top, a glow that brightens and fades as the music or voice sounds come through the radio. To the first observers the experiment was simply a new and fascinating mystery, as deep as any other. Immediately preparations were made to find out something about it. Many men contributed to the work, of course; Crookes was one of the most important.

Noticing that the color and intensity of the glow varied with the different kinds of glass used in the tubes, the scientists began to look for materials that would glow more brightly, and within a short time the standard material we use today had been found. A specially treated zinc sulphide proved to give the brightest glow with the weakest current in the tube. You've probably seen zinc sulphide glowing with its yellow-green color under the impact of bombarding electrons, just as the scientists of the 1870's did. The radar operator, watching his radar 'scope hour after hour, sees the glow of zinc sulphide under electron bombardment. When you tune your radio to your favorite station by watching the little scissoring shadow in the familiar magic-eye tuning gadget, you are watching a pattern of electrons bombarding zinc sulphide. The radar 'scope tube, the magic-eye tube, and those early vacuum tubes that led to the modern developments in atomic science—all three are cathode-ray tubes.

Crookes and his associates wanted to make the glow definite and bright so that they could see better what was happening. They no-



Electronics—A.D. 1870. Casting shadows of things to come.

ticed that the glow appeared only near the positive electrode, or anode, but a few experiments soon showed that *the rays came from the negatively charged electrode, or cathode.* The experiments were simple. If a piece of metal shaped like a cross was mounted on a hinge between the two electrodes, so that it could be made to stand up or, by tipping the tube a bit, to lie down, it could be shown that when upright it cast a definite shadow. Both the size and the direction of the shadow clearly indicated that the mysterious radiation causing the glow, whatever its nature was, streamed from the negative plate toward the positive plate and tended to travel in a straight line, as you will see from the drawing above.

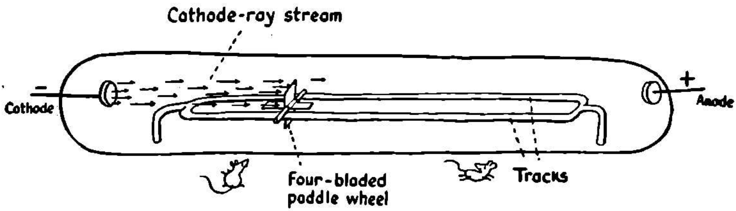
The next time you see one of those magic-eye tuning gadgets, take a good look. There are two hairline shadows, one on each side, in addition to the bigger shadow with which you tune the set. The fine shadows are thrown by a pair of little metal support rods holding the small metal cap that conceals the red glow of the hot cathode inside the tube. Those shadows are exactly like the ones that convinced the scientists that cathode rays travel in straight lines from the cathode to the anode. The large tuning-indication shadow in the magic-eye tube is of the same general nature, but it has an added feature that accounts for its changeable size. We'll see the reason for this later on.

The mysterious radiation, however, remained mysterious; naming it cathode rays made its nature no clearer, any more than naming the water from the sky "rain" made the process of evaporation, condensation, and precipitation any clearer to whoever first used the word. It simply provided a term for common reference. The scientists of the 1870's needed more information. Sir William Crookes wanted to know whether the radiation consisted of a continuous shotgunlike bombardment by minute particles or whether it was due to a radiation similar in nature to light. Was it or wasn't it mechanical bombardment by solid *things?* Sir William made an invention to give him an answer.

The radiometer gadget you may have seen in the window of an optical shop spins its little vanes around when light falls on it. It works because of the presence of air in the tube. Light alone will not supply pressure to drive the mechanical, relatively massive rotor, and the vanes will not spin if they are put in a really well-pumped tube. But, Crookes reasoned, if this cathode radiation is made up of mechanical particles and they are bombarding the anode, then they should be able to do mechanical work and push a windmill around. The sketch on the next page illustrates the device Crookes set up.

The little four-bladed paddle wheel rested on a metal axle across two small metal rails. If the cathode rays consisted of particles traveling from cathode to anode, they would push against the upper blade of the little paddle wheel and spin it, just as a river pushes the paddles of a mill wheel. Many a modern electronics engineer has become so accustomed to thinking of electrons as immaterial electrical charges that he forgets that the electron very definitely has mechanical properties. Sir William's paddle wheel proved this by spinning and rolling along its tracks toward the anode. The cathode rays were definitely composed of some bulletlike particles.

Now men were rapidly approaching the electron. Whatever there was in that cathode ray, it was much more remarkable than anything they had encountered heretofore—a wind that sprang from nowhere, blew hard enough to push a paddle wheel around, and vanished into nowhere. Crookes demonstrated his electron paddle wheel in 1870. The next important discovery was not made until 1895. That twenty-five-year lapse is not surprising when we remember that no man then knew which of the many mystifying facts of nature were the key pieces in the puzzle.



Electrons start pushing things around—A.D. 1870.

The glow in an empty tube didn't seem so important as other things that were happening in those years. Edison's electric light and the development of electric power systems were demanding the attention of physicists. It was in the 1870's that Hertz demonstrated radio waves—incidentally, he demonstrated radar at the same time and used the same kind of radar antennas and tight-beam projectors that our Army and Navy used nearly three-quarters of a century later! The cathode-ray tube was more or less forgotten and for nearly a generation remained in the dusty papers and apparatus cluttering old storage closets.

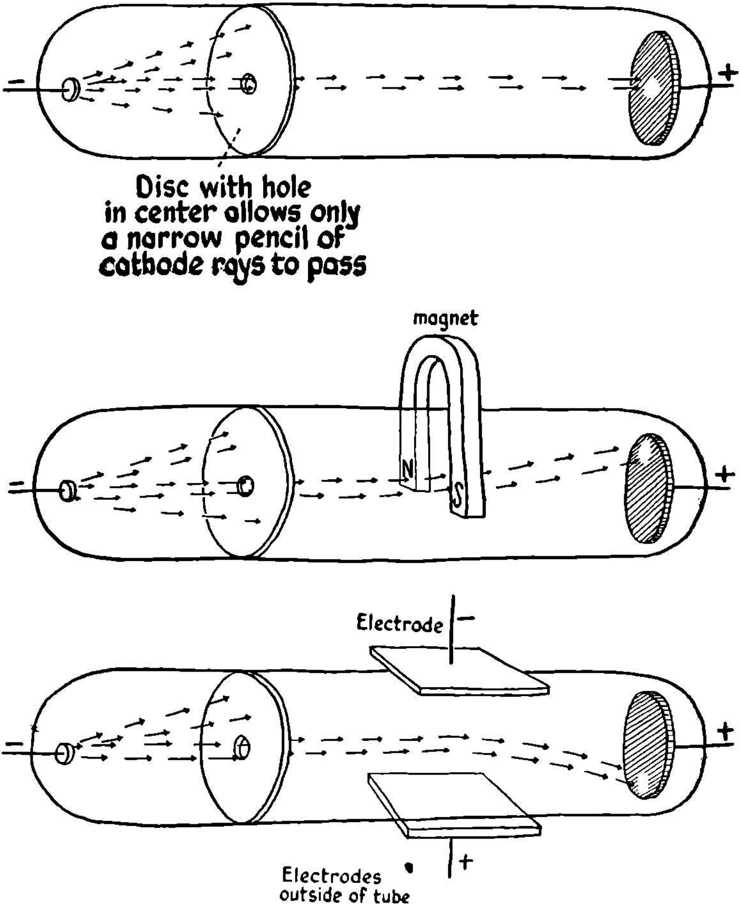
If they had kept at it just a bit longer, our grandfathers might have had electronic devices, vacuum-tube amplifiers, and most of the things in that line that we regard as new and modern today. For all they could see, however, the cathode ray was nothing more than an interesting scientific parlor trick. Investigation was still haphazard and without real direction.

3. *ATOMIC ENERGY IS RECOGNIZED*

SOME SCIENTISTS are fascinated by old and generally forgotten experiments the way detectives are by unsolved crimes. In 1895, Jean Perrin, in France, began to re-examine all the testimony in the case of the cathode ray. He set up a cathode-ray tube similar to the one with the hinged metal cross, but there were a few changes in the arrangement. Instead of getting a small shadow on a large luminous screen, he made a large shadowed screen glow under the bombardment of a narrow beam of cathode rays emerging from a hole in a metal disc, as the topmost of the three drawings on page 35 indicates.

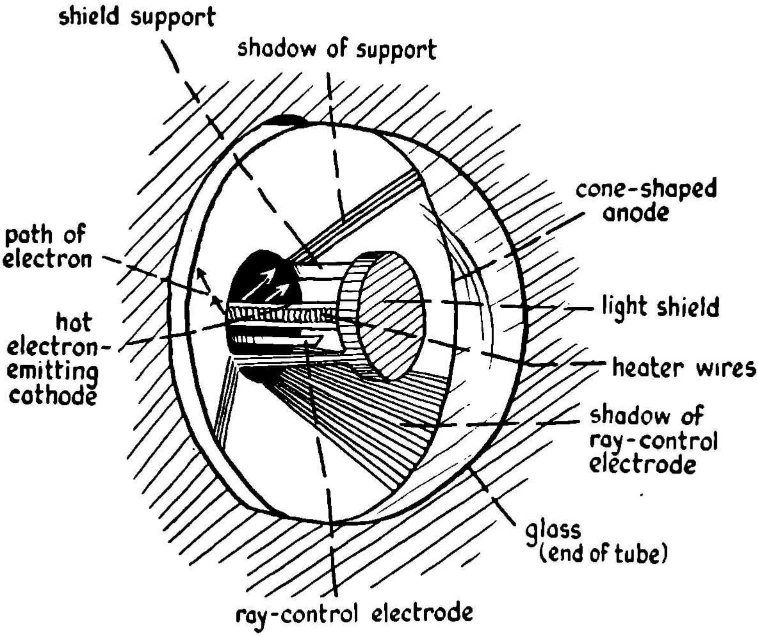
The disc with a hole in it was very important. It embodies the basic principle of the modern cathode-ray oscilloscope, the radar 'scope tube, the television kinescope picture tube, the television camera tube, the electron microscope, and a hundred other modern electronic devices. Also, it permitted Perrin to make an observation that had been missed up to that time. If a magnet was brought near the tube, the pencil beam of cathode rays bent. The cathode rays themselves could not, of course, be seen; only the spot of impact on the glowing zinc sulphide screen indicated that something important had happened. The spot had moved. The middle drawing gives the idea.

Perrin next brought electrically charged electrodes near, but outside the tube. Again the spot moved. The direction of movement in each case indicated that the mysterious particles, which Crookes had found were solid enough to push a windmill around, were negatively charged. If a positively charged plate was put below the tube and a negatively charged plate above, the beam bent downward. If the charges were reversed, the beam bent upward. The arrangement is shown at the bottom of our three drawings. Perrin's experiments can be repeated in your own home if you have a magic-eye tuning tube on your radio; the picture on page 36 will give you a pointer.



First oscilloscope. It took 25 years to invent the hole in the disc!

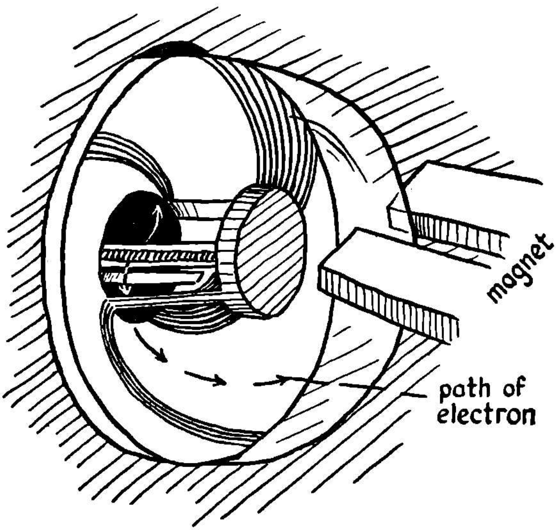
Put a magnet near the green-glowing end of the tube; the pattern of the glowing, electron-bombarded area and the shadowed but unbombarded area will writhe and twist as though some invisible wind were swirling through the walls of the glass tube. Almost any magnet—dime-store variety or stronger—will cause the reaction. If the air is dry and you can get a good static charge on your pocket comb or your fountain pen by rubbing it on a wool suit or dress, try that; the usual plastics, when rubbed on wool, develop a strong negative charge. The pattern of light and shadow in the eye tube will cringe away, going far down into the narrow neck of the tube,



The "Magic Eye" tuning gadget of your radio set—lineal

for negative charges repel each other. The effect of rubbing a glass rod on wool is to charge the glass positively, but the effect on the eye tube is confused by the fact that positive charges attract electrons, and the electrons in the cathode-ray beams within the tube will bend upward. Since, however, they are unable to penetrate the glass wall of the tube, they will stick to the inner surface. These electrons, trapped on the inner side of the tube, neutralize the effect of the positive charge outside—until the positively charged glass rod is withdrawn. Then the trapped electrons on the inside constitute a strong negative charge and repel the electrons in the streams below. Again—but for only a short time, until the trapped electrons leak away—the pattern retreats into the tube.

If Faraday had been able to watch the shift of electron beams in a cathode-ray tube when magnets were brought near and if he had known that electrons were electricity, he could have seen why his electric motor turned. Electrons in a magnetic field are forced to follow a curved path. Since electrons ordinarily can't escape from a copper wire when they are flowing through it, and since the wire is in a magnetic field, they push the wire sidewise in their effort to



Descendant of the first electronic tube!

follow the curved path dictated by the magnetic field. The electrons flowing in the wires in your vacuum-cleaner motor try to follow the same sort of path as the electrons in your magic-eye tube when they are in a magnetic field, and this is what makes the vacuum-cleaner motor spin. The same sort of effort of the electrons whirls the giant rotors in the huge electric motors of a modern aircraft carrier, and the same forces are at work, though in a more complicated manner, in an electric generator.

Perrin's discoveries caused an immediate revival of interest in cathode-ray tubes. The revolution in physical science that came in the next three years was as great as the revolution in thought that followed the Hiroshima explosion in 1945.

Only four ways of storing energy had been known to man: the energy of chemicals, such as coal, oil, or wood; the energy of stressed matter, such as a compressed spring or compressed gas; the energy of mechanical motion—which includes the energy of heat; and the energy of position, such, for example, as that possessed by a lake high in a mountain. The Sun is the source of the Earth's warmth and energy, and after astronomers had measured the Sun's size and weight, it was possible to calculate just how much energy could be stored in that much matter—granted, of course, that there were only these four kinds of energy. The total could be added up and divided by the amount of energy the Sun gave off every year, to give you the answer to how long the Sun would continue to shine. Figuring backward, you could find out how long the Sun had been shining on the Earth; the answer, the astronomers said, was about 25,000,000 years—no longer than that. Paleontologists and biologists were expected to cram the story of the evolution of all the animals on Earth into 25,000,000 years. And geologists had to squeeze the entire history of the crackings and sealings of the Earth's crust into that same period. Meteorologists, who had to help geologists explain how at least four successive ice ages had come and gone in that period, girded against the findings of the astronomers.

Astronomers did not know then that the Sun burns a fifth kind of energy—atomic energy. When this stupendous source of energy was recognized in the late 1890's, all the sciences had to rearrange their calendars. The astrophysicists discovered that the Sun could have been shining at its present rate for at least 5,000,000,000 years and probably longer. They didn't know just how the Sun did it, but experiments from 1895 to 1900 proved that this fifth form of energy existed.

In 1897 the Englishman J. J. Thomson succeeded in measuring the charge per gram on electrons, and the answer he got bewildered the physicists. It was possible to measure the electrons' charge per gram in a cathode-ray tube by setting up a magnetic field of known strength to deflect the cathode-ray beam downward while an electrostatic field of known strength was simultaneously tending to deflect the beam upward. A mathematical analysis of the conditions present when the electric deflection just equals and cancels the magnetic deflection makes it possible to measure the charge per gram of the particles in the beam.

In formal and forbidding technical terms the charge was 5.31×10^{17} electrostatic units per gram. In more understandable terms this means that if you could perform the fantastic feat of collecting one gram of cathode-ray particles in New York and someone else gathered together one gram of cathode-ray particles in San Francisco, the repulsion between the two collections of negatively charged particles, even at that great distance, would reach the fantastic figure of *2,000,000,000 tons.* No wonder these strange particles were so active!

Experiments had indicated that the cathode-ray particles were elementary units of electricity—that they were to electricity what atoms were to chemistry—and the name "electron" was attached to them. The electron, then, was discovered in the cathode-ray tube—or, to be accurate, the particles discovered in cathode rays were called "electrons." The physicists did not then know how universal the electron was; they only knew for certain that they had discovered a particle—a something—with practically no mass, but with an appalling quantity of electric charge.

The discovery of such an incredible amount of electric charge on a particle of so little weight brought a new question into the foreground. Cathode-ray particles—particles *of what?* And for that matter, since they were comparable to chemistry's atoms, just what were atoms made of? If an atom of gold was the least possible particle of gold, then what was that atom made of? Not gold, for by definition it was itself the least possible particle of gold. Chemists had been getting along nicely with Dalton's atomic theory for nearly a century; they simply regarded atoms as hard, unbreakable pellets that never wore out or changed. But pellets of what?

The electron's concentration of electric charge began to suggest some very strange ideas. If someone who had never seen liquid air were to measure the amount of air given off by this cold, bluish liquid, he would probably be amazed at the amount of air "dissolved" in the liquid. It might take him quite a while to realize that the liquid did not simply have air dissolved in it, but *was* air—air in an unheard-of form. Similarly, physicists began to realize that the electron was not a particle carrying a charge of electricity, but *was* electricity—something like a frozen knot of pure electric force.

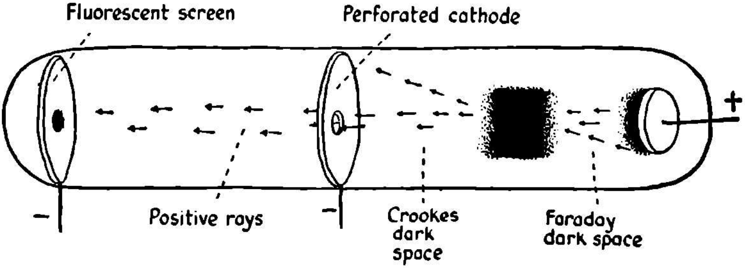
Experiments were beginning to show that electrons could be obtained from any kind of matter, that electrons were in all kinds of atoms. That suggested very strongly that, since electrons were bits of negative electricity, atoms must contain positive bits of electric charge to balance the electrons. Only if the terrific negative charge of the electron balanced with an equally potent positive charge somewhere near by could any gram of electrons stay within millions of miles of any other gram of electrons.

The hypothesis that atoms were not uncuttable—that they were, in turn, made up of other things—rapidly gained favor. Apparently atoms were composed of electrons and some positive charged particles of pure electricity. No wonder chemistry couldn't break down an atom; chemicals can't attack pure electricity.

One of the advantages of the scientific method is that if you have a good theory, it will not only explain what you already know, but may accurately predict things you haven't yet discovered. This one did, for it was a good theory. If atoms consisted of positive and negative electric particles, it was a sound guess that the lightest atom would have the simplest structure and the fewest particles. The easiest place to look for positive electric particles, then, should be the hydrogen atom. Since the cathode-ray tube had been such an enormous help in finding electrons, it might prove helpful in finding the positive charges, if it were modified a bit

The positive-ray effects were first indicated by the fluorescence of the anode end of the tube when it was evacuated completely and Crookes' dark space had filled the entire tube. But if just a trace of gas is left in the tube and the cathode is perforated, a fluorescence will show up on a zinc sulphide screen placed behind the cathode. The fluorescent screen must be connected to the negative voltage supply as the perforated cathode is; otherwise positive charges will accumulate on the fluorescent screen and repel the following positive particles. The arrangement is shown on page 41.

These positive rays can be deflected by a magnet. They can also be deflected by electric charges—but they are attracted toward negative charges and repelled by positive, exactly opposite in behavior to the cathode rays. The same technique of causing magnetic deflection one way and counterbalancing it with an equal and opposite electric deflection can be used to measure the charge per gram of the positive-ray particles. The answer the nineteenth-century scientists got, however, was quite surprising. With hydrogen gas in the tube the particles proved about 1,800 times as heavy per unit of charge as electrons. Other gases, as the scientists had expected, proved still heavier per charge. After many experiments it was ap-



Turning the cathode-ray tube backward yielded the ion-ray tube—great grandpappy of the Oak Ridge U-235 separators.

parent that the hydrogen atom consisted of a single positive-charge particle and a single negative-charge particle. The negative-charge particle had already been named the electron; the positive-charge particle was now christened the *proton.* The charge-to-mass measuring experiments had shown that the weight of the proton, or positive-charge particle, was 1,800 times as great as that of the electron; but the two particles carried exactly equal, though opposite, charges. The hydrogen atom was found to have only one of each type of particle—and therefore the simplest possible structure. Oxygen was tested and found to consist of 16 protons and 16 electrons—which explained why the chemists found oxygen atoms about 16 times as heavy as hydrogen atoms.

Two of the great discoveries necessary before the atomic story could really get under way had at last been made; the electron and the proton were both known. A fairly sound and accurate picture of the atom could now be drawn. The electron is pure negative electricity, the fundamental unit of negative electricity, the "atom" of *negative* charge. It has very little weight, or mass, to use the more accurate term of the physicist—so little that in nearly all atomic discussions its mass can be taken as zero. Roughly speaking, then, this character in the story is *negative-charge-without-mass.* The proton is pure positive electricity and corresponds to the electron in being the fundamental unit of *positive* charge. It's fairly easy to remember that *P*rotons are *P*ositive, and *P*rotons are *P*lump. They weigh 1,800 times more than electrons. In all atomic work they can be regarded as the unit mass. This plump, positive proton character is *unit-mass-with-unit-positive-charge.*

Atomic science was booming ahead in high gear during 1895, 1896, and 1897. Thomson's work in measuring the charge-to-mass ratio of electrons was done in 1896. Measurements of the charge-to-mass ratio of hydrogen and other gases were first made after Thomson's experiments—in 1896, 1897, and much later years; scientists are still at it, for reasons that will become clear later.

A year before Thomson made his measurements another experimenter working with cathode-ray tubes had made a valuable observation by sheer chance. Most scientific laboratories are not at all as Hollywood pictures them. Apparently no true scientist ever bothers to disassemble and put away the apparatus of one experiment until its scattered equipment gets in the way of a new experiment. More than once this untidiness has proved highly rewarding. In 1895 a German experimenter, William Roentgen, was studying the strange properties of cathode rays while some crystals of a barium chemical used in a previous experiment were still lying on the bench. Since he was studying cathode rays and observing the fluorescence in his tube, the room was darkened. He noticed after a while that the barium salt lit up brightly every time his tube was turned on.

That was not on the schedule at all. The cathode-ray particles, electrons, had no business coming out of the end of his tube, driving through several feet of air, and making the barium salt fluoresce. Many experiments, Roentgen knew, had shown that the electrons could *not* get out of the tube. Roentgen immediately wrapped the cathode-ray tube in black paper so that no light could escape.

Scientists already knew that invisible ultraviolet light could cause fluorescence; so the first step was to rule that out. Nevertheless, the barium lit up as before. Soon Roentgen found that the rays were coming from the spot where his cathode rays struck the anode of the tube and that they had properties that marked them as something completely new and unknown. Since X was the standard mathematical symbol for the unknown, he called the radiations X-rays.

Roentgen's X-rays caused a lot of argument among physicists before they were finally identified. Obviously they were immensely significant. A few weeks after Roentgen's discovery X-rays were being used in connection with a difficult surgical operation at a Vienna hospital. Putting a different emphasis on the matter, the State of New Jersey debated a proposal to prohibit by law the use of X-rays in glasses or binoculars at public entertainments; there was a slight misunderstanding about the ability of X-rays to see through materials. At any rate the news of X-rays spread quickly through the world of science. A professor of chemistry in France believed that anything man-made instruments could do, Nature had probably done first, and he had a rather good idea of how to go about hunting for a natural X-ray emitter. That French chemist, Henri Becquerel, with his simple experiment, turned up a fact that threw the whole scientific structure of the day into chaos.

Atomic energy was discovered by Becquerel in 1897—more accurately, nuclear energy. A chemist, John Dalton, had first given proof of the existence of indivisible atoms; not quite a century later this other chemist, Becquerel, proved that the atom was not indivisible, but could explode of its own accord.

His experiment was simple both in concept and in execution. If there *was* a natural X-ray emitter, it certainly could not be one of the common materials, or it would have been noticed. Since X-rays could darken photographic film through opaque paper, it would be easy to test a great number of substances to discover if any of them emitted the mysterious rays. Becquerel gathered a large collection of the more unusual minerals he could find, put a piece of each on a sheet of photographic film wrapped in opaque paper, with a bit of metal opaque to X-rays—a key, a coin, anything of that sort—between the mineral sample and the wrapped film. If a piece of film were defective and already fogged, or if light somehow leaked in through the paper wrapping, there would be only a general darkening. But if X-rays came from one of the samples, there would be a darkened film with the shadow of a key or coin in bold relief.

This experiment is represented in the section of photographs in this book by a demonstration of the radioactivity of uranium. In the modern version a sample of uranium nitrate crystals was sprinkled over letters fashioned out of sheet lead and taped down to a piece of cardboard. The cardboard was placed on a sealed envelope containing a sheet of ordinary photographic film and left there for 72 hours. The film was then developed; the lower of the two pictures shows the result.

Of all the samples Becquerel tried, pitchblende, a uranium-bearing ore that he got from Austria, was the most active. As a chemist Becquerel was largely interested in determining what substance in the pitchblende was responsible for the reaction and in concentrating that substance in its pure form. Pitchblende was not the only mineral that reacted, however. Thorium minerals, among the most complex of minerals and containing practically everything in the table of chemical elements, and several other uranium minerals also had the effect of darkening film.

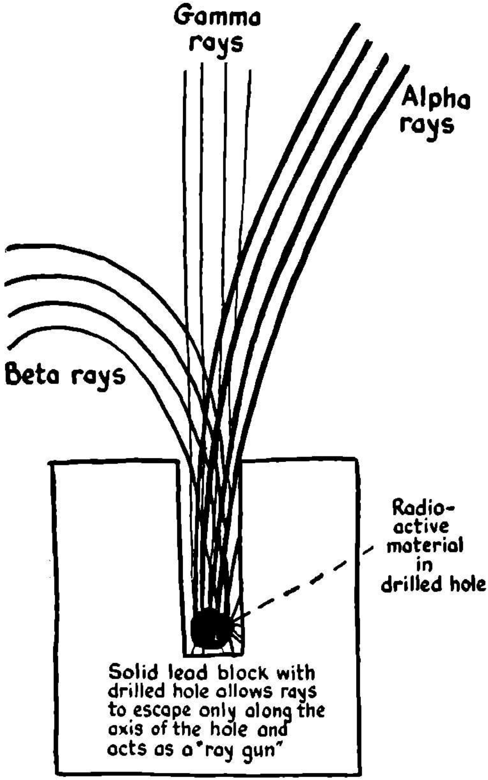
The Curies, of course, were the ones who disentangled the chemical snarl. Essentially they were trying to discover perhaps half a dozen completely unknown elements, with no clues but the weakening or strengthening of X-ray emission from their solutions under different chemical treatments. That method is difficult when half a dozen different elements are involved, and the experiments were further complicated by a gas that gave off the mysterious rays. This gas behaved as no gas had a right to, for it had no chemical properties. Lord Rayleigh and Sir William Ramsay had discovered, three years before Becquerel's experiments, a rare inert gas in air and had named it *argon,* from the Greek word meaning "lazy." Now the Curies decided they had found a gas that wouldn't do anything—anything, that is, but give off rays of great power.

The chemists—the Curies and others who immediately plunged into the strange new research—found additional remarkable phenomena. Here, for instance, was a solution containing a minute amount of some chemical substance that precipitated out and acted chemically like thorium, a well-known element that emitted relatively weak rays, or, in other words, was only mildly radioactive. The mysterious stuff, which had derived from uranium, was extremely radioactive. Photographic film and electroscopes both showed that it had great activity. Three days afterward the solution was much less radioactive—and by then the radioactive material, whatever it was, no longer resembled thorium. Apparently in the course of three days the chemical element that had separated had changed itself into an entirely different chemical element with different chemical properties. If that were true, then the scientists had actually found in their test tubes the thing the alchemists had sought for centuries—the transmutation of one element into another.

The Curies are most widely known for this discovery of radium in uranium ore. Radium, however, was neither the first nor the last element the Curies isolated from pitchblende. Polonium—named for Poland, the native country of Mme. Marie Curie—was the first element they isolated. In many ways this was better than radium for the purposes of nuclear physicists; for other purposes a relatively crude concentrate of uranium and its associated radioactive products was more suitable and cheaper.

The first work of the physicists was done on crude pitchblende itself, for it was in crude pitchblende that Becquerel had found a source of radiation suggestive of X-rays. The most definitive experiments were made by Lord Ernest Rutherford, who was to become the Grand Old Man of nuclear physics. There are really three Grand Old Masters of nuclear physics; Lord Ernest Rutherford, Niels Bohr, and Albert Einstein played the greatest roles in the development of modern nuclear physics. Rutherford, Bohr, and Einstein participated in the research from the earliest days, when natural radioactivity gave men the first suggestion that atoms were not really unbreakable and that they actually contained great stores of energy capable of release.

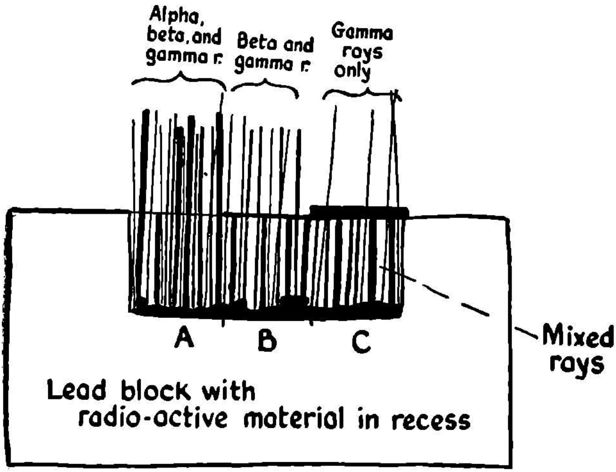
These three men were beginning their great careers when science first realized there was something *to* an atom. They established the existence of the nucleus and its energy. And these same three men worked on the Manhattan Project that devised the first atomic bomb. Within not merely the lifetime of men now living, but the active scientific careers of men now living, the whole science of nuclear physics has been discovered, developed, and become an engineering rather than a laboratory problem. Within forty-five



Separating the mysterious rays of uranium by electrical characteristics. There's an invisible magnet at work; one pole is just behind you, the other on the other side of the page.

years science has advanced from total ignorance of the existence of the nucleus to the ability to release its vast energies.

Rutherford concentrated on the rays emanating from uranium ores—the "Becquerel rays." His experiments proved they could be divided into three groups, which he named alpha, beta, and gamma rays, after the first three letters of the Greek alphabet. Essentially he was simply calling them Ray 1, Ray 2, and Ray 3, for a name means little or nothing until you define the properties of the thing to which it applies. Rutherford found that the first and second types of rays—alpha and beta rays—were affected both by magnetic forces and by electric forces. The gamma ray was not so affected. The diagram below shows the difference.



Separating the rays of uranium by filters.

Imagine that a horseshoe magnet is placed at right angles to the drawing just above the little "ray-gun" arrangement so that one pole is on this side of the paper and the other pole on the other side. Although both alpha and beta rays are deflected, the deflection is in opposite directions. The characteristic of being subject to deflection by electric and magnetic fields indicates that alpha and beta rays consist of charged particles. The gamma ray's indifference to the magnetic and electric forces indicates either that it is composed of uncharged particles or that, like radio waves and light waves, it is a true radiation.

The next important series of investigations was concerned with the penetrative power of the rays. Alpha rays are easily blocked off—a piece of tin foil from a candy bar is enough to stop them. Beta rays are much more penetrative and can drive through more than ten times as much solid metal. Finally, gamma rays will go through very thick layers of quite dense metal. Today radium capsules, which give off gamma rays, are used for inspecting heavy metal castings; sometimes steel as much as 18 inches thick is successfully "radiographed"—the technical term for photography with radioactive rays instead of light rays.

The nature of the different rays was soon discovered. Beta rays proved identical with the negatively charged cathode rays—ordinary electrons shot from the radioactive material with great velocity. By using Thomson's technique of balancing the deflection of the rays by magnetic forces against the deflection by electric forces, it was possible to measure the charge-to-mass ratio of electrons. The deflection by either magnetic or electric forces was in the same direction that the electrons took. Since the beta-ray particles acted exactly like electrons, they probably were electrons. "Beta ray" might be remembered now as the radioactive name for the unit better known as "electron." You'll hear about beta-ray electrons often as the story goes on.

Alpha particles can be deflected by both magnetic and electric fields, but show a positive instead of a negative charge. Measuring the charge-to-mass ratio of these particles proved that they were heavyweights—but also heavily charged, for they carry two units of positive charge and have four units of weight. Since they can penetrate thin foils, one of the early experiments called for placing a bit of radioactive matter and an evacuated thin-walled tube close to each other for a time and later testing to see what, if anything, could be found inside the sealed tube. Alpha particles, according to expectation, had been able to penetrate one wall of the tube, but had not had enough power to get out again through the other wall. Beta particles, being much more penetrative, had sailed through both sides. There were, of course, no holes in the tube as a result of this ultramicroscopic bombardment. The tube contained trapped alpha particles that, once they stopped moving at the furious rate of the atomic explosion that originally expelled them, had simply picked up a couple of negative charges apiece—electrons, that is—and settled down quietly as neutral atoms. The spectroscope showed that the newly born atoms were ordinary helium.

"Alpha particle," then, is the radioactive name for ordinary helium atoms—ordinary except that, because of moving in such a furious hurry, the outer fringes of the helium atom, the two electrons, have been knocked off. This leaves the helium atom with two positive charges, but it's a very, very temporary situation. About two millionths of a second after it slows down to a speed below 1,000 miles a second or so, the helium nucleus picks up the missing electrons. Since the world is composed of atoms, and since all atoms have electrons surrounding them, there are always lots of electrons around. The electron-hungry helium nucleus has no trouble finding them.

Next, gamma rays had to be identified. This was much more difficult. It was shown that gamma rays were of the same general nature as the X-rays Roentgen had discovered. But this wasn't too much help, because X still stood for "what-is-it?" Having demonstrated that "gamma rays" was a radioactive name for X-rays, the scientists still had to identify X-rays. There were, however, differences in degree between the two rays. The X-rays emitted by the tubes built in 1900 could be stopped cold by an inch or two of steel, while the gamma rays of radium went through a foot of the same stuff. X-rays, when they fall on a piece of matter, drive out electrons; gamma rays do the same—but with much more power. These differences, though, were matters of degree, not of kind. With modern superhigh-voltage tubes we can produce X-rays that are a great deal harder to stop than the rays that radium generates.

After a great many experiments and mathematical analyses the answers appeared. X-rays and gamma rays are exactly like radio waves and light waves. They differ only in wave length. Broadcast radio waves, the long-wave kind used for ordinary programs, pass right through ordinary houses and buildings, but are bounced back and forth between the ground and a conductive layer of ionized gas in the high stratosphere, a layer they can't penetrate. FM and television short waves act differently because of their much shorter wave lengths. These waves pierce that layer of gas in the stratosphere, are not bounced, and consequently cannot be picked up around the bend of the Earth. They're good only for short distances—30 to 50 miles. These shorter waves *cannot* penetrate buildings; instead, they bounce.

Gamma rays play a first-rank role in the atomic story. Their properties should be kept in mind for future reference. They are the most penetrative radiation known to science—they will penetrate anything in the world. Lead does not stop them in the same way that a heavy, case-hardened, nickel-steel armor plate stops a bullet. Lead simply absorbs them gradually, the way a thick layer of insulation muffles sound by absorption. If a centimeter of lead stops half the gamma-ray energy, two centimeters of lead will *not* stop all of it. The second centimeter stops only half of the energy that got through the first centimeter. A third centimeter will stop only half of what's left. You can never stop *all* the rays. However, you can soak up a high percentage so that the remainder no longer counts.

Actually, lead is not the best material for stopping these rays. Strangely enough, there is nothing in the world that absorbs gamma rays so well as pure metallic uranium. It isn't to be recommended as a gamma-ray stopper, though, because uranium is also an excellent source of the rays. The next best material is iridium metal, but this unfortunately is about ten times as costly as platinum. Platinum, gold, and osmium—osmium's a bit more expensive than platinum—come next in line. Tungsten, which follows, might be used except for one thing—you can't cast it. It melts only at 3,500° C., and at that temperature every other substance is already a liquid, a gas, or in the process of boiling rapidly away. So we use lead. It is about two-thirds as effective as gold or platinum, which means that there is no point in using the more expensive materials. The power of a material to stop gamma rays depends on the weight of each atom and, naturally, on how many atoms are crowded into one centimeter of its thickness. Uranium is the most effective material for the purpose, because it is nearly twice as dense as lead and has the heaviest atom that is found in natural materials. But *all* substances impede the passage of gamma rays to some extent, even hydrogen, the very lightest and least dense. A half-mile of air is much more effective than a half-inch of iron.

Gamma rays are deadly. They're pure essence of poison. Like nearly all powerful poisons, they are immensely valuable medicinal agents under proper control—regulated in intensity and quantity so that they can be made to destroy a cancer without destroying the human patient. But out of control they are the most dangerous of all rays. They can quite literally poison "unto the third and the fourth generation"—and on to the end of time, for that matter. Gamma radiation can so change the germ cells of unborn children that the child will not have the same heredity as its parents. The change can be for the better or for the worse; it's pure chance. A heavy dose of the rays can render adult animals and plants sterile. Still greater doses can cause a type of cancer that may not reveal itself for weeks, months, or years. Many of the very early workers with both X-rays and radioactive materials, not knowing the dangerous nature of the rays, discovered these facts by bitter personal experience. And, of course, an extreme dose of gamma rays can cause instant death. These rays are intensely concentrated, tremendously powerful packets of raw energy. They're dangerous! You won't be astonished to find the gamma ray entered in the Cast of Characters as the villain of the atomic story (see front of book).

That list of characters, by the way, may be helpful as a reminder every now and then if you find you do not recognize some of the actors. One of the leading characters has not as yet been mentioned. In fact, though the investigators now had the conception of atomic energy, which is the central theme of the atomic story, they had not yet discovered the heart interest. The nucleus was still waiting in the wings for its cue.

4. DISCOVERY OF THE NUCLEUS

THE INVESTIGATION of the different sorts of rays from radium and other radioactive elements had spurred the scientists to a search for their sources. In 1897 there was no theory that could explain the nature of the energy that produced these rays. But there were methods of measuring the amount of energy the rays released. For example, a strong solution of radium bromide is always warm, and this warmth can be measured with calorimeters and thermometers and the amount of energy calculated that it represents. Results of such calculations had forced all the sciences dealing with the history of the Earth to revise their calendars. The amount of energy that one gram of radium released in the course of its ceaseless activity was almost unbelievable. Even more awesome was the implication of terrible hidden energies in all things. The atoms that scientists had known for nearly a century—which, before the discovery of radioactivity, had seemed as commonplace to the scientists as cobblestones—were now mysterious and frightening. It was as though, moving about in a room barely lit by a dim ray of moonlight, the vague, massive shape you had taken for a large chair had stirred noiselessly and stretched huge muscles before settling back into watchful waiting.

The atom was the infinitesimal brick of which all things were built. But it wasn't really a brick, an inert thing. It was a mechanism of unguessable complexity in which forces of immense magnitude were at work. It was dynamic, and its impenetrability might be thought of as comparable to that of a spoked wheel spinning with silent but enormous speed. No force under man's control had ever been able to touch that dynamic defensive wall of the atom. But now perhaps he would be able to get inside, to break through, by using as tools the energy that radioactive atoms themselves produced.

None of the old tools of science could unlock the atom. Chemical energies could, and did, move atoms, but they moved them as a whole. Mechanical energy, no matter how great, won't do chemical work effectively. The strongest elephant in the world or the mightiest steam engine can't break water into the hydrogen and oxygen of which it is made. It takes only a little energy to do that—but it takes *chemical* energy. To explore the inside of the atom, men needed atomic energy. It was not only immensely more energy they required; they had to have a more concentrated energy. If you push a pea with the end of your finger, the pea moves; if you push with the point of a sharp needle, the needle exerts a force so concentrated that it penetrates. Atomic energy is concentrated beyond anything human imagination can conceive. The energies locked up in the heart of a helium atom—the helium nucleus that is also the alpha particle—represent the potentials of a lightning bolt hundreds of feet long, compressed and bound by forces even more violent than these potentials into a space less than $\frac{1}{500{,}000{,}000{,}000}$ of an inch in diameter. An atomic nucleus is pure quintessence of energy compressed and bound under seals of still greater power; it is like the genie of the *Arabian Nights* forced into an invisibly small bottle and sealed with a mystic sign that holds it and all its fury.

Sometimes, as with radioactive elements, the seal on the atom slips just a trifle. Then an electron escapes from the seething fury inside and comes driving out at 300,000,000 to 500,000,000 miles an hour. Sometimes such a concentration of energy has been crammed into one bottle that not even all the power of the binding energy can hold the clamps in place. Then, bit by bit, some of the energy escapes. That is what is happening in the elements we call radioactive. Evidence of this is given by the strange rays that issue from radium and uranium. Ordinarily the nucleus can be reached only by a particle coming from outside the atom and attacking with a violence similar to the violence already present inside the nucleus. Lesser forces are turned away by the outer fringes of the atom—the outer electrons. Before radioactive elements were discovered, science lacked the means of driving a particle against an atom with such energy, and it remained impossible to explore the interior structure.

These voltages, or electrical pressures, may give an indication of what was required to discover that there *was* a nucleus: A flashlight dry cell generates about 1.5 volts; a group of them in a radio B battery delivers about 90. Ordinary household power is 110 volts. An average radio set uses about 300 volts. Cross-country high lines of the power networks may vary from 50,000 to a present maximum of 280,000 volts. Dentists' X-ray machines usually operate on 75,000 volts; a few hospitals now have deep-cancer therapy machines using as much as 1,000,000 volts. In 1900, 50,000 volts was about the highest electrical pressure that could be generated and controlled.

Here is what those voltages are capable of doing to an atom: 1.5 volts will cause some minor chemical reactions; other chemical reactions required up to 4.0 volts. It takes about 15 volts to pull a single electron from the outermost of the mercury atom's fourteen rings of electrons. That's what's happening in the familiar blue-green mercury vapor arc lamps. Household power-line voltage—110 volts—could get through several electron shells before being bounced out again; that is still remote territory, however, and the defenses of the nucleus remain practically intact. Cross-country power-line and dentists' X-ray equipment voltages can drive the attack through to the main line of the outer defenses—the inner electron rings; the attacking particle is hurled back so violently now that the impact generates X-rays—which are what the dentist wants.

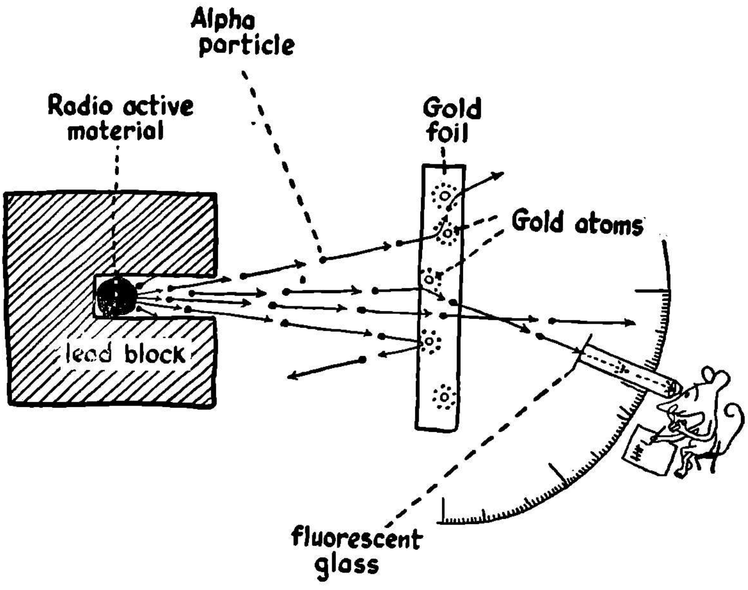
The nucleus itself—the inner citadel—hasn't yet had to react to its own defense and therefore hasn't betrayed its existence. Only an attacking particle that is driven in with 500,000 volts or more can penetrate far enough to encounter the nucleus, lying screened behind layer on layer of defending electrons. That picture of the atom is one we have gained by exploring with just such violently driven atomic particles. In 1900 scientists' picture of the atom was very different, for, lacking high voltages, experimenters had not been able to drive their attacks deep enough.

Experiments before 1900 had revealed the electron and the proton and had shown that all the atoms heavier than hydrogen seemed to have several protons and a number of electrons in them. But *how* were these particles in the atom? The theory of atomic structure current in 1900 might be called the plum-pudding theory. It visualized the structure of the atom as resembling more or less an old-fashioned plum pudding, with the positive charge filling the whole sphere of the atom and the negative electrons embedded in it like the plums in the pudding. This theory was not well supported by evidence. No one had made any investigations of what went on inside the atom; scientists knew only that there were somehow two different kinds of electrical charge in the atom and that positive electricity seemed to account for its mass.

With radioactive atoms for their artillery, Rutherford, Bohr, and Einstein were ready to begin. Nuclear physics found its great experimentalist in Rutherford; Bohr and Einstein were its mathematicians and theoreticians. Bohr, the Danish scientist, was a very young man in 1910, but already a great theoretician, deeply interested in the data that were beginning to come from Rutherford's English laboratory. In the decade of 1900–10 practically none of the instruments necessary for modern atomic research existed. Cyclotrons, Geiger-Müller counters, vacuum-tube amplifiers, ionization gauges, Wilson cloud chambers—all these apparatus of modern nuclear physics lay in the future.

Lord Rutherford set out to measure the diameter of an atom. He did it with an extremely simple apparatus. Becquerel had discovered radioactivity with a hunk of rock and a piece of film. Rutherford measured the diameter of the atom with a bit of radioactive matter, a block of lead, a piece of fluorescent glass, and a protractor—a protractor not much more complex than the one you used in high school to measure angles.

Rutherford set up an atomic "gun," consisting simply of a bit of radioactive material at the bottom of a hole drilled in a block of lead. The radioactive material threw out alpha particles in all directions, but only those going out of the barrel of the gun were not stopped by the lead block. They either went straight down the bore of the drilled hole or were absorbed. Rutherford wanted to "feel" the size of the atom, and since the only thing small enough to feel an atom is another atom, he intended to use as his "feeler gauge" the helium atoms shot out by the radioactive material in his atomic gun. The detailed procedure was complicated, but we can outline the experiment. Rutherford set his lead-block atomic gun to fire atomic particles at very thin gold foil. Some of the alpha particles or helium nuclei that were his projectiles would go straight through, completely missing the gold atoms in the thin foil. Others would make head-on collisions and be bounced directly



How to measure the diameter of an atom with household gadgets.

back toward the atomic gun. Still others would make glancing hits and carom off at various angles.

With his atomic gun Rutherford could know the direction of the projectile before it hit. With a small microscope he could actually see the impact of a single alpha particle on a tiny piece of fluorescent glass—simply a bit of glass coated with the same zinc sulphide that had made cathode rays visible. He could detect the particles in this way after they had passed through the gold leaf, and the protractor made it possible to measure the angles at which the particles had been bounced. By counting the number of minute flashes caused by the projectiles from his atomic gun when no gold leaf was present, he could determine how many projectiles he was firing in five minutes. Then by counting the number of flashes showing on his fluorescent glass at various angles during a five-minute run, he could determine what percentage of alpha particles rebounded at each different angle.

All the necessary materials for this sort of experiment may very well be in your home now. Any solid chunk of metal with a small hole drilled in it will do for the gun; it doesn't have to be lead. A magic-eye tuning tube contains a zinc sulphide fluorescent screen. A tiny scraping from the luminous hand of a watch or clock will supply you with the alpha-ray emitter; a fluorescent material is mixed with such material, but that won't matter. Almost any good protractor can be used. A strong magnifying glass completes the apparatus, save for the gold leaf—and there's probably some of that around on a picture frame or a book cover. Silver and copper foils were also used in Rutherford's experiments, if you are interested.

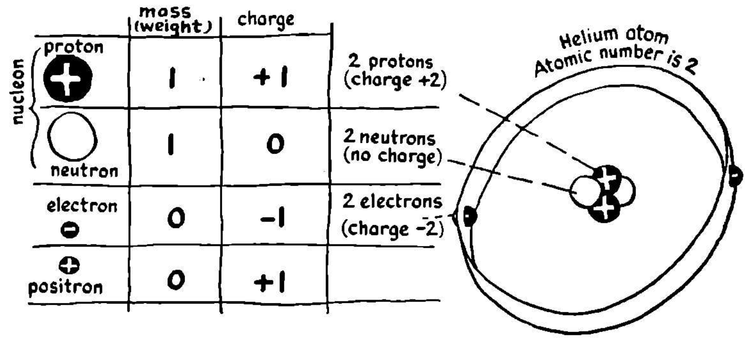
With just this kind of material he measured the diameter of the atom. His results were bewildering to the older generation of physicists and thoroughly disposed of the plum-pudding theory. He found that *all* atoms had essentially the same diameter—about 10^{-12} cm. That system of writing the huge numbers of physics and astronomy is simple, handy, and worth remembering. Since we use a decimal number system, the "10" is used as the basic unit. The minus sign in the superscript means that the number after translation will be a fraction; if there were no minus sign, it would be a whole number. The "12" means that there are 12 zeros behind a 1. Therefore, in normal—but cumbersome—numbers, the diameter of an atom is about $\frac{1}{1,000,000,000,000}$ of a centimeter. All atoms, apparently, had the same diameter. Why should that be? Gold, silver, copper, and even the light helium atoms were the same size—but a gold atom is about fifty times as massive as a helium atom.

The factual data gathered by Rutherford were interpreted by Niels Bohr, and his atomic theory, published in 1913, has become the basic theory of modern atomic science. A few modifications of its details have been made, but the essential structure remains unchanged. The atom, as most people today know, is a miniature solar system. Almost all the mass of the atom is concentrated in the nucleus—just as nearly all the mass of the solar system is concentrated in the Sun; the mass of the planets is insignificant by comparison. In the atom the mass of the electrons is equally negligible.

These electrons are arranged in successive layers, or shells, at various distances from the nucleus. The distances are enormous by comparison to the diameter of the central nucleus—which is what Rutherford had actually measured. The Sun is much larger in comparison to the enormous distances of the solar system than the nucleus in comparison to an atomic system. Atoms are very nearly nothing but empty space. Their appearance of solidity is a deception somewhat like that practiced by a good goalie in a hockey game. The goalie can't be everywhere the puck is, but a good one gets around so fast that the effect is the same—the puck can't get through. Similarly, the atom isn't actually everywhere in all that space, but its parts move around at such blistering speed that it might as well be. Nothing else can get in there successfully unless it's going even faster.

The electron shells stretch far beyond the minute nucleus, and it is these outer shells that stop all ordinary invaders. Rutherford was firing helium nuclei with enormous velocity at gold atoms. The outer electrons defending the gold atom weigh about a two-thousandth of a hydrogen atom. Since the nucleus of a helium atom is four times as massive as that of a hydrogen atom, it is 8,000 times as heavy as an electron. Traveling at tens of thousands of miles a second—as alpha particles or helium nuclei do when they're fired out of a radioactive atom—and being 8,000 times as massive as the defenders of the gold atom, the helium nuclei had simply crashed straight through, smashing electrons out of the way like snowflakes exploding in the path of a baseball thrown forcibly into a snowbank.

The helium nucleus is bounced only when it has driven through to the region of the gold nucleus. That is something that even a 10,000-mile-a-second alpha particle cannot penetrate. Both the gold nucleus and the helium nucleus bounce. The explanation for the bounce is simple enough. The gold nucleus carries 79 positive charges, the helium nucleus 2. You may remember the calculation we mentioned earlier that indicates that a single gram of electrons in New York would repel a gram of electrons in San Francisco with a force of 2,000,000,000 tons. Electric repulsion forces increase as the *square* of the distance between them diminishes. If those electrons in New York were brought half the way to San Francisco, the repulsion would be not merely doubled, but quadrupled; at a quarter of the original distance it would be 16 times as great. When two positive atomic charges get within billionths of an inch of 79 positive charges, the repulsion between them is almost incalculable.



The helium atom.

It is great enough to stop an alpha particle traveling 10,000 miles a second, turn it around, and send it back as fast as it came.

Other data Rutherford gathered from his experiments indicated that, contrary to the plum-pudding theory, the number of positive charges in the atom was not equal to the number of atomic weight units. The proton—the elementary positive-charge unit that is the whole nucleus of the hydrogen atom—has both unit positive charge and unit mass. Then, if a gold atom, for instance, has a mass equal to 197 hydrogen atoms, one might expect its nucleus to have 197 positive charges. Rutherford's work clearly indicated, however, that the gold nucleus had 79 positive charges.

In the chemist's list of elements, known as the periodic table, hydrogen, being lightest, is No. 1; helium comes next as No. 2; the next heaviest, No. 3, is lithium. Going on up the table in this way, we find oxygen, weight 16, as the eighth element in order of weight.

Silver, weight 107.8, is the forty-seventh. And gold is the seventy-ninth element in order of weight. The atomic number of gold—that is, its order in a table of elements arranged by weight—is 79. Rutherford's data indicated that it had 79 positive charges on the nucleus. The two items added up to something, for silver showed 47 positive charges and was forty-seventh in order of weight.

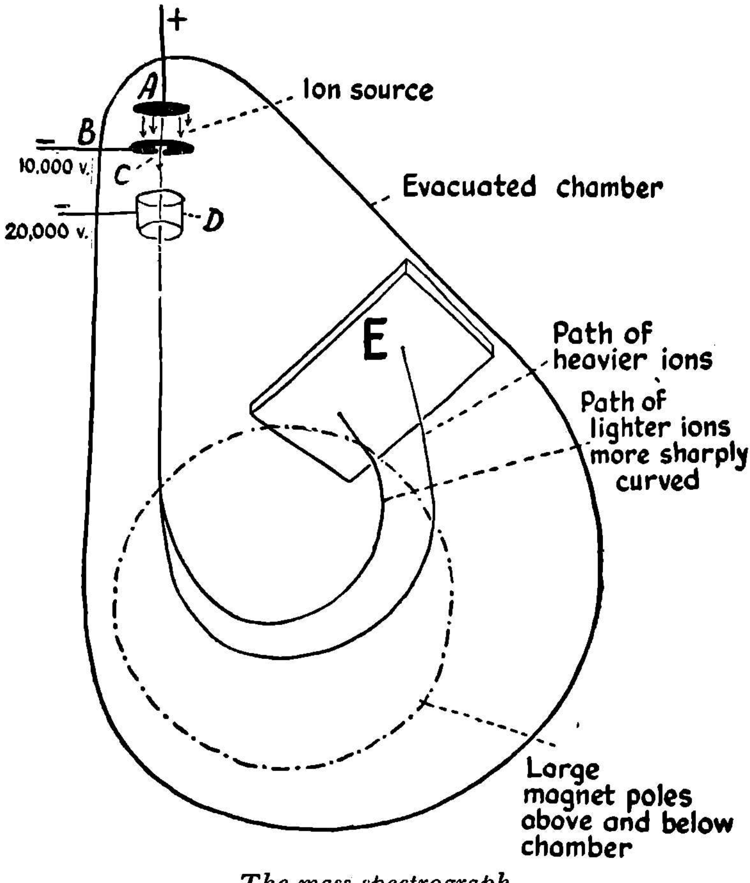
The nucleus, Bohr theorized, contains all the massive protons and therefore contains all the mass of the atom. But in addition to the number of protons making up its atomic weight, it also contains a large number of electrons, bound within the nucleus itself; the number of electrons is equal to the difference between the atomic weight and the atomic number. That meant, for example, that there were 197 protons in the gold nucleus, and 197 minus 79, or 118, electrons. The 118 electrons neutralized the positive charges of 118 protons, but left 79 proton charges unneutralized. These 79 charges were neutralized by the 79 negative charges of the 79 electrons in the electron shells surrounding the nucleus. The differences between chemical elements, according to Bohr, were determined solely by the outer electron shells; the nucleus was so deeply buried behind shell after shell of outer electrons that it had no direct influence on chemical reactions. Its positive charge held the electrons in the shells, of course, and was thus indirectly responsible for the chemical behavior of the element.

Since only the *number of charges* on the nucleus was responsible for holding electrons together and the nucleus had no direct influence on chemical behavior, it seemed that the *weight* of the nucleus was unimportant in chemical work. It seemed not to matter whether a gold nucleus weighed 150 or 250; all that mattered was the fact that it had 79 positive charges. Evidently, however, some natural law prevented a nucleus with, for instance, 79 protons and no electrons within it from being stable. A large nucleus made up purely of protons must be completely unstable, because, of course, no such nucleus exists in nature. Similarly, a nucleus with too few protons in proportion to its weight must be unstable. Yet some slight variation might be permissible. That would explain why silver showed an atomic weight of 107.8 and chlorine showed 35.5. The decimal values were too large to be due to errors of measurement. A chlorine atom of 35.5 protone just didn't make sense. But if there were two sorts of chlorine atoms, one kind having 35 protons and 18 electrons, giving a net positive charge of 17 units, and another kind having 36 protons and 19 electrons, also giving 17 net positive charges, the two types of atom would behave exactly alike so far as the chemist was concerned. If he found them mixed, he could never separate them; in determining their weight he would have to give an answer between 35 and 36. This kind of atom was called an *isotope*.

If the theory was correct—if two atoms could have different weights but the same chemical properties—there was a method that should be able to prove it. If there actually were chlorine atoms of weights 35 and 36, both having 17 charges on the nucleus, there would be two kinds of chlorine, with different charge-to-mass ratios. The positive-ray device—the cathode-ray tube in reverse—that had been used to measure the charge-to-mass ratio of protons should be able to detect that difference. But in this case, since the problem was to detect a difference in charge to mass rather than to measure the charge to mass, a slightly modified system proved more advantageous. The device that was used is known today as the *mass spectrograph.*

In 1915 "isotope" and "mass spectrograph" were new ideas, interesting only to a small group of physicists. Thirty years later, in 1945, they were to be of enormous importance to everybody. It was a uranium isotope that devastated Hiroshima, and a modified mass spectrograph was used to separate it from other uranium isotopes.

In the mass spectrograph the gas-discharge tube of Herr Geissler has shrunk away till it has become simply an appendage, now known as the "ion source." The original anode and cathode are still there, but the cathode has a slit through which the positively charged ions can pass. An ion is simply an atom that has been stripped of one of its outer electrons. Getting the atom to part with a single electron is not particularly easy; that is the toughest problem about the mass spectrograph. The best way is to knock one electron out of the neutral gas atom by slamming an electron into the atom hard enough to blast out another electron. The atom must have one or more electrons knocked out of it so that we can get hold of it—preferably one, for a neutral atom won't react to electric or magnetic forces. Once the electron is knocked out, its net positive charge can, roughly speaking, be used as a handle. The apparatus is diagramed below.



The mass spectrograph.

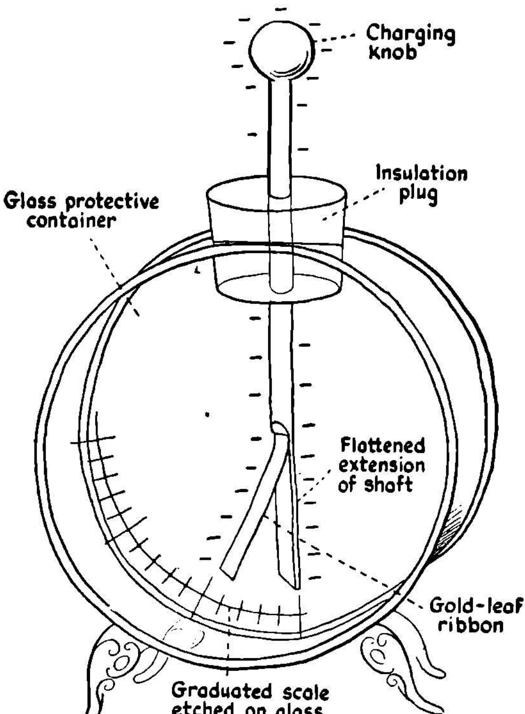
After the gas ions are generated and passed through the slit at *C,* they are further speeded up by accelerating voltages applied to the plates at *D.* Then the beam of ions—an invisible ribbon of flying charged particles—passes out into the region of the magnetic forces applied between the big magnet poles shown by dotted lines. The magnetic force deflects them and bends their path into a loop, which ends on the plate at *E*. That plate is usually a photographic film; the ions pounding on it darken it. Since the magnetic force exerts its energy on the electric charge, it will push equally hard on all ions having one positive charge. It is a lot easier to deflect a light ion—one weighing 35 units—than a heavy one; so if there is a mixture of ions of different weights, the path of the light ions will be bent more than that of the heavy ions.

The mass spectroscope was developed and promptly applied to elements that showed odd-value atomic weights. Chlorine's 35.5-unit atomic weight turned out to be really due to there being two isotopes; they weighed 35 and 37 units, and the proportion of the light to the heavy was just right to average 35.5.

The work of Rutherford and Bohr had yielded a fairly clear idea of the structure of the atom by 1915, but there were many arbitrary statements in the Bohr theory. For instance, it visualized the uranium nucleus, which had a weight of 238 units, as a grouping of 238 protons and 146 electrons, all crammed into a diameter of 10^{-12} cm. That certainly seemed adequate reason for the uranium nucleus to be unstable and to discharge radioactive rays. The problem, indeed, was why the uranium atom held together for even the briefest instant. According to all known laws the repulsions between those 92 unneutralized protons, crammed into such extremely close proximity, should have blown the nucleus apart. Quite clearly it didn't blow up. Something—some force—was holding the nucleus together. That force was not electric, it was not gravitational, and it was not magnetic; none of those forces was strong enough. At first the problem was by-passed. The nucleus obviously did hang together, and the physicists had to let it go at that until further data were available.

The science of nuclear physics urgently needed some new tools—some sort of observational equipment. At that time nuclear physicists had only two such instruments. One was the "spinthariscope," a frightening word that translates into "piece of fluorescent glass with a microscope for observing the impact of individual alpha particles." Rutherford had used one in his atom-diameter experiments. The spinthariscope could detect the impact of individual alpha particles, and that is about as close as man is apt to come to seeing a single atom. Then there was the electroscope, an equally simple contrivance of almost equal sensitivity. It consisted of a bit of gold leaf hung on an insulated metal rod in an evacuated chamber; the setup is shown below.

The electroscope was a very old device, but it proved extremely sensitive to radioactivity. The principle is simple. Since like charges



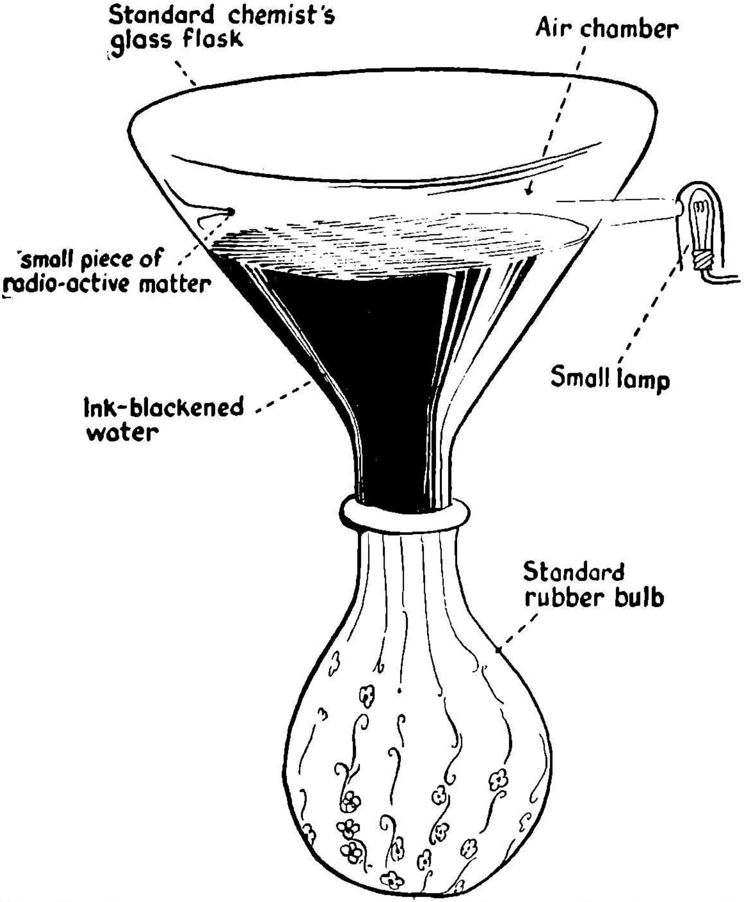
Simple—but highly sensitive—the gold-leaf electroscope.

repel each other, if a negative charge—a collection of electrons—is applied to the charging knob, the rod, its flattened extension, and the attached gold leaf will all become negatively charged. The charge on the gold leaf repels the charge on the flattened extension of the shaft. The thin gold leaf is so flexible and so nearly weightless because of its thinness that it bends away from the now repellent flattened extension. The degree to which it bends outward depends on the amount of charge on the electroscope. A well-made electroscope, because of the extremely high insulating value of the materials used, will trap electrons on its plates for many hours, and the gold leaf will stand out for long periods. But if some high-energy radiation—alpha particles, beta-ray electrons, or gamma rays—passed through the air in the electroscope chamber, it would make the air slightly conductive and thus discharge the electroscope. The difficulty with the electroscope is that it is incapable of showing from what direction the radiation that affects it comes and of measuring the energy of the radiation. It can only detect its presence.

During the First World War one of Rutherford's associates, C. T. R. Wilson, devised the most important of all tools for nuclear physics. It remains today the pre-eminent instrument of research in individual atomic collisions. As the spinthariscope can show the *impact* of one alpha particle on its screen, the Wilson cloud chamber makes visible the *movement* of a single atomic particle. It makes every atomic bullet a tracer bullet and takes a picture of the trace.

The principle of the cloud chamber is extremely simple, and the apparatus itself, in its original form, is as uncomplicated as the spinthariscope or the electroscope. The device consisted of a chemist's flask about three-quarters full of black ink and a rubber bulb from the squeeze-it variety of automobile horn in general use at that time and more recently popular with Harpo Marx. Add a bit of radioactive matter, and that's all there is to the equipment, which makes visible the careening flight of an alpha particle driving along at 20,000 miles a second or the trace of an electron fleeing from an exploding atom at more than 6,000,000 miles a minute.

The cloud chamber is based on two facts. Water vapor in clean, dust-free air cannot condense, even though the air is more than saturated. It must first have some sort of center, some "lump" in the air, on which to start the process of condensation. The more irregularities there are in the air, the more readily water vapor can condense to the liquid; this is demonstrated regularly in London by the famous pea-soup fogs, consisting of droplets of water vapor condensed on particles of the city's soot, grime, smoke, and dust. The other fact is that when an alpha particle blasts its way through the air, it creates many irregularities. It leaves behind it a trail of



The simplest, yet most potent, tool of the atomic science—the Wilson cloud chamber.

damaged atoms, reeling electrons, and masses of ions produced by the alpha particle's habit of exploding electrons out of its way. These charged ions constitute such irregularities in the air as water vapor needs to condense into droplets. Wilson put the two facts together, assembled his chemist's flask and rubber bulb, and set the facts to work.

Our picture shows the equipment in its simplest form. The flask is filled with water that has been made opaque by the addition of a black dye, and the rubber bulb is fitted to the neck of the flask. Then the flask is inverted. The ink fills the bulb now and leaves an air chamber at the top—which used to be the bottom—of the flask. The device has to stand until it has reached room temperature; then it's ready for work. First, the bulb is squeezed. The only compressible part of the system is the air chamber; so the air is compressed somewhat. Compressing air causes it to grow warmer. Warm air can absorb more water vapor than cool air; so a bit of water from the surface of the inky water goes into vapor form, and the air, now warmed, is more or less saturated with water vapor in a few seconds. Then the bulb is released suddenly. That, of course, reverses the former sequence—the air is abruptly cooled by expansion; the extra water vapor is no longer wanted and must condense out. But since there is no dust in the air, condensing isn't easy. So the water vapor condenses on any ions that are present and forms a little chain of fog droplets on the ions left behind by driving alpha particles or electrons.

Gamma rays, incidentally, do not ordinarily show up in a Wilson cloud chamber. It takes energy to form ions, and the procedure of knocking out electrons rapidly uses up the energy of alpha particles and electrons, or beta particles. This is, in fact, why these two types of radioactive rays travel comparatively short distances through matter. Gamma rays are extremely penetrative, because they do not waste their energy en route by ionizing atoms; since they don't, the only gamma rays a Wilson cloud chamber can detect are those that make head-on collisions with atoms in the chamber. Such an event ends the flight of the gamma ray, but the demise is spectacular enough to register.

The modernized version of the Wilson cloud chamber simply replaces the rubber bulb with a small motor-driven pump that automatically compresses and expands the chamber. A further improvement is an automatic movie camera that takes pictures of each cycle. In the course of a few hours this mechanical atomwatcher can photograph hundreds of cycles of the chamber, and it stands an excellent chance of spotting anything interesting and making a permanent photographic record of it. The camera is so arranged that, with the aid of a mirror, it takes a photograph of the scene as viewed from above and simultaneously as seen from a line parallel to the surface of the water. The blackened water makes the white fog droplets stand out clearly. The two photographs, together, supply a three-dimensional study of the movements of every particle in the field.

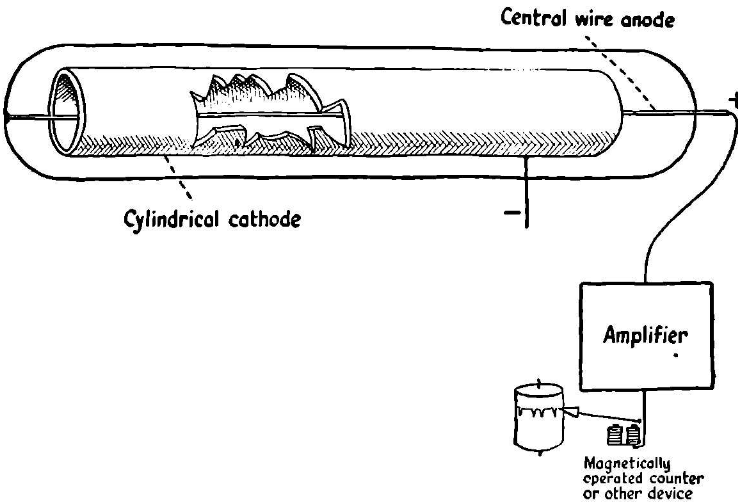
Some cloud chamber photographs are included in our section of photographs. Three of these show alpha-particle bombardments of different gases, and the fourth shows the discovery of the positron. The first three are similar to the original Cloud Chamber photographs taken in Lord Rutherford's laboratory.

The first shows that an alpha particle from a radioactive source out of the picture—the rays fan out from the source—has made a direct hit on an atom of the gas in the chamber. In this instance, the gas was hydrogen. An alpha particle is a helium nucleus, and has a mass of four units, and a nuclear charge of two units. A hydrogen nucleus is a simple proton—mass of one unit, charge of one unit. When an alpha hits a hydrogen atom, the alpha is deflected mildly, while the hydrogen nucleus careens off at high speed. Owing to its lower charge and mass, the hydrogen leaves a thinner trail of ions.

The second cloud chamber photograph shows an alpha-particle-helium nucleus colliding with a helium nucleus in a helium-filled cloud chamber. The resultant track shows precisely equal trails, branching at equal angles from the original. It would have been easy for a physicist to measure the angles of the two trails, and to calculate what type of nucleus could have made the alpha particle bounce in just that way.

The third photograph of the series shows a collision with an oxygen nucleus. An oxygen nucleus has 8 nuclear charges, and a mass of 16 units—it's four times as heavy and four times as powerfully charged as the helium nucleus. In this picture, clearly the alpha particle has done nearly all the bouncing; its track breaks and turns at a broad angle. The importance of the cloud chamber in the recognition of the positron is described on page 90.

Just as it takes a transmitting station and a receiver capable of detecting the transmitted signal to make a radio system work, it takes two kinds of instruments to carry on nuclear physical research. Natural radioactive elements had been the only "transmitting stations" at first available, and the first detector had been Becquerel's photographic film. The electroscope and the spinthariscope were the next detectors; then came the cloud chamber. All of these were invented before the end of the First World War. One other detector, invented somewhat later, should be spoken of here, for it is the latest important detecting instrument.



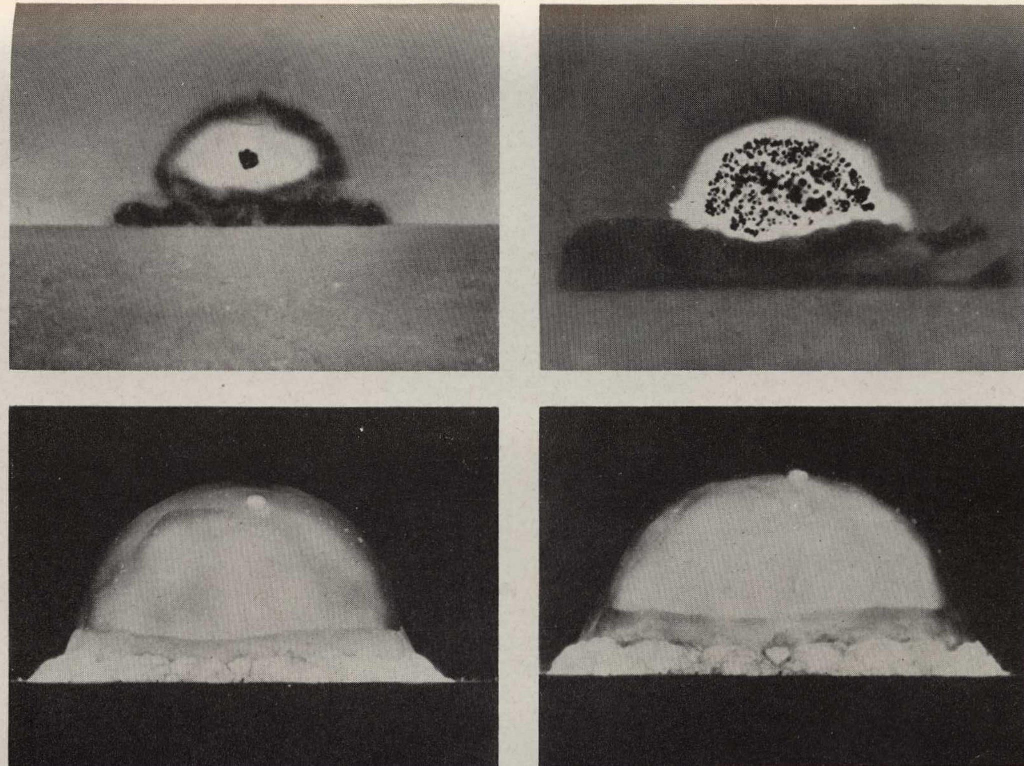
The Geiger counter is the ubiquitous detector of all radioactive rays.

This is the Geiger-Müller counter, referred to more frequently as the Geiger counter. It is not simple in theory, as the earlier detectors are, but it is simpler in mechanical design. It is essentially an electronic tube with the special characteristic of receiving and detecting ionizing radiation instead of radio or light waves. The Geiger counter is most useful for gamma-ray detection and for cosmic-ray studies, but it also reacts to beta and alpha rays. The mechanical arrangement is shown above.

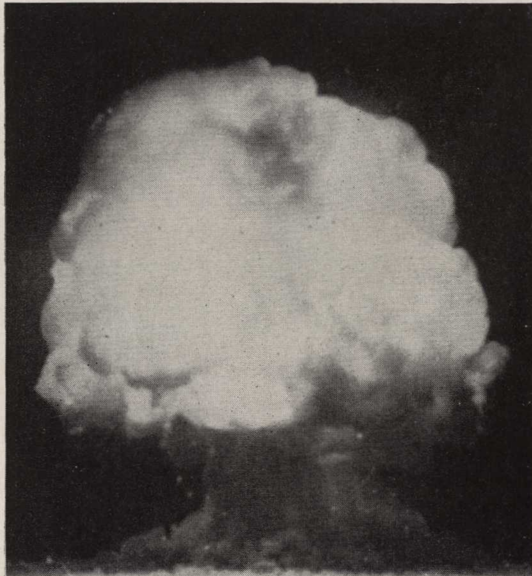
A glass tube containing a hollow cylindrical metal cathode, with a fine wire anode stretched through its length, constitutes the whole mechanism of the Geiger counter proper. The physical form of the apparatus is of little importance. Sometimes the cylindrical cathode consists of an extremely thin copper or silver mirror plating on the inside wall of the glass tube; sometimes there are simply two parallel wires in a glass tube. At the Massachusetts Institute of Technology a functional Geiger counter is on display that is made of an ordinary dinner fork and spoon. Two pieces of metal in a partially evacuated glass tube are the only necessary properties. The auxiliary apparatus consists of a high-voltage supply, an amplifier, and whatever recording device is wanted for the particular job at hand. About 1,000 volts are applied across the Geiger tube, between the cathode and the anode. The voltage is carefully adjusted to a point just below that which would cause the tube to break down and start a gas discharge like a neon lamp. The insulating value of the remaining trace of gas in the tube prevents such an accident.

If some ionizing radiation strikes into the tube, however, it will cause the formation of an ion by knocking an electron out of one of the gas atoms. The electron, attracted by the 1,000-volt positive charge on the anode, instantly heads toward it. The ion, meanwhile, is powerfully repelled by that 1,000-volt positive charge and attracted toward the negative charge of the cathode, and it heads in a direction opposite to that taken by the electron. Both particles very quickly—in millionths of a second—pick up a high velocity and then crash into some atom of gas that happens to get between them and their goals.

Let's suppose that the electron strikes an atom and hits it hard enough to dislodge another electron. Now both electrons start for the 1,000-volt positive charge on the anode, while the newly formed positive ion heads the other way. Inevitably these new ions get into traffic accidents, too; they collide with neutral atoms on the way, ionize them, and cause them, in turn, to start for the charged plates. This phenomenon is called an "electron avalanche." In something under a millionth of a second, quintillions of electrons are smashing toward the anode, and quintillions of positive ions are smashing toward the cathode. This sudden, powerful surge of current trips the sensitive circuits of a vacuum-tube amplifier, and the am-

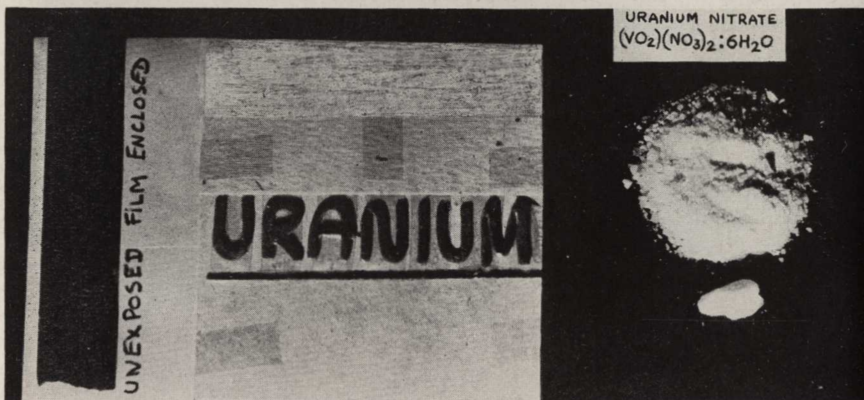


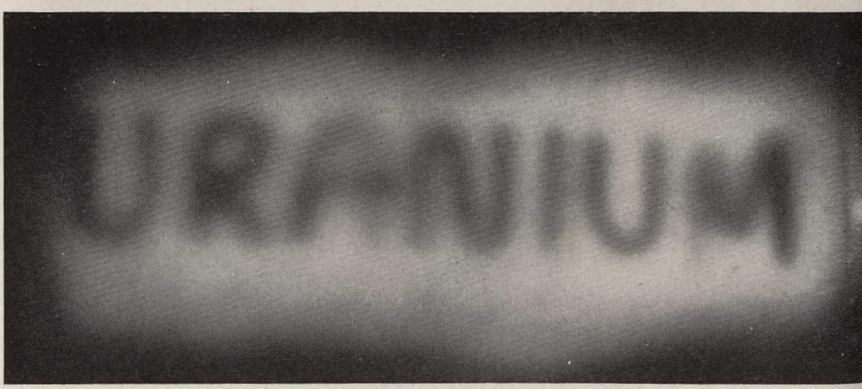
Atomic Bomb No. 1—photographs from the New Mexico test. The black spots in the first picture were actually the areas of most intense light; in later pictures the ground begins to show up. They represent the sound wave generated by the detonation. See page 215. *(Press Association, Inc.)*

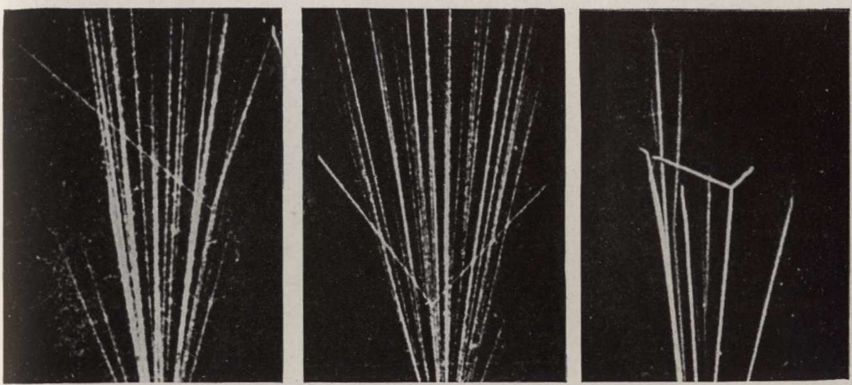


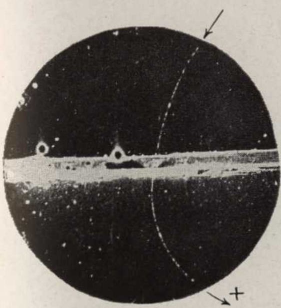
Here is the characteristic mushroom-shaped cloud that developed from the New Mexico test explosion. *(Press Association, Inc.)*

A simple experiment to show the radioactivity of uranium. At the top, letters of lead sprinkled with uranium nitrate are laid on an envelope. Below, you see that when the envelope is opened the shadows of the letters are found printed on the film inside. *(Copyright 1946, Street & Smith Publications, Inc.)*

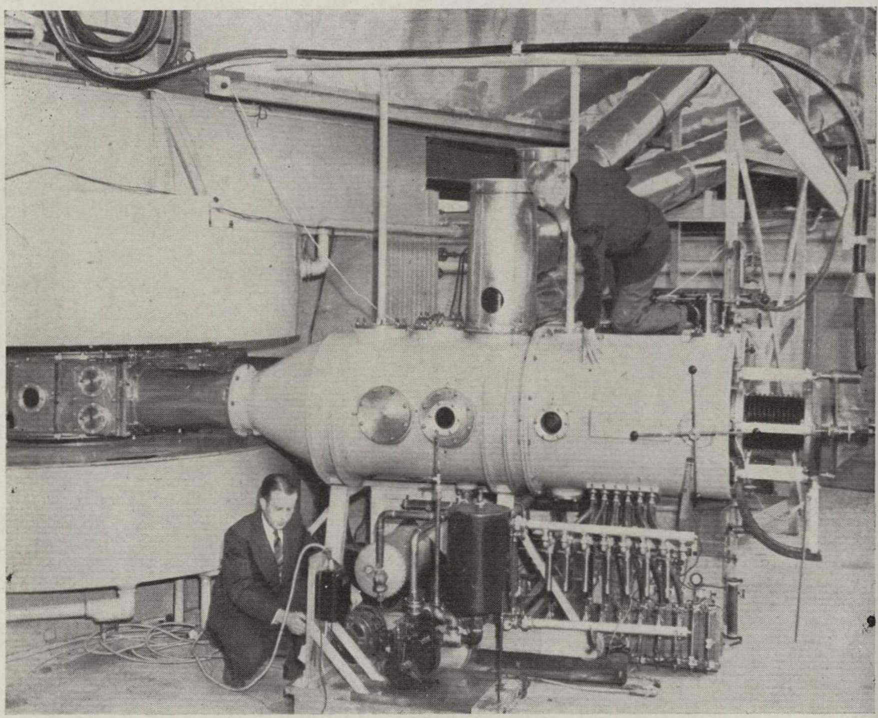








A positron is observed at the left in these Wilson cloud-chamber photographs; see page 90. The other pictures show collisions of an alpha particle with a hydrogen atom, then with a helium atom, and finally with an oxygen atom. *(D. Van Nostrand, Inc.)*



This great cyclotron at the University of California is one of the master tools of atomic research; see page 86. *(Wide World.)*

plifier in turn can run a small magnetic counter or almost any other desired device.

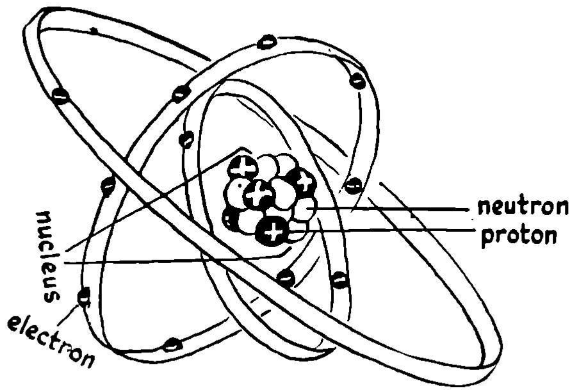
The nucleus had been discovered, but a great deal of theoretical work remained to be done.

5. *THEORY RIPENS—THE ATOM SPLITS*

So FAR as nuclear observational work was concerned, the period from 1920 to about 1930 seems to have been inactive. No major discoveries were made, nor were any important new tools developed—a situation that was strikingly reversed after 1930. The '20's were not unproductive, however, for a great deal of valuable paper work was accomplished. Since the atom is too small to be seen or observed directly, mathematical and imaginative analysis took the place of instruments for the time being. The greater advance in the 1920's was the full development of a single negative concept. Mathematicians and theoreticians conclusively proved what the atom was *not.* When you're trying to find truth, it is important to know where truth isn't; that avoids much blind-alley research. Unfortunately the new definitions of atomic terms that this period developed are almost impossible to translate from the language in which they were written. A great part of the work was done by Heisenberg, Schroedinger, Einstein, Bohr, Broglie, and Dirac—three Germans, a Dane, a Frenchman, and an Englishman—all writing in the native language of nuclear physics: mathematics.

In the earlier days of nuclear research the electrons were said to travel in orbits about the nucleus; Bohr's original theory expressed it in like terms. Now, however, it seemed that the orbit was more three-dimensional than the word implied. Much of the work clearly indicated that it was impossible to get a mechanical analogy for the electron system. Electrons aren't electrically charged particles; they *are* electricity. Nothing can be in two places at once, but an electron isn't a "thing" in the sense of a material object. Inside the atom the electron isn't "in an orbit" or even "in a shell" around the nucleus. It seems that the electrons *are* a shell around the nucleus.

The most fundamental theoretical concept of nuclear physics had already been formulated by Albert Einstein, concurrently with the development of his Theory of Relativity. This was an equation known as the mass-energy conversion equation. When it first appeared in 1905, it seemed fantastic. It was, however, very simple:



The Bohr model atom—pre-1935 style.

$E = mc^2$, when E stands for energy, m for mass, and c for the velocity of light in appropriate units. It directly implied that mass—that is, matter—could be converted into energy with the annihilation of that matter and that, contrariwise, energy could be annihilated and matter created as a consequence. So long as men thought of matter as composed of hard little pellets, the formula remained unintelligible.

By 1930 the idea of the universe as a solid mechanical structure had become forever outmoded. Just as scientists had been startled, a good deal earlier, to discover that atoms were in reality powerful but incredibly minute dynamic machines, so the new generation of scientists found a new reason for insecurity. The dynamic machines weren't machines. They were simply energies without mechanism. Gamma rays had been proved to be pure radiant energy—but this energy acted mathematically very much as if it were made of particles. Electrons, on the other hand, could be described mathematically by waves! But accurate equations that checked exactly with experimental tests said that the *wave length* of an electron varied with the velocity of the *particle.*

The years from 1905 to 1930 were a preparatory period in which physicists had the opportunity, though few of them could realize it at the time, of adjusting their imaginations the better to understand the discoveries that were to come. And the most important part of this adjustment had to do with the recognition of the fact that energy—"immaterial" energy—was as much a part of the structure of an atom as electrons and protons. The nuclear physicist in 1930 thought of an atom as a thing built of electrons, protons—and energy. He was beginning to believe that electrons and protons were themselves energy.

One electron is a tight knob of energy equal to ½ Mev. "Mev" was a new symbol that had recently come into general use; it was an abbreviation for "million electron volts"—the energy acquired by one electron in falling through 1,000,000 volts. It is difficult to translate this unit into terms of ordinary usage. It is an atomic physicist's unit, invented because ordinary energy units were unsuitable for his purposes. We may, however, get some idea of its relationship to ordinary atomic things. The energy released by burning one atom of carbon with two atoms of oxygen is about two millionths Mev, or 2 electron volts. The energy of an exploding uranium atom is about 200 Mev.

Atomic energy is as real as electrons and protons because it is absolutely all that electrons and protons consist of. They are pure electrical energy. Gamma radiation is pure radiant energy. The two energies are interchangeable under certain conditions, which will be explained later. A gamma ray of 1,000,000-volt energy can be annihilated in empty space, and from that empty space two particles can be created from the energy of the gamma ray. The two particles, on the other hand, can collide, annihilate each other, and create a gamma ray.

By 1930 the mysterious force that bound the protons and electrons together inside the nucleus had been named, but it remained unidentified. The physicists called it simply "binding energy." The force remains mysterious to this day, but what it does is better understood than it was even a few years ago. When any two atomic particles get closer to each other than 10^{-12} cm., the binding energy overwhelms any other force that may be operating. Within that range the enormous repulsion between protons seems to disappear. It seems to be a very arbitrary force, closely associated with mass. A hydrogen nucleus—a proton—crashing through atoms of air, smashes electrons out of its way. Protons have an enormous attraction for electrons; why doesn't the proton capture an electron and weld itself and the electron into a single neutral particle? The answer is that the binding energy doesn't let them get together. Any electron that comes within 10^{-12} cm. of a proton is bounced.

Today, as in 1930, for all our progress, we're still trying to figure out just what that force of binding energy is. We have much more data and a rather complete set of pragmatic rules. We know *that* many things happen, but we have little knowledge of *why* they happen. The physicists of Faraday's time discovered the basic laws governing the behavior of electric current by experiment and experience. They didn't know what an electric current was, nor why it behaved as it did, but they could work with it very effectively. We are in somewhat the same position today with respect to binding-energy forces.

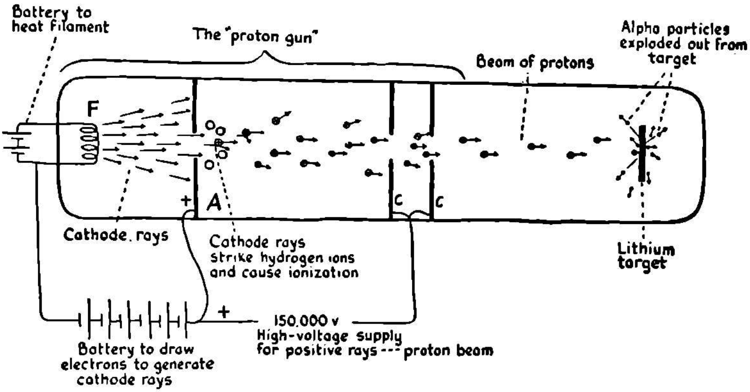
Experimental atomic physics made a fresh start in the early 1930's with new tools and the discovery of new atomic particles. Lord Rutherford and his associates were still at the forefront of atomic research. Rutherford had been the first to show that alpha particles, those electron-deficient helium atoms, could bring about transmutation and change nitrogen atoms into oxygen atoms and hydrogen. In 1930 he was convinced that it was not a unique property of alpha particles that caused the transmutation. It was simply that alpha particles had enough energy of impact to do the job. If only some means could be found to give other particles an energy of the same violence, he reasoned, those other particles, too, could cause transmutation. So he began to build a machine to accelerate protons—hydrogen-atom nuclei—to the same high level of energy. For this he needed an apparatus that would be, in essence, a positive-ray tube, but one using about 1,000,000 volts to accelerate the positive ions.

Today we can build 2,000,000-volt X-ray tubes for commercial work, and there is at least one 100,000,000-volt X-ray machine in operation. Remember that voltage is the equivalent of pressure in electrical phenomena. A high-pressure hose squirts a hard-hitting, fast-moving jet of water just as a high-voltage positive-ray tube squirts a hard-hitting, fast-moving jet of ions. Pressure—really high pressure—is hard to contain. It breaks its way out explosively, whether it is electrical pressure or mechanical pressure. A lightning bolt strikes when the high electrical pressure on a cloud escapes to the Earth. We normally think of rubber as an insulator—but ordinary rubber-insulated wire will burst if an electrical pressure of perhaps 3,000 volts is applied to it. In 1930 the techniques for generating and holding 1,000,000 volts hadn't been developed. In principle the problem seems simple. If you wind a big transformer with 110 turns on one winding and 1,000,000 turns on the second winding and apply ordinary house current to the primary, you should get 1,000,000 volts on the secondary. But 1,000,000 volts can jump several feet through air or smash its way through several inches of glass insulation—so how are you going to insulate that transformer winding? Getting such high voltages was a major problem in electrical design and required several years of research, but Rutherford didn't see any point in delaying his program while this engineering problem was being worked out. He suggested to two of his associates, J. D. Cockcroft and E. T. S. Walton, that it might be possible, using equipment already available, to get some results even with relatively low-voltage particles.

In 1932 Cockcroft and Walton announced that they had got results. Their discovery is of great importance; it should be remembered in detail, although it was almost forgotten in the years between 1935 and 1945. *This experiment was the first known instance in which the atom was split*—the first recognized atomic fission, in other words, though it was not so designated at the time. The general mechanism of the apparatus used in the Cockcroft-Walton experiment is shown in our diagram on page 77.

A beam of protons is generated by the "proton gun" and shot at the target. The proton gun consists of a hot filament *F*, which gives off electrons just as the hot filament in a radio tube does. These electrons are accelerated by the positive voltage applied to the plate at *A*, and they shoot through the hole in *A* as cathode rays. But the fast-moving, hard-driving electrons hit and ionize atoms of hydrogen in the space between *A* and *C*. The strong negative voltage—150,000 volts—applied to *C* attracts the positive-charged protons, hydrogen nuclei, and repels the electrons back toward *A*. The cathode rays are used only as a means of making hydrogen ions; once they've done that, the experimenter is through with them. The protons head for *C*, and a certain number of them pass through the hole in *C* and out into the space beyond as a beam of 150,000-volt energy particles.

The target used in the Cockcroft-Walton experiment was lithium. Lithium is an extremely light metal—lighter by far than



Proton gun used in the Cockcroft-Walton experiment—the atomic fission experiment of 1932.

aluminum or magnesium—and a fairly common element. It sells for about $10 a pound in 100-pound lots, but because it is as soft as cheese and corrodes almost immediately in air, its only buyers are chemists and nuclear physicists. When a lithium atom is struck by a 150,000-volt proton, the proton enters the lithium nucleus and increases the natural atom weight from 7 to 8; simultaneously it increases the charge from 3 to 4. But this newly created nucleus is a monstrosity, and it instantly explodes, breaking exactly in two as helium nuclei of atomic weight 4 and nuclear charge 2. These are, in effect, alpha particles created by man-made transmutation. The interesting thing about them is that each particle comes out with an energy of 8.5 million volts. Only 150,000 volts of electrical energy were used to start the action; the output is 2 × 8.5, or 17 Mev—more than 100 times the original force.

It is as though a one-horsepower motor ran the oil burner in a furnace that generated steam for a 110-horsepower power plant—except that the Cockcroft-Walton gun shoots protons instead of droplets of oil, and the protons combine with lithium nuclei, not with oxygen of the air. Unfortunately there is one other difference. Every proton that enters a lithium nucleus gives off 100 times as much energy as was used for firing it at that nucleus, but not one proton in many, many hundreds of thousands succeeds in making a direct hit. Most of them are slowed down by collisions with electrons that gradually dissipate the necessary 150,000-volt energy, or they make glancing hits instead of bull's-eyes. The lithium nucleus is an exceedingly small target for the proton, and hitting it successfully is something like hitting the points where strands of chicken wire intersect. If you fire a machine gun at chicken wire, some of the slugs will hit those cross-over points, but you'll be hitting empty air most of the time.

The Cockcroft-Walton experiment was extremely important in another way. The weight of hydrogen nuclei could be measured precisely. The weight of the helium nuclei, or alpha particles, produced by the experiment had been carefully measured. The exact weight of a lithium nucleus was also known. The energy with which the helium nuclei were expelled in the final explosion of the monstrosity nucleus formed by hydrogen and lithium could be measured accurately. *Here, then, was a chance to make a direct experimental check of Einstein's mass-energy formula*—to see whether energy in ergs *does* equal mass in grams times the square of the speed of light in centimeters per second. Cockcroft and Walton had finally found a reaction involving such huge energy changes that it should be measurable!

Scientists began adding up weights:

Masses of Things Used Up

Mass of hydrogen nucleus	1.0081
Mass of lithium nucleus	7.0182
Mass of 150,000-volt energy	.0002

Total	8.0265

Masses of Products

Mass of alpha particle	4.0039
Again, for two have been produced	4.0039
Total	8.0078

Difference: 8.0265 — 8.0078 = 0.0187

This 0.0187 difference must be the mass of the kinetic energy—the energy of velocity—of the expelled alpha particles. Working this into the Einstein mass-energy formula, that much mass would be equal to 17.4 million electron volts. The measured energy of each particle was 8.5 Mev, or 17.0 Mev for the two. The experimental difficulties are certainly great enough to account for a loss of 400,000 electron volts of energy somewhere. The agreement of theory and experiment is excellent. Einstein was right. The mass of an atom can be transmuted not only into another kind of atom, but into another kind of *energy*.

This experiment proved the existence of vast stores of energy within the atom that could be released by man-made apparatus. When the results were first announced, there was naturally a great deal of excitement; but the excitement was almost immediately quieted by the nuclear physicists, who pointed out that it took more energy to make the hits than could be obtained from the reaction, even though each successful hit did yield a huge profit. No practical source of atomic energy had yet been discovered, but the Cockcroft-Walton experiment pointed the way. It involved the splitting of an atom to produce two equal parts, with the consequent release of a huge amount of energy. At least this one thing should be remembered about the experiment: One atomic weight unit of hydrogen plus 7 of the lithium yields 17.0 Mev of energy.*

Developments in experimental nuclear physics after 1930 came

* It should be remembered for this reason: Uranium fission involves 235 weight units and yields only 200 Mev of energy, or less than one Mev per weight unit. The lithium-hydrogen reaction yields more than twice as much energy per weight unit. It will be shown later that, under the right conditions, the lithium-hydrogen reaction becomes an explosive chain reaction.

with such speed that they kept overlapping chronologically. In 1932, Bothe and Becker of the University of Giessen in Germany bombarded a plate of beryllium metal with alpha particles. Beryllium is another of the extremely light metals—lighter than aluminum—and has a low atomic weight. In the notation of nuclear physics it is ${}_4Be^9$—meaning that it is the fourth element in the periodic table, is named beryllium, and has an atomic weight of 9. This same style of notation makes ordinary hydrogen ${}_1H^1$, ordinary helium—or alpha particles—${}_2He^4$, and lithium, the third element in the table, ${}_3Li^7$. Bothe and Becker found that a very penetrating kind of radiation—they didn't know whether it was a particle or something like a gamma ray—came from their bombarded beryllium plate. They tried to identify the radiation as charged particles of some sort, but soon gave up that notion. The penetration was far greater than a charged particle could reasonably be expected to make; so they concluded that the reaction produced a new kind of transmutation and gave off gamma rays of unusually violent energy. They were wrong. There were gamma rays coming from the reaction, but the penetrative radiation they had found was something completely new. Science at that time felt that it had a pretty sound idea of what went into the make-up of an atom, and it was hard to imagine that a new particle existed.

J. Frédéric Joliot and his wife, Irène Curie, daughter of the famous Pierre and Marie Curie who isolated radium, became interested in the alpha-particle beryllium experiment and repeated it with a few changes. They found that when the penetrative radiation fell on a block of paraffin, protons with a remarkably high energy exploded out the other side. But they, too, supposed the penetration was due to high-power gamma radiation.

In England, James Chadwick wasn't satisfied with the explanation, and he started digging into the problem himself. The result of his research was the discovery of the *neutron*. He had repeated the earlier experiments and tried a few of the same sort as those performed by the Curie-Joliots, but he had used materials other than paraffin. His series of answers couldn't fit any gamma-ray explanation. He suggested that a new particle, uncharged, but of mass equal to that of the proton, had been produced.

The third particle of the nuclear family had finally been discovered. The electron is negative-charge-without-mass, the proton is positive-charge-with-unit-mass, and the neutron is mass-with-no-charge. This new particle was called the "neutron" because it is neutral. How had physicists missed the neutron all these years? How could their nuclear theory, developed when they had no knowledge of the neutron, be worth anything if there really was such a thing?

Bohr, in his original atomic theory, had proposed that the nucleus of an atom contained enough protons to account for the mass and enough electrons to balance the charge of some of the protons. In beryllium, for instance, which has a mass of 9 units and a charge of 4 units, Bohr's original theory would have indicated that there were 9 protons—giving a gross mass of 9 and a gross positive charge of 9—and 5 electrons, which didn't change the mass detectably, but reduced the net positive charge to 4, because the electrons carried 5 negative charges. After the discovery of the neutron the beryllium atom was more simply described. It consists of 4 protons and 5 neutrons; the 4 protons have 4 positive charges and 4 weight units, the 5 neutrons adding only mass, to the required mass total of 9.

Essentially a neutron is a combination of an electron and a proton. Bohr's original atomic theory was perfectly sound, but he had not stated that the electrons in the nucleus were actually merged with some of the protons. And, of course, he didn't know that the neutron could exist as a unit outside the nucleus. It was easy now to see why the neutron had been overlooked for so long. Uranium gives off, naturally and continuously, not only alpha, beta, and gamma rays, but also a weak discharge of neutrons. The alpha, beta, and gamma rays had always been detected by electroscopes, photographic film, Wilson cloud chambers, Geiger-Müller counters, and the like. All of these detectors depend on the ionization caused by one of the three rays. But neutrons, since they carry no charge, don't particularly disturb electrons. They rarely cause ionization except when they are moving with terrific speed. And normally they slow down so quickly that they are very hard to detect directly unless you know how to set traps that will betray their presence.

The discovery of the neutron explained a lot of things and supplied an enormously useful tool of atomic investigation. Getting a proton to hit a nucleus is an extremely difficult job. The nucleus is positively charged; so is the proton. They repel each other violently, and the violence of the repulsion increases as they get closer. If there is the slightest chance to dodge, one or the other will turn aside enough to cause a miss. It would be hard enough to shoot hummingbirds with a slingshot using buckshot as the projectile. But to knock down one hummingbird by using another hummingbird as the projectile would be even more difficult. Not only will the target try to duck, but the projectile will try to duck, too.

Neutrons, carrying no charge, do not experience that same violent repulsion of electric forces. They make infinitely better atomic ammunition, if you can shoot them. Neutrons, however, are tricky things to handle. They have no charge, which makes them useful as projectiles, but also makes them impossible to get hold of. To return to the weird analogy of our slingshot, it would be like trying to use a drop of quicksilver as the projectile. It is quite suitable if you can only figure out a way to throw it and not have it leak off or around the slingshot.

Nuclear physics had need of another discovery—and it was not long in coming. It came, in fact, the same year. In 1932 the Cockcroft-Walton experiment fissioned lithium atoms by bombarding them with protons. In 1932 the first indications of the neutron were reported. And in 1932 Harold C. Urey, of Columbia University in New York, first isolated "heavy water."

Ordinary water is H_2O, hydrogen and oxygen. Heavy water, too, is hydrogen and oxygen, but the hydrogen in it is different. Ordinary hydrogen has the simplest possible atom—one proton with one electron in its electron shell. But *heavy hydrogen,* or *deuterium,* is a hydrogen isotope having a nucleus consisting of one proton and one neutron. The atomic weight is 2 instead of one, but since the nuclear charge is still one, it is chemically plain hydrogen. Because the atomic weight is 100 per cent greater, however, deuterium has slightly different chemical properties and is the only isotope that shows any real difference from its fellow isotopes in chemical reactions. This, of course, is due to the 100 per cent difference in weight and a less agile response to chemical stimuli. Somewhat later a third hydrogen isotope—an atom consisting of 2 neutrons and a proton—was discovered. This one is of no great importance, however, since it is extremely rare, and the relatively abundant deuterium serves most purposes. Deuterium constitutes one part in 4,000 of the hydrogen in ordinary water. The ratio is small, but when you remember the immense amount of water on earth, you may appreciate the quantity of heavy water that exists.

Heavy water was needed for further atomic research. Since the hydrogen in heavy water is deuterium, there is a 50–50 relationship of neutrons to protons. Protons have an electric charge that you can seize and direct with electric and magnetic forces. Since the neutron in the deuterium atom is firmly attached to the proton, when you move the proton, you also move and can manage the slippery and otherwise unmanageable neutron.

If you want to bombard a nucleus with neutrons, there are several possible ways to do it. If you bombard it with heavy-hydrogen nuclei—usually called *deuterons*—that will, in some cases, do as well as if you had used isolated neutrons. But if isolated neutrons are essential, you can slam the deuterons through a thin layer of some substance; since the protons have charges, they will be violently resisted in their effort to drive through. The attached neutron has just as much mass, but doesn't experience any retarding force. If the proton is resisted violently enough, the bond between the proton and the neutron will snap—and the neutron will go on alone in the original direction to bombard the target. This system of separating neutrons from deuterons might be compared to a truck and trailer sliding backward down a steep hill. The trailer has no brakes. When the truck driver puts on the truck's brakes violently, the truck slows down, but the trailer breaks its tow link and goes careening down the hill on its own.

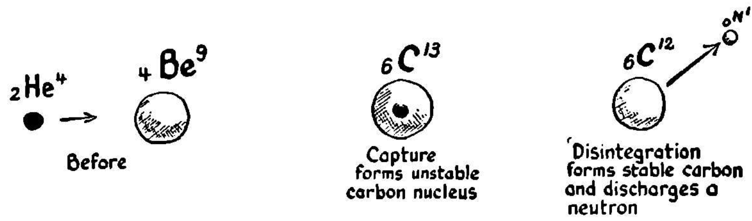
Of course another perfectly good way to get neutrons for bombardment purposes is the simple and highly effective method originally used in their discovery. A tiny capsule of radium or some radium product can be sealed in a little beryllium tube and a steady supply of neutrons will emerge from the beryllium tube. It will be a long time before either the radium or the beryllium is used up. Neutron emission would be detectable from such an arrangement some 100,000 years after it was assembled. If uranium metal, which is also an alpha-particle emitter, is sealed in a beryllium tube, neutron emission, after 4,700,000,000 years have passed, will still be half as strong as it was originally.* Other materials besides beryllium will yield neutrons, under bombardment by alpha particles, but beryllium is the standard material.

What happens to the beryllium to make it yield neutrons when an alpha particle strikes it? In the nuclear physicist's shorthand notation, it is:

$$_{2}He^{4} + {}_{4}Be^{9} \longrightarrow {}_{6}C^{12} + {}_{0}n^{1}$$

That is: Helium nucleus plus beryllium nucleus yields carbon nucleus plus neutron. The neutron might properly be regarded as the most simple atom, for it has only a nucleus and no chemical properties.

The reaction might be sketched somewhat like this:



A great difficulty was that, although the beryllium would supply all the neutrons anyone wanted, there was no way to get enough alpha particles to deliver a satisfactory yield. A radioactive element is one that breaks down naturally and continuously, throwing off radiations and changing itself into a different and more stable element. This process goes on without interruption, the atom throwing off piece after piece in an effort to make itself more stable. Uranium is mildly unstable and gradually disintegrates to

* A life insurance company can predict accurately the average life of a human being, but not even an insurance company can tell any individual man how long he will live. Similarly, of one quintillion atoms of the carbon isotope called carbon 14, for example, one-half will have changed in 1,000 years. It is statistically certain that the next 1,000 years will see one-half of the remaining atoms change. Another 1,000 years will find one-half of that part remaining. How long this process will continue it is impossible to say. Reference to the *life* of a radioactive is meaningless. Reference to its *half-life* is intelligible, and physicists use the term "half-life" when referring to radioactives.

form an alpha particle and a lighter element. This lighter element, however, is even less stable and soon undergoes another change, to form another alpha particle and a still lighter element. But this one isn't stable either; it discharges a beta-ray electron, becomes a new element . . . and so on. Eventually the atom does become stable and rests as lead.

If a particular step in the process is very unstable, the disintegrating particle will change rapidly to the next step. Radium C″ alters in about a ten-thousandth of a second. Radium itself is fairly stable; it takes nearly 1,800 years before half of it has changed to another substance, radon. Radon is a gas and quite unstable; it changes at such a rate that half of any given quantity transmutes itself in three and a half days.

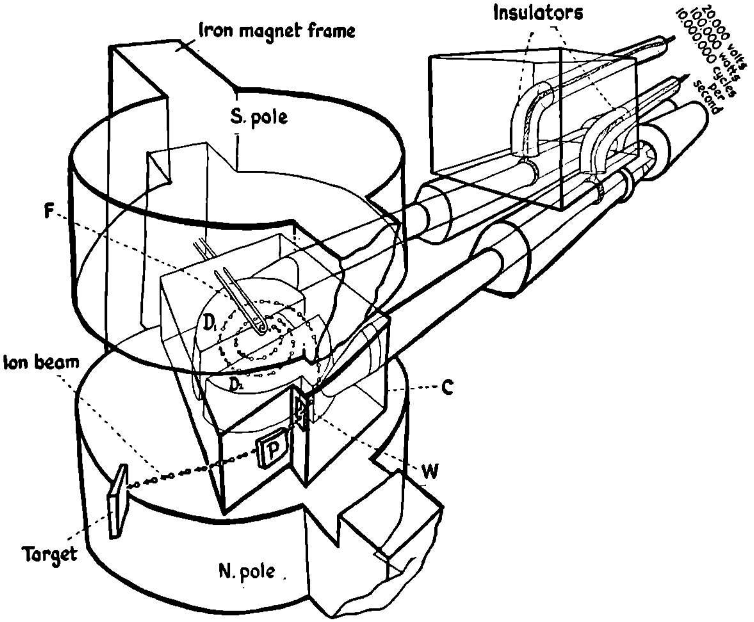
There is a lot of uranium in the world—more uranium, actually, than there is copper. Its natural radioactivity produces alpha particles and starts the whole chain of disintegrations through radium and radon and radium C″, and what began as uranium ends as lead. But it takes 4,700,000,000 years for half of any given ton of uranium to change. Consequently in one particular year there is very little changed uranium produced. But all the radium there is in the world was produced from changed uranium, and radium itself changes at a much faster rate—half in 1,800 years. Similarly, all the radon in the world was produced from changed radium, and radon destroys itself at a rate of half in 3.5 days. Obviously, at any given moment there will be an enormously greater amount of uranium than radium, and there will be far more radium than radon. Radon is, therefore, decidedly rare. Radon would be a fine alpha-particle source. One gram of radon will throw out an enormous number of alpha particles in the course of an hour. Obviously, the faster an element is changing, the faster it produces rays—but also, inevitably, the less of it there will be in the world. Nuclear physics needed something that would produce atomic bullets in enormous quantities—not dole them out at such a fantastically parsimonious rate that the supply wouldn't be half gone in four million millenniums! Physicists needed an atomic-bullet machine that they themselves could control.

At the same time that Cockcroft and Walton were experimenting with their bombardment of lithium and Rutherford was trying to develop a 1,000,000-volt machine for atomic bombardment, a young professor of physics at the University of California was working with a machine of his own devising. Ernest O. Lawrence had an idea. Rutherford and his associates were wondering how to keep 1,000,000 volts from going where it wanted to go instead of where they wanted it to go. They were worrying about insulation and switching, rectifiers and filters, and also their personal safety. Lawrence, in California, thought the problem could be handled better by trickery than by methods of brute force. Since 1,000,000 or more volts were so extremely unmanageable, it might be easier to figure out a way of using 100,000 volts ten or a hundred times over on the same ion; 100 times 100,000 volts would be the equivalent of 10,000,000 volts. Lawrence developed his machine, the cyclotron, so successfully that it has become the standard laboratory tool of nuclear physics. No nuclear research laboratory is complete without one. Modern cyclotrons readily produce up to 25,000,000-volt particles—energy considerably more violent than any natural radioactive process affords.

The cyclotron develops its high-voltage kick in much the same way a man builds up speed in a wheel by giving it a push each time it comes around. No single push is very hard, but after the wheel has been pushed fifty or sixty times it has collected a lot of energy. The pushing of ions in a cyclotron's "wheel" is done by electric forces that are turned on and off 10,000,000 times a second, with some 200,000 volts of push each time. The "wheel" spins on an "axle" of pure magnetic force. The 200,000 volts are turned on and off by a high-power short-wave radio transmitter about twice as powerful as those owned by the largest broadcasting stations. A cyclotron is neither small nor simple to set up, but it has the supreme virtue that it works. Nothing else that has been tried does. The cyclotron is diagramed on page 87, and the big cyclotron at the University of California is shown in the photograph section.

Inside a flat, pillboxlike evacuated chamber *C* are placed two plates, called dee-plates because they are shaped like the capital letter D, and a small ion source. This last item has been reduced to a simple heated filament and a very slight trace of the gas that the experimenter intends to use—usually hydrogen or deuterium, less commonly helium; in theory any gas can be used. Electrons from the hot filament cause some ionization—and the ion is off on its wild ride.

Suppose that, at the instant of ionization, D_2 is negative and D_1 is positive, with some 200,000 volts across them. The ion, we'll say, is where the small dot is, near the center. It is violently repelled



The cyclotron—the atomic physicist's tool that made experimental atomic physics practicable.

from D_1 and attracted toward D_2 and picks up considerable speed in falling toward D_2. But since the whole apparatus is being acted on by the powerful forces of the big electromagnet, the ion cannot travel in a straight line, but is forced to move in a curve, its path curling back on itself so that it emerges from the hollow D_2 plate into the space between D_2 and D_1 again. During the time the ion is swinging around, however, the high-frequency radio transmitter has been at work, and the voltages on the two plates have been reversed; the emerging ion discovers that D_1 is 200,000 volts negative, and it falls eagerly toward D_1—in a curve because of the magnet. But since it has fallen through 200,000 volts twice now, it is moving far faster, and even the powerful magnetic force can't bend its course so sharply this time. It is swinging wider on the turns of the peculiar race track.

Because of the wider swing, it has to travel farther each time around. The laws of electric force and magnetic force and the laws of moving masses are such that no matter how fast the ion is traveling, it will always take it exactly the same length of time to get halfway round; more speed—farther to go. One ion may just be starting, making its first loop, with only 200,000 volts of speed; another ion may just be heading into its last loop after having fallen through the 200,000 volts 99 times, so that it is traveling with a speed equivalent to 19,800,000 volts. The slow ion, taking the short cut, will make a half swing in a twenty-millionth part of a second. The fast ion, swinging wide because of its enormous speed, will need the same fraction of a second to get around. Both the fast ion and the slow will arrive at the space between plates just in time to find that the voltages have been reversed by the high-power radio transmitter.

On the last lap, however, something must be done to break the swing—otherwise the ions would simply spiral out at odd angles until they struck and dissipated their energy against the outer walls of the evacuated chamber. To prevent this a small opening on one side of one of the dee-plates is made, and a deflecting plate is placed just outside this opening. The application of about 100,000 volts of charge to this plate will cause the ions to swerve outwards as they pass it on the last lap and thus will supply the valuable beam of high-energy particles.

The cyclotron provided a basic tool for later observational work.

6. *FROM MAN-MADE RADIOACTIVES TO URANIUM FISSION*

EINSTEIN had indicated in 1905 what an inexhaustible store of atomic energy was waiting to be tapped. Lord Rutherford had proved in 1919 that atoms could be transmuted. In the first five years of the 1930's it became evident that within a very short time men were going to be able to work with atoms as they had been working with chemical molecules a century earlier. The cyclotron had now given nuclear physicists the means of generating beams of high-energy particles more powerful by a thousandfold than the combined output of all the natural radioactive substances the world had produced since Becquerel discovered uranium's activity.

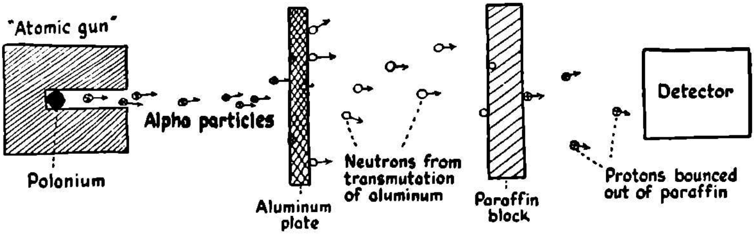
A discovery made in 1932 added still another leading character to the nuclear family. This was the *positron.* Some years earlier P. Dirac, an English mathematical physicist, working out a few of the mathematical implications in the quantum mechanics equations that were the research specialty of nuclear physics during the 1920's, had derived some curious equations. They implied the existence of something that should act like an electron, but have a positive instead of a negative charge. It would be positive-charge-without-mass—quite unlike the proton, which is positive-charge-*with*-mass. Dirac's calculations also indicated that the new particle was not going to be at all easy to find, for if anything of the sort existed, it would combine immediately with any electron it approached, to their joint annihilation. Since this new particle would have a strong positive charge and would therefore be attracted to an electron, its life would be incredibly short wherever there was matter. But it could, according to the theory, exist briefly, if it moved at an extremely high speed.

Matter can be annihilated; energy can be annihilated—but matter-energy cannot. That is, matter can be annihilated only to release energy, or energy can be consumed only to produce matter; the total mass-energy combination, however, remains unchanged. The positron-electron pair is a good demonstration of this truth. The positron has a very brief life before joining an electron. Immediately both are destroyed, but they are replaced by two gamma rays with exactly the same mass as the electron and the positron had. For Dirac, however, all of this was theory—and such tenuous theory that it was not taken too seriously even by Dirac himself. It remained for another to prove experimentally that there was such a thing as a positron.

C. D. Anderson proved it while working with Lawrence in California, in the course of photographing cosmic-ray effects in a Wilson cloud chamber in a strong magnetic field. Cosmic-ray energies are a very large subject; what matters about them here is simply that they produce extremely high-energy gamma-ray effects. The trail of an electron in a Wilson cloud chamber is quite recognizable—but ordinarily a positron trail looks exactly like an electron trail and is not detected as something different. In a magnetic field, however, a positively charged particle curves one way, while a negatively charged particle curves in the opposite direction. In our section of photographs the picture that occasioned Anderson's discovery is shown.

The particle was moving down from top to bottom. The white band across the photograph is the edge of a lead plate in the cloud chamber; the plate was put there for the specific purpose of retarding particles on their way through and thus of showing, with the help of the magnetic field, which way they were going. A curved path alone might be that of an electron moving from bottom to top or of a positron moving from top to bottom. This trail has a sharper curvature below the lead plate than it has above; a sharper curvature means it was traveling slower. Therefore it could only have been made by a positive particle moving from top to bottom, because plowing through a plate of solid lead does *not* make particles go faster.

The discovery of the positron in 1932 was a necessary preparation for the next great finding. Irène Curie and Frédéric Joliot had been studying for several years the effects of alpha particles on different substances. Irène Curie's distinguished parents had done pioneer work on radioactives, and she and her husband did equally distinguished work in developing the idea of radioactivity. They barely missed discovering the neutron in 1932. In 1934 they were studying the production of neutrons from aluminum bombarded with alpha particles, and in the course of their investigation they made some very valuable observations. Their experimental arrangement is sketched below.



Setup of the Curie-Joliot experiment that disclosed synthetic radioactivity.

The alpha particles were coming from some polonium in an atomic gun, which was essentially the same as the one used by Rutherford many years before, and were bombarding the aluminum plate. The aluminum stopped all the alpha particles, but neutrons shot out and appeared on the far side of the plate. Since the neutrons couldn't be observed directly, they were allowed to smash into paraffin. Here, colliding with one of the many hydrogen atoms in paraffin, the neutron was stopped, but a high-speed hydrogen nucleus, or proton, was bounced out, much as a cue ball in billiards hits and transfers its motion to one of the other balls. The ion detector then readily detected the charged proton.

Everything went quite according to plan. The reaction, in nuclear notation, is this:

$$_{2}He^{4} + {}_{13}Al^{27} \longrightarrow {}_{15}P^{30} + {}_{0}n^{1}$$

That is: Helium nucleus plus aluminum nucleus yields a nucleus of a phosphorus isotope of atomic weight 30 plus a neutron.

Quite their most notable observation was made after they had finished the experiment. The alpha-particle source was removed, but the aluminum plate was still giving out some kind of particles! The two physicists investigated those particles. Their finding was unprecedented, for the particles turned out to be positrons. Careful repetition of the experiment confirmed the results, and the Curie-Joliots were able to report the production of the first synthetic radioactive nucleus. Now they had another nuclear equation:

$$_{15}P^{30} \longrightarrow {}_{14}Si^{30} + {}_{1}e^{0}$$

That phosphorus atom with 15 positive charges and atomic weight 30 is unstable. Natural phosphorus comes in one form and one form only, $_{15}P^{31}$; that is the only natural isotope of phosphorus. We now know of three isotopes—atoms having the same chemical properties, but different weights—of phosphorus: the natural isotope, $_{15}P^{31}$; the one the Curie-Joliots made, $_{15}P^{30}$; and another synthetic isotope, $_{15}P^{32}$. Neither of the two synthetic isotopes is found in nature for the excellent reason that they are both highly radioactive. The Curie-Joliots' isotope of atomic weight 30 is half gone in just 2½ minutes; the synthetic isotope of atomic weight 32 is half gone in 14.3 days. The Earth is about two billion years old, and if there ever had been any of these isotopes around, they would long since have disappeared, for, unlike the radioactives that are found in the natural world, they are not being constantly produced from still heavier, longer-lived elements.

The Curie-Joliot experiment precipitated immediate interest in the possibility of making other elements into synthetic radioactives—of finding radioactive forms of other elements up and down the chemical table. Out of all the research came several fundamental discoveries. Though we still do not know what the mysterious binding energy is that holds nuclei together, we do know a great deal more than formerly about what it will and will not allow. A few basic rules make it easier to understand what happens in these synthetic radioactives and in the phenomena about uranium that were discovered later. A very new term that may be helpful here is *nucleon.* A nucleon is simply any particle that goes to make up a nucleus—in other words it may be either a proton or a neutron. The term is generic, covering both those kinds of particle—it's a new term, remember, not a new particle.

Item One of the basic rules is very simple: If a new isotope that is not found in nature is synthesized, it will almost certainly be radioactive. Natural elements apparently contain all the isotopes that are stable.

Item Two: If the isotope does occur in nature, it is almost certain to be stable. An exception is the heavy-element series of radioactives, but the unstable isotopes that occur in nature outside the heavy-element group are *extremely* long-lived. Radioactive potassium, for instance, has a certain instability, but it takes about 40,000,000,000 years for half of it to break up.

Item Three: The chemist says there are 92 elements, but so far as the nuclear physicist is concerned there are about 500 separate and distinct "elements." Hydrogen and deuterium, for example, are entirely different things for the nuclear physicist, though for the chemist they act the same. Again, the chemist says that one radium product, radium D, is ordinary lead—but a Geiger-Müller counter chatters busily when radium D is around. Radium D is a highly radioactive isotope of lead—inseparable from it chemically, but alien to it physically.

Item Four: This is more complex and is quite as inexplicable as most of the other facts about nuclei; it just *is*. If you have a certain number of nucleons in an atom, there may be more neutrons than protons, or there may be an equal number of neutrons and protons—but there will not be more protons than neutrons. At least there won't be for very long; something will happen to step down the number of protons. An excess of them creates an explosive situation.

There is one exception, however. At the light end of the atomic table are two atoms that have three nucleons each; one is a hydrogen isotope of atomic weight 3, the other a helium isotope of atomic weight 3. The hydrogen isotope contains two neutrons and a single proton and is mildly radioactive; it gives off beta rays. Now a beta ray is an ordinary electron; where does an electron come from if the nucleus consists of nothing but one proton and two neutrons? That is the internal business of the nucleus. Just how it is managed remains a secret, but somehow the strange and terrible pressures that exist inside the nucleus force one of the neutrons to discharge an electron. If you take one negative charge from a neutral particle, that leaves it with a positive charge. The neutron affected has not lost any appreciable mass; it still has a mass of one unit. But it now has one unit of positive charge—and a positive-charged unit mass isn't a neutron; the neutron has become a proton. The nucleus now has two protons and one neutron, or a net positive charge of 2. It has converted itself into a variety of helium atom. About half of any given amount of hydrogen 3, or $_1H^3$, will convert itself into this light isotope of helium, $_2He^3$, in a thirty-year period. That is one way for an unstable atom to regain stability: by converting a neutron into a beta-ray electron and a proton.

There is a synthetic isotope of carbon, $_6C^{11}$, which is radioactive. Normal carbon is $_6C^{12}$. To be stable, either the $_6C^{11}$ isotope should have another neutron, or one of the protons should be a neutron; there is a stable isotope of boron, the element next lower in the table, that is $_5B^{11}$. Why $_6C^{11}$ isn't stable we don't know; we simply know from experience that it is not stable, while $_6C^{12}$ or $_5B^{11}$ is. The chemical designation of "carbon" or "boron" is of no importance; what counts is the figures. An atom with 11 nucleons should have 5 protons, not 6; an atom with 6 protons should have 12 nucleons, not 11. So the nucleus of the carbon isotope proceeds to readjust itself.

The example of the neutron's firing out an electron and becoming a proton suggests strongly that a neutron is just a merger of a proton and an electron. But in the second instance one of the protons fires out a positron, thus dispensing with its positive charge and becoming a perfectly good neutron! Evidently, then, a proton is really a neutron with a positron somehow merged with it. Or is it? Apparently both suppositions are wrong, and both the neutron and the proton are pure energy, which may or may not be partly in the form of a positive charge.

All the synthetic radioactives that have been made are emitters either of beta-ray electrons or of positrons. They are, in other words, synthetic atoms either with too many neutrons or with too many protons. Some of them are extremely unstable and change to a new and more stable form in a tremendous hurry; some are very nearly stable and have very long lives. One isotope of lithium, with

8 nucleons, 3 of them protons, is half gone at the end of 0.88 seconds. Another synthetic isotope of carbon, with 14 nucleons, 6 of them protons, has a half-life of a thousand years.

Physicists were a long time learning these facts. Most of the work was done while cyclotrons were new and very hard to get; the few cyclotrons that had been built were overworked, and the few competent nuclear physicists found themselves so busy manufacturing radioactives with the aid of cyclotrons, for biochemical researchers, that they could get little of their own proper work done. Scientists were so eager for cyclotrons and cyclotron products that priority ratings and schedules of operations were set up for cyclotrons long before the war started. All this activity interfered with the pursuit of theoretical atomic physics, because nuclear physicists were few and far between, and it was they who had to operate the cyclotrons.

Nevertheless, nuclear research was pressing ahead steadily, if slowly. Progress from 1932 to 1941 can best be summarized in this table of the number of synthetic radioactive isotopes that were known from year to year:

In 1932, artificial radioactivity was unknown.

In 1934, 3 artificial radioactives were known.

In 1937, 190 artificial radioactive isotopes were known.

In 1939, 270 artificial radioactive isotopes were known.

In 1941, 370 had been recorded. Publication of such reports was then temporarily discontinued.

Finding new radioactives was urgent, because in discovering what made a nucleus unstable and how it became unstable—as a positron emitter, an electron emitter, or a gamma-ray emitter—more could be learned about the strange force called "binding energy." Binding energy binds nucleons together to make a nucleus. It's very particular about what it will bind and what it won't, about the conditions under which it will let a new particle in and conditions under which it won't. We may eventually find the reason for its frequent disregard of the rules, but in the meantime we need the rules.

One of the rules that was found quite early in nuclear research could be put this way: Generally speaking, if a neutron gets into a nucleus, it is easier for the nucleus to fire out a small particle—usually an electron—than to evict the large neutron. And also, generally, if a neutron gets into a stable nucleus, it makes that nucleus unstable, so that something has to be evicted. For example, if silver is bombarded with neutrons, the neutrons slip into the nucleus of a stable silver isotope and increase the number of nucleons by one. There are two silver isotopes in nature, and both are stable; one has 107 nucleons, the other 109. If a neutron is added to either, it produces a radioactive isotope, for both silver of 108 and silver of 110 nucleons are unstable. Both react by discharging beta rays and increasing the atomic number—that is, the net positive charge on the nucleus—by one unit, which turns one neutron into a proton. The result in either event is a cadmium atom, in one case ${}_{48}Cd^{108}$ and in the other ${}_{48}Cd^{110}$. Both of these are stable isotopes.

Some atoms, however, don't react that way. Cadmium is a key element in nuclear physics, because it is almost unique in its ability to soak up neutrons indefinitely without the slightest sign of reaction. The reason for this is that cadmium has a long series of entirely stable isotopes, including ${}_{48}Cd^{106}$, ${}_{48}Cd^{108}$, ${}_{48}Cd^{110}$, ${}_{48}Cd^{111}$, ${}_{48}Cd^{112}$, ${}_{48}Cd^{113}$, ${}_{48}Cd^{114}$, and ${}_{48}Cd^{116}$, so that when a nucleon is added to cadmium, it simply turns one perfectly stable isotope into another equally stable isotope of the same element, without any easily detectable change. Cadmium, moreover, is an ideal sponge for mopping up neutrons when the nuclear physicist really wants to get rid of them; it will absorb even the slowest moving.

Since almost any element can be made to accept a neutron—the uncharged neutron is not repelled from the nucleus the way charged protons or alpha particles are—and since most of these absorptions result in radioactivity, a great deal of work on artificial radioactives was done on a more or less mass-production basis in the early 1930's by bombarding various elements with neutrons and investigating the results.

Shortly after Chadwick had identified the neutron in 1932, Enrico Fermi, a brilliant young Italian nuclear physicist at the University of Rome, recognized the possibilities of the neutron for causing transmutations. Fermi immediately began to investigate what happened when each element in the chemical table was bombarded. He discovered a large number of the synthetic radioactives formed by the process we have just described. At that point Fermi staged the great and final act of the preatomic age. He had observed that each of his radioactives produced by adding a neutron expelled an electron, so that the atomic number was raised by one and the next higher element in the atomic table was produced. What, he wondered, would happen if he bombarded uranium with neutrons? Uranium was the highest element known in nature—the top of the table. If his previous experience gave any indication, adding a neutron to uranium would cause it to transmute to a new element *beyond the border of contemporary knowledge.*

Several other things might happen instead. Cadmium, for instance, along with a few other elements, soaks up neutrons without reacting. Perhaps no reaction would occur with uranium, either. The three isotopes of uranium that were known were apparently equally unstable, lasting only some 4,700,000,000 years! Instead of building the next heavier element, the addition of a neutron to uranium might simply cause the normal alpha-particle emission to take place immediately instead of a few billion years hence. Finally, nuclear theory suggested that all elements heavier than uranium would necessarily be so unstable that they would immediately disintegrate into uranium or other elements that are lighter. The trial was made. After a long period of neutron bombardment in a cyclotron, the uranium did exhibit an entirely new kind of radioactivity—of a very complex nature. First, there was the normal alpha-particle emission of ordinary uranium. There were also traces of radium activity. But, ignoring those, there were four new types.

The method of identifying new radioactives consists in timing the rate at which the radioactivity diminishes and keeping a careful chart of it for a considerable period—days or weeks in some cases, months or years in others. The plotted graph of any single radioactive substance will show a gradual decline of activity as the unstable atoms transmute themselves—a falling curve that drops steeply at first, then diminishes toward zero more and more slowly, yet never quite gets to zero. Radioactive curves for all substances have the same general shape. They are simply graphs of statistics reporting the number of deaths in a community that has no births and whose death rate per hundred thousand is constant. The only difference between curves of radioactives is in the time scale. Half the atoms in a given quantity of radon will be gone in 3.5 days; half the atoms in a quantity of radium will be gone in 1,800 years; half the atoms in a quantity of uranium will be gone in 4,700,-000,000 years. The *shape* of the curves is the same; the *scale* is different.

By graphing the radioactivity in his unknown sample Fermi got a curve representing the combined effects of all the radioactives present. He knew the shape each of the separate curves had to have. Studying the shape of the composite curve made it possible for him to determine how many separate curves of that special shape had been added to make the peculiarly lumpy resultant curve. Then, after studying those separate curves, he determined the scale of each of them. Four types of radioactives were revealed. One had a half-life—was half gone—in 10 seconds; another had a 40-second half-life; the third, a 13-minute half-life; the fourth, a 90-minute half-life. There were indications of still longer half-lives, but natural radioactive substances inevitably present in uranium seemed to confuse the signals.

Fermi was highly delighted. There were three known stable isotopes of uranium, ${}_{92}U^{234}$, ${}_{92}U^{235}$, and ${}_{92}U^{238}$. It might have been possible to make, from these, some heavier radioactive isotopes of uranium—but it was a fair guess that one of the four observed radioactive isotopes was an unstable isotope of the unknown, unnatural element 93. The problem now was to find it.

If a new chemical element had been produced, it should be possible to separate it by chemical means, because it would necessarily have chemical properties different from those of uranium. In the original discovery of induced radioactivity by the Curie-Joliots the experiment consisted of bombarding aluminum with alpha particles, which produced radioactive phosphorus. If the aluminum plate were dissolved in acid and a small quantity of nonradioactive natural phosphorus were added, the aluminum and phosphorus could be separated by chemical processes. The synthetic radioactive phosphorus is, for all the purposes of chemistry, genuine phosphorus; it would join its chemical brother atoms and separate from the aluminum atoms. Hence, starting with a radioactive aluminum plate, you would finish with a solution of radioactive phosphorus in one test tube and a solution of nonradioactive aluminum in another. But how to apply that principle to Fermi's element 93? He had no natural 93; he could not know the chemical properties of 93, since it had never been found.

Fermi looked for information in the table of chemical elements. The great Russian chemist Mendelyeev, who first arranged this table, had been able to predict with almost magical accuracy the chemical behavior of elements that had not been discovered at the time he described them. Applying the principles of Mendelyeev to his own problem, Fermi decided that element 93 should have chemical properties very much like those of manganese and masurium, and manganese was known and available. The relationship should be strong enough so that these two could induce the strange new substance to follow them. In isolating radium the Curies had made use of the fact that it was chemically similar to the already known element barium. Fermi hoped he could do the same sort of thing in isolating element 93.

The method seemed to work. Fermi added a manganese salt to his uranium solution after it had been bombarded with neutrons and then precipitated the manganese. About one-sixth of the 13-minute and the 90-minute activity went with the manganese, but none of the natural uranium activity. This proved that the newly created radioactive was akin to manganese and not chemically related to uranium. Everything known up to that time indicated that this was proof that man had at last hit on an element beyond uranium in the periodic table. Fermi believed that he had created element 93 in a laboratory.

Proof that his conclusion was wrong was the weightiest part of this last great chapter of the preatomic age. Development of that proof was, however, extremely difficult and apparently unnecessary. The need for a better explanation was not apparent then. Only the determination of every true scientist to pin down every last detail with care and exactitude led to the great discovery. Other nuclear physicists, assisted by competent chemists, went to work on the problem of elements heavier than uranium, or "transuranic" elements. By 1935 the several teams at work had proved that the new activity was not due to any uranium isotope nor to an isotope of any element between mercury and uranium in the periodic table. They had, in other words, eliminated all known elements at the upper end of the periodic table. It seemed that the new radioactivity was really due to a transuranic element or possibly to more than one such new element.

In the following years Otto Hahn and Fritz Strassmann, at the Kaiser Wilhelm Institute in Berlin, tried to identify, actually to separate, the element or elements responsible for the various radioactivities. A considerable number of these activities were on record now. In addition to the four Fermi had observed, five more had been found by other observers, bringing the total up to nine. And there was no guarantee that these were all. The problem of identification was knotty. Hahn and Strassmann finally produced a provisional theory of successive transmutations that accounted for their many physical and chemical observations—but to achieve it they had to assume that all three of the known isotopes of uranium were transmuted, each by a different and devious path, through complex chains of successive superheavy elements. This assumption gave them not only element 93, but also elements 94, 95, 96, and 97!

Their theory also required some very curious radioactivities of the uranium isotope $_{92}U^{238}$, the most abundant of the three natural isotopes. They had made observations under three different conditions of neutron bombardment of uranium. First, a sample had been prepared by bombarding the uranium with extremely fast, high-energy neutrons. A second sample had been prepared by bombarding uranium with neutrons of moderate energies, from 25 to 1,000 volts. Finally, a sample had been prepared by bombarding uranium with very slow neutrons that just drifted along like a slowly diffusing cloud. The sample prepared by very fast bombardment turned out to be almost the same as that prepared by very slow bombardment. But the middle sample, prepared by moderate-energy bombardment, had quite different characteristics. In trying to account for these characteristics Hahn and Strassmann made their theory seem inordinately complex and arbitrary. It didn't ring true. No one liked it particularly, and neither Hahn nor Strassmann seems to have been really satisfied with it, for they stuck doggedly to their research.

They concentrated on one particular type of activity—one that they had found could be precipitated with barium. Barium is the fairly common earth element that is usually used to precipitate radium in separating radium concentrates from uranium ores. Hahn and Strassmann had suggested that one of the products of the uranium-neutron reaction was an isotope of radium—not the ordinary radium produced by natural decay of uranium, but a new isotope, chemically identical, but with a different sort of radioactivity. They were forced to that opinion because radium is an alpha-particle emitter, and this new material was not.

The chemical problem had been particularly tough because of the infinite variety of the new radioactive elements, which bore chemical resemblances to about half the periodic table—from element 30 up to element 60. It looked as if Hahn and Strassmann had discovered an entirely new periodic table beyond the range of the known elements! This complexity led them to concentrate on their supposed radium isotope. After much careful work they proved that it could indeed be nothing other than radium—or possibly barium, since they were using barium as a coprecipitating material. All that remained to be done was to prove that the material was not barium, and the case would be closed.

The process for the separation of radium from barium was standard in the preparation of commercial radium. So Hahn and Strassmann confidently added some known radium to their solution and started the fractional crystallization process required for separation of barium and radium. Chemically speaking, their technique was perfect; the known radium separated precisely as it should have done. But the strange radioactivity, their so-called radium isotope, *didn't go with the radium;* it stayed with the barium. Only one conclusion was possible. They had already, and most elaborately, proved that the unknown could be only radium or barium; they had now proved just as authoritatively that it wasn't radium. So it must be barium.

Barium! A radioactive isotope of barium prepared by bombarding uranium! If that were true, then all the strange radioactives that had shown up, all the products that had seemed "chemically similar to" half the elements in the periodic table, probably *were* half the elements in the periodic table! Instead of working in a strange land of superheavy and supersuperheavy elements beyond the end of the table, they had been working blindly with familiar elements in the middle of the periodic table. They hadn't recognized the elements, because they hadn't expected to find them. Bombarding uranium with neutrons might reasonably be expected to produce some element like radium, or radon, or something a bit heavier than uranium; but nothing in past experience had even remotely suggested that the uranium atom would *break in two* and produce these elements that were lighter by 100 neutrons.

For some strange reason, though, the uranium atom, when a single neutron was added, instead of sending out a little chip–an electron, a positron, or even an alpha particle–split almost in half, discharging a colossal fragment, a whole barium atom. It was a discovery to thrill any nuclear physicist—and also one to make him feel a bit foolish. He hadn't recognized barium when he worked with it! No wonder the strange material had precipitated with barium; it was barium. No wonder, either, that Fermi's original test for the hypothetical element 93 had shown the presence of something that precipitated with manganese; it was manganese.

Hahn and Strassmann were excited. They were on the trail of a tremendous triumph for the science of nuclear physics. The massive uranium atom, ${}_{92}U^{238}$, was splitting to produce barium, which is element 56. That would leave 92 minus 56, or 36 positive charges on the other fragment of the uranium atom, and an atom with 36 positive charges would be an isotope of krypton, a rare gas much like helium in its chemical properties, since it has none; it doesn't do anything whatsoever chemically. The heaviest known isotope of krypton, a radioactive isotope itself, is ${}_{36}Kr^{89}$, while the heaviest known barium isotope, also radioactive, is ${}_{56}Ba^{139}$. The positive charges, $36 + 56$, add up to 92 all right, but the total masses, $89 + 139$, add up only to 228, a full 10 weight units shy of the 238 weight units of uranium. Even assuming the lightest uranium isotope, ${}_{92}U^{234}$, were the one involved, the totaled masses were 6 units shy. The splitting of the uranium atom must be an affair of incredible violence with a stunning release of energy.

The existence of atomic energy was first recognized as a result of work with uranium. Now uranium was to be hailed as the element most likely to give men the first clue to atomic energy that might be put to use. The Cockcroft-Walton experiment, growing out of

Lord Rutherford's work, had succeeded in producing atomic fission as a laboratory stunt, spectacular but unusable so far as anyone could then see. Hahn and Strassmann's work pointed out an atom that could not simply be split, but split so as to release an enormous amount of energy as a result that could be relied on.

7. URANIUM—CHAIN REACTION?

POLITICS had already begun to stir into scientific affairs when the work of Hahn and Strassmann reached its culmination. A Jewish physicist, O. R. Frisch, forced to flee Nazi Germany, had gone to Denmark to assist the great Danish nuclear physicist, Niels Bohr. He was joined by his cousin, Lise Meitner, also a physicist, who had worked with Hahn and Strassmann. The refugees told Bohr of a shrewd guess they had made about Hahn and Strassmann's work. They suggested that neutron bombardment caused the nucleus of the uranium atom to split. Now, in essence, the secret was out; it had safely escaped Germany and was on its way to the rest of the world.

Early in January, 1939, Hahn and Strassmann published a report of having produced an isotope of barium by neutron bombardment of uranium. Bohr came to the United States that same month, partly in order to discuss certain theoretical questions with Albert Einstein, who had found haven here. Other refugee scientists who had gathered at Columbia University, Fermi among them, were agog over Hahn and Strassmann's report; and word of the still more exciting guess at the true explanation of the Germans' experimental results spread from Bohr to these men.

Bohr and Fermi met at a conference of physicists in Washington in January, 1939. Before the sessions were over, Bohr received word that experiments in his laboratory in Copenhagen had confirmed the guess that the uranium atom split under bombardment. Numerous experiments were immediately undertaken over here, and positive results were soon reported in the *Physical Review* from several of them. The scientists saw that splitting the uranium atom must release an amount of energy so great that even simple apparatus could detect it. Once they knew what to look for, it was not much of a job to find it.

Nuclear physics hadn't been able to explain the laws of the binding energy that holds the atom so firmly together, but pragmatic data made it possible for the scientists to estimate the violence of the uranium fission ahead of their tests. The periodic table of elements supplies figures for "binding energy per particle" for atoms of different sorts. Nucleons—whether protons or neutrons—exert a powerful attraction on other nucleons, once they come within a certain distance of each other; that is, within 10^{-12} cm., the diameter of an atomic nucleus. The more nucleons there are in a nucleus, the greater the binding energy. You can add nucleons . . . and add nucleons . . . and just have different elements, with progressively greater binding energy; but you can't get greater binding energy indefinitely. Powerful as the binding energy must be to hold together the 92 protons of the uranium nucleus, for instance, against their impulse to repel each other, it has its limits.

Any analogy for what goes on as nucleons are added is necessarily feeble, but here is one from psychology that may not be too bad. Let's say a new restaurant is opened, and a few stray passers-by wander in. Their presence will attract other customers, since human beings are gregarious. Still others, seeing that there is quite a crowd in the new establishment, decide that it must be worth trying. But beyond a certain point the size of the crowd, instead of attracting, repels. One of the customers thinks that if there is such a demand for restaurants, he had better start one of his own. When he opens up, half of the first restaurant's customers go over to his place. Crowding does not exert an attractive force now, but a repellent one.

Nucleons don't make decisions, of course, but they do react to forces. The first few nucleons in an atomic nucleus build up an attractive force that causes other nucleons to join them. In the lighter elements the force with which a new nucleon falls into the nucleus varies considerably. After the trend is established, however, the energy released per neutron added increases regularly till it reaches its highest point in elements about the middle of the periodic table; iron, nickel, and cobalt are right in the middle of the table. Then the energy released per nucleon added begins decreasing again gradually. The crowding in the nucleus is beginning to discourage prospective customers. Finally the crowding becomes so great that the nucleus is utterly unstable—and it splits apart, or fissions.

The Cockcroft-Walton experiment, in which lithium and hydrogen reacted to produce two helium nuclei and 17 Mev of energy, is possible, we now know, because of one of the irregularities in the increase of binding energy per particle that are found at the low end of the table. In helium the binding energy per particle is exceptionally high. This is why the helium nucleus keeps showing up as a radioactive discharge particle; it has extreme stability and extremely high binding energy. The lithium nucleus has a relatively low binding energy per particle, and the unnatural nucleus formed when a proton is added to it has a very low binding energy per particle. The altered nucleus proceeds, therefore, to divide suddenly and with enormous violence into two separate nuclei of very high binding energy per particle, the difference in energy appearing as the energy of motion of the two helium nuclei so formed.

Theoretical calculations had suggested that, at the heavy end of the periodic table, the tension from nuclear crowding would become so great that a nucleus containing 250 nucleons would explode spontaneously. Uranium is very near that limit, since its three known isotopes have respectively 234, 235, and 238 nucleons. The scientific conference was electrified by Bohr's news because the nuclear physicists realized that, if the uranium atom really split, the reaction was basically similar to the lithium-hydrogen reaction—but on a far greater scale. The overcrowded uranium atom would be splitting into two nuclei of much lighter weight, but of much greater binding energy per particle—into two atoms about the middle of the table, where the binding energy per particle reaches its highest intensity. Hurried calculations indicated that perhaps 200,000,000 electron volts of energy could be expected from such an event.

That in itself was exciting enough. But there were other and immensely more exciting aspects to the situation. The reaction occurred when slow neutrons were used. That meant that the neutrons could drift slowly, bouncing from atom to atom, until they were absorbed and caused a reaction. The difficulty with the Cockcroft-Walton atomic reaction was that a proton had to hit a nucleus with a force of 150,000 volts and that practically none did hit. On successful hits you could make a profit in terms of energy, but your percentage of successful hits was so low that you wound up with a net loss. Using slow neutrons, however, you couldn't avoid hitting a nucleus in time. If a neutron missed at first, it would simply bounce against another atom. Inevitably, sooner or later, it was bound to make a real hit. That factor alone made it seem that the vast store of energy in the uranium nucleus could be released profitably—that is, with a profit in terms of energy recovered as against energy expended.

The crowning consideration concerned the balance of protons and neutrons in light and heavy elements. Elements around the middle of the table, where the binding energy per particle is highest, have almost equal proportions of neutrons and protons. Nickel has 28 protons and 32 neutrons. Krypton, one of the products found in Hahn and Strassmann's uranium solutions after bombardment, has 36 protons and 46 neutrons. Near the heavy end of the table it seems to take more neutrons to hold things together. Lead has 82 protons, but 126 neutrons. Uranium has 92 protons and 146 neutrons; there's a distinct preponderance of neutrons as against protons up there. Split exactly in half, a uranium atom would produce two atoms, each with 46 protons and 73 neutrons. An atom with 46 protons is palladium, a platinumlike metal, but palladium's heaviest stable isotope has only 64 neutrons. If uranium split into two palladium atoms, the new nuclei would immediately have to make major readjustments to become stable.

If an atom with 46 protons and 73 neutrons were formed, there might be several ways it could alter itself to become a stable isotope. It could discharge nine neutrons in rapid succession and become the heavy stable palladium isotope $_{46}Pd^{110}$. It could discharge four beta particles or high-speed electrons in succession, changing four of the excess neutrons to protons and thus producing an atom with 50 protons and 69 neutrons. Such an atom is a stable isotope of tin, $_{50}Sn^{119}$. It could do a little of each, throwing off a few neutrons and a few beta particles or electrons, and perhaps reach a compromise solution such as the stable isotope of cadmium, $_{48}Cd^{116}$. The nuclear physicists considering the problem thought this possibility as the likeliest.

Now if the products of the uranium splitting, or fissioning, with their huge neutron excess, would just release a few neutrons, say two or three, for each uranium atom that split . . . If fission produces one or more neutrons that cause more uranium fissions, then the reaction can be made a self-sustaining nuclear fire!

The tests established definitely that uranium split, under neutron bombardment, into two lighter elements. Which two seemed to be a matter of chance. Usually the two portions were unequal; the mass might cleave into 100 and 136, producing rubidium and caesium, two metallic elements, or into barium and krypton, as in the experiments of Hahn and Strassmann. In the first rush the great excitement was confirmation of the fission of the uranium atom. Only one physicist reported that he had incidentally detected a 23-minute activity that seemed to be due to something Fermi thought he had found years before, the superheavy element 93. This incidental observation seemed trivial as compared to uranium fission.

That 23-minute activity was tremendously significant, though. It was due to a synthetic isotope of uranium, formed from $_{92}U^{238}$ by the addition of a single neutron. The new isotope, $_{92}U^{239}$, was unstable; it gave off a beta ray—exactly as Fermi had hoped, back in 1932 and 1933—and turned itself into a new element. That element over and above the old table of elements is now called neptunium—for the planet Neptune, which is just beyond the planet Uranus. When $_{92}U^{239}$ discharges an electron, it becomes $_{93}Np^{239}$—and that, in turn, is an unstable isotope. It, too, discharges an electron, which raises its atomic charge from 93 to 94 and produces another new element, plutonium. The isotope of plutonium so formed, $_{94}Pu^{239}$, is relatively stable. It has a half-life of about 10,000 years and, like most of the reasonably stable heavy elements, emits an alpha particle, which turns the isotope of plutonium into an isotope of uranium, $_{92}U^{235}$. That isotope of uranium was going to end a war—a war that had not yet broken out.

The nuclear physicists were all busy now with the great number of problems the uranium fission discoveries had raised. Could any other element be made to undergo such a fission? It had been found that a neutron moving at a very low speed would do the job on uranium. How could such an unenergetic particle precipitate so violent an explosion? And which of the known isotopes of uranium was responsible for the result? And—*were any neutrons released in the debris of the explosion?* This last was the most pressing question.

A fire burns when you heat wood in the presence of air because the wood undergoes a chemical reaction that produces heat. This heat will heat additional wood, which will in turn undergo a chemical reaction that produces more heat. This new heat is more than enough to keep the wood burning and can be used to heat still more wood, which in turn . . . and so on. That is a chain reaction. *A* does something to *B* that makes *B* undergo a change that produces another *A*, but it produces more of this second *A* than was needed to make *B* undergo the change that produced it. So long as more *A*—whether *A* means heat, or dollars, or neutrons—is produced by the reaction *B* than is consumed by *B* in getting started, the thing will spread. That principle applies whether *A* is dollars and *B* is a chain grocery store, or *A* is heat and *B* is combustion of wood, or—physicists began to wonder and hope—*A* is neutrons and *B* is the fission of uranium.

If they were right, uranium would be able to sustain a chain reaction, producing the neutrons required to cause the fission that produced the neutrons that . . . and so on. If it turned out that uranium wouldn't do it, there were two other general possibilities: first, that other heavy atoms would be found to fission as uranium did and that these other heavy atoms would sustain a chain reaction, and second, that a fission reaction using some particles other than neutrons as the bombarding agent might be found. Both these possibilities had to be investigated.

Theory was able to advance more rapidly than experiment. There are a large number of elements, and a large number of isotopes of elements, each of which could react differently. Trial-and-error methods of finding which elements might be fissioned would take an incredible length of time. But nuclear theory had advanced sufficiently to narrow the field almost immediately. Two possible regions were indicated by it in the table where fissionable elements might be looked for: down among the very light elements, where there are irregular increases in binding energy, and up at the extremely heavy end of the table. The elements in the middle were ruled out, because there the binding energy per particle is at a maximum; fission might be caused, but it would consume an enormous amount of energy rather than release it.

As to other bombarding particles that might cause fission, theory had suggestions, too. Evidently it was a question of energy relationships; if the uranium nucleus was excited sufficiently, its inherent instability was manifested by abrupt splitting. But then *any* type of bombarding particle that could get into the nucleus and excite the nucleons would do the job. The one essential was that the particle should actually get inside the nucleus; no matter how violently any particle may collide with the nucleus, if it bounces off, the effect will be to move the *nucleus as a whole*. Only a particle that actually enters the nucleus can excite the *nucleons within*.

Experiment confirmed this theory with respect to uranium. The nucleus can, of course, be fissioned by neutrons, which readily enter the nucleus. It can also be fissioned by protons, deuterons (heavy-hydrogen nuclei), alpha particles, and gamma radiation of very high intensity. Incidentally, there is a converse to this. Occasionally a neutron will strike and enter a fissionable nucleus, and then, instead of the expected explosion, we find that the nucleus succeeds in regaining its threatened stability. It discharges the newly acquired excess of energy by emitting a high-energy gamma ray. If this same gamma ray strikes another uranium nucleus, it may bring about the fission that eluded the first one. It's somewhat as though a man standing on the sidewalk were suddenly struck by a small boy chasing some playmate. The man, knocked off balance, will usually fall over, but if another man is standing near, the first man struck may save himself from falling by grabbing his neighbor, so that the energy of the small boy's impact is transferred to the second man. The one who was originally struck doesn't fall—but his unfortunate neighbor is now off balance and does fall.

Investigation had yielded still more data. Of the heavy elements at the top of the periodic table, only three could be made to fission: uranium, as was already known, and two others—thorium and protoactinium. Both thorium and protoactinium required fast-neutron bombardment to produce any reaction at all, while uranium could be fissioned with slow, medium, or fast neutrons.

Theoretical studies of nuclear stability indicated that all three of the known uranium isotopes, ${}_{92}U^{234}$, ${}_{92}U^{235}$, and ${}_{92}U^{238}$, could be fissioned, but that only the first two would yield to slow neutrons. The next step was up to the experimenters. Would actual tests confirm the still somewhat uncertain calculations of the theorists? To perform their tests the experimenters had to obtain samples of the two light isotopes of uranium, separated from the heavier U-238 isotope. Finally minute, submicroscopic samples of U-234 and U-235, separated from U-238, and also of U-238, separated from the two light isotopes, were produced by a complicated laboratory technique. The tests completely confirmed the theory; U-234 and U-235 reacted to slow neutrons, but U-238 ignored the neutrons completely when they moved at slow speeds. Only when the neutrons had very high energy would U-238 fission.

Another characteristic of U-238 was learned. While the U-238 isotope ignored very slow neutrons completely, neutrons moving at intermediate speeds—energies equivalent to 25 volts or more—were very readily and rapidly absorbed by U-238 nuclei. When that happened, the reaction Fermi had originally been seeking resulted; the U-238 absorbed the neutron peaceably, became U-239, an unstable uranium isotope, emitted a beta particle (electron), and became a new element, element 93. It did not fission; it absorbed a neutron and emitted an electron. That immediately explained why the millions of tons of uranium in the Earth's crust hadn't blown up ages ago. Ordinary uranium consists of the three isotopes, with U-238 constituting more than 99 per cent of the whole. If a neutron should enter a mass of ordinary uranium, the chances would be more than 100 to 1 that it would be absorbed harmlessly in a U-238 atom. The presence of the U-238 acts as a damper; it's as though the mass were 99 per cent sand and less than 1 per cent gunpowder. Thus, although uranium is more plentiful than copper in the rocks of the Earth, the presence of the neutron-absorbing U-238 keeps the natural mixture perfectly safe; the Earth is in no danger of exploding like an atomic bomb.

The political Earth, however, was on the brink of explosion, and on September 1, 1939, it erupted in a war perhaps best described as the First Technical War. Victory, instead of following the biggest guns, seemed to follow the best technical brains. Uranium fission assumed new and terrible aspects now that war was spreading over the world. Atomic research had, in the nine years since 1930, developed tools of unprecedented power, and physicists immediately put them to work. Even with the weaker tools of natural radioactivity the neutron had been discovered, and a parallel line of research in cosmic rays had led to the discovery of the positron. With cyclotrons as the heavy artillery and natural radioactives as the small arms progress had been so rapid that few outside the field of nuclear physics realized how close men had come to control of the atom.

The Germans, the Japanese, the scientists of every nation, all knew the basic facts, because up to that time science had conducted an international search for knowledge that recognized no national boundaries. Here is a summary of detailed knowledge of uranium fission that was common to all the world in 1939:

1. Uranium, as it occurred in nature, consisted of three isotopes, U-234, U-235, and U-238—we can omit the subscript 92, since all U atoms are by definition $_{92}U$.

2. If a slow or "thermal" neutron—one moving with an energy equal to the natural drift of warm molecules of a gas—encountered either a U-234 or a U-235 atom, it was absorbed, and a catastrophic atomic explosion took place, splitting the uranium atom into two huge, nearly equal pieces and releasing an immense amount of energy.

3. Neutrons that were slowed to thermal speeds—less than 1 volt energy—had no effect whatever on U-238 and were not absorbed. But neutrons moving at an intermediate speed of 25 electron volts were absorbed by U-238, and an unstable uranium isotope, U-239, was produced, which subsequently underwent radioactive decay and became the transuranic element 93. U-238 could be made to fission by a bombardment of fast neutrons; the U-239 formed under those conditions had more energy than could be dissipated by simple discharge of an electron or two—so great an excess of energy, in fact, that it was forced to undergo fission in turn. A similar reaction explains why the U-235 formed by adding a slow

neutron to U-234 is unstable and fissions, though U-235 seems normally to be a stable isotope. Stable U-235 can be formed by alpha-particle emission from radioactive plutonium, ${}_{94}PU^{239}$; it results then from a heavier atom's *losing* energy instead of a lighter one's *gaining* energy.

4. The products formed by the splitting of a uranium atom were violently radioactive. That is easily understandable. If U-236, the instantly fissioning unstable isotope formed when U-235 acquires an extra neutron, split exactly in half, it would produce two atoms of atomic charge half of 92, or 46, and of atomic weight half of 236, or 118. The atom that has an atomic charge of 46 is palladium, a metal very similar to platinum. Palladium has several stable isotopes, the heaviest of which is ${}_{46}Pd^{110}$. Palladium, the newly formed material, must discharge 8 neutrons in rapid succession in order to achieve stability. The atom could, however, rearrange itself in another way. By discharging a series of electrons it could convert some of the excess neutrons into protons and so reach stability. Discharging from the new nucleus in rapid succession four beta rays, or electrons, would raise the atomic charge from 46 to 50. There is a natural and stable isotope of element 50, which is tin, having a weight of 118; this is ${}_{50}Sn^{118}$.

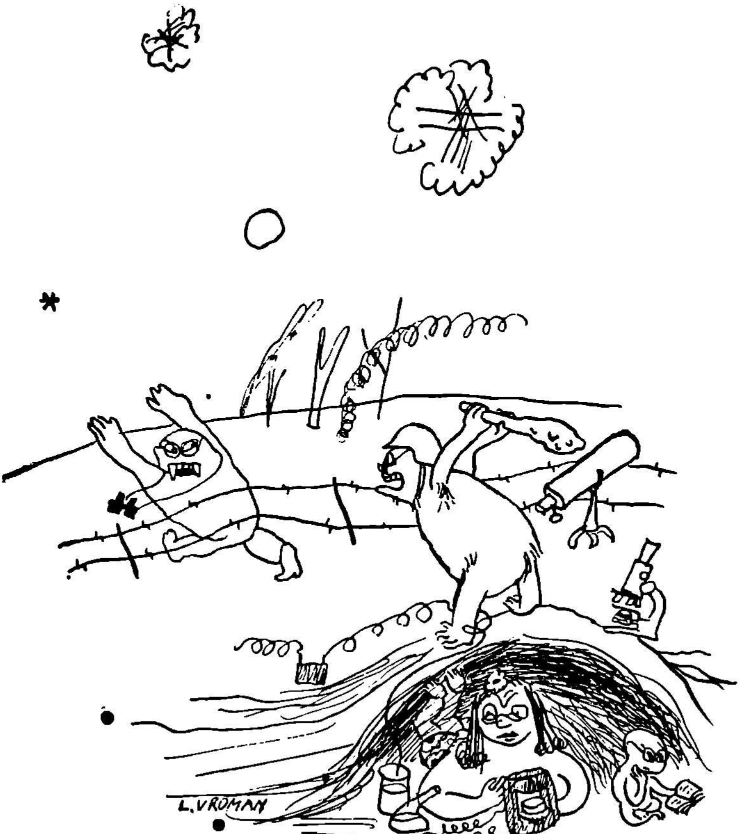
Some violent readjustments necessarily had to be made by the two fission products of the uranium explosion, and there were two ways of readjustment. The new nuclei invariably had too many neutrons for the number of protons. Either they could discharge neutrons, or they could discharge electrons and convert neutrons into protons to redress the balance. If each of the newly formed palladium nuclei discharged 8 neutrons to make itself into ${}_{46}Pd^{110}$, there would be a net gain of 15 neutrons in the reaction, from beginning to end. One neutron went into the U-235 to start the reaction, and 16 neutrons were expelled as the palladium formed sought a balance. It makes little difference which pair of nuclei you choose—whether the U-236 formed breaks into two equal ${}_{46}Pd^{118}$ nuclei or into unequal fragments such as krypton and barium; there will always be too many neutrons in the fragments, and they must change to attain stability.

If they change by discharging electrons, no new neutrons will be produced to replace the one used in starting the process, and the reaction will not be self-sustaining. The fire will simply go out. But *if they change by discharging neutrons,* there will be a net gain of neutrons, with which the process can be made to spread and grow—a chain reaction.

From the start it was clear to nuclear physicists that the nation that first gained control of nuclear energies would win the war. However desperate the military situation of any nation might be, it had only to fashion atomic weapons ahead of the rest to be the final and absolute victor. If the Nazis had got the bomb at a desperate moment when they had been driven back into a mountain fastness, they would have had—not tomorrow, but that very day—the world.

PART TWO

MAKING THE ATOMIC BOMB


L. VROMAN

8. THEORY OF THE URANIUM PILE

IN 1939, nearly two and a half millenniums after Democritus speculated that all matter is composed of atoms, scientists believed they had discovered in uranium a key that would unlock the treasury of energy in the nucleus of the atom. In the second part of this book the work that was accomplished between 1940 and 1945 is described. So much was done, so many laboratory experiments were suddenly enlarged in scale to projects in atomic engineering, that it is very easy to be dazzled by the display of human energy and to misinterpert it. The United States, in forming an international policy for the years immediately ahead, must realize that *the great atomic bomb project simply converted internationally known theory into engineering practice. No addition to basic knowledge was made in those few years except that uranium would support a chain reaction.* That was the one *atomic* secret the United States held on August 5, 1945. The first use of the atomic bomb, on August 6, revealed that secret to the world in the most convincing fashion.

Theoretical knowledge of uranium reactions was so complete by 1941, when international exchange of scientific information was prohibited by censorship, that many science-fiction stories were able to describe the nature of atomic bombs accurately. In March, 1944, a science-fiction story that detailed the complete design and arming mechanism of an atomic bomb appeared in an American magazine. It was a spy story in the course of which the hero disarmed an enemy's atomic bomb; the arming mechanism had to be described in detail. This description was so exact and pertinent that military intelligence inquired into the source of the author's information. The fiction writer had described an arming mechanism that bore a disquieting similarity to what was then being developed at Los Alamos.* The writer's imaginative description was based on a careful study of papers published up to 1941 in technical journals of physics. Every item of information necessary for the design of an atomic bomb, down to and including the arming mechanism, had appeared in those prewar publications. Our national policy for the next several years *must* reckon with the fact that all the secrets of the atomic bomb are *purely engineering secrets.* Any group of competent engineers with adequate financial backing could rediscover them. If a science-fiction author can outline the structure of an atomic bomb accurately enough to worry military intelligence, it may fairly well be assumed that the scientists of many nations can do at least as well.

The one fact missing, the one item of theoretical knowledge that was still needed, in 1941, was the ability of uranium to develop a chain reaction. The science-fiction author could assume that point; that he was right was demonstrated over Hiroshima, Japan, in August, 1945. But the scientists and engineers of the United States did not know and could not blithely assume that a chain reaction would occur. They had to find out. So far we have followed the theoretical development of the atomic story up to the announcement of the fission of uranium and its experimental confirmation early in 1939. A few more discoveries were made between January, 1939, and mid-1940, when scientific information became subject to censorship.

"Uranium" is a chemist's word. For the nuclear physicist it means simply all nuclei having 92 positive charges on the nucleus. A table published in 1941 lists five isotopes of uranium. Natural uranium was known to consist of a mixture of 0.006 per cent U-234, 0.71 per cent U-235, and 99.28 per cent U-238. Which kind—or kinds—of uranium atom was it that underwent fission? And which was responsible for the absorption of neutrons of 25 electron volts that led to the production of element 93? Was one and the same atom reacting to high-speed neutrons and to low-speed neutrons—or was each of the three different isotopes playing a distinct role?

Niels Bohr began a mathematical analysis of the stability of the nuclei of the three natural uranium isotopes, as well as of the

* The story was "Deadline," by Cleve Cartmill, *Astounding Science-Fiction,* March 1944.

other heavy elements, which perhaps would also fission. Simultaneously, experimental physicists were trying to observe fission of other heavy nuclei, and they found that thorium and protoactinium would also fission. The results that Bohr obtained can be better understood if you have a clearer idea of what the word "unstable" means with respect to heavy nuclei. It does *not* mean that they will break down if struck lightly or that they are likely to fall apart at the first sign of resistance. Uranium, the least stable of all atoms, is tough enough to stay in existence for 4,700,000,000 years before natural radioactivity has changed one half of it. So far as blows from outside are concerned, nothing imaginable can crack even this "unstable" structure. When one uranium atom fissions, the internal parts blast out with the terrible violence of 200,000,000 electron volts. The heat and pressure at the heart of the Sun itself are insignificant when compared to the violence of a uranium atom's fission. We ordinarily think of TNT as a powerful explosive; yet it releases less than a single electron volt of energy in its detonations.

Driven with all the fury of the bursting uranium atom, the newly formed barium and krypton nuclei crash into neighboring "unstable" uranium atoms—and bounce off. Unless the nucleus is actually hit by a neutron, the fearful energies released at the center of the atomic explosion cannot damage it. The uranium nucleus is impregnable to outside attack. The atomic nucleus is the only thing in the Universe whose defenses can withstand the force of an atomic bomb.

The uranium nucleus is rather like a large family living in a small house. The overcrowded inhabitants get on one another's nerves. They have explosive tempers. But Heaven help the stranger who tried to attack one of the family, for then all the members rally against the outsider. To transfer this analogy to nuclear physics, even if a massive barium-nucleus fragment, traveling at 300,000,000 miles an hour, attempts to crash into the uranium nucleus, the united group of uranium nucleons bounces it away. A neutron may, however, slip into the uranium nucleus without a battle. It is something like adding a new son-in-law to the already overcrowded family; explosive tempers are further excited, and the battle starts.

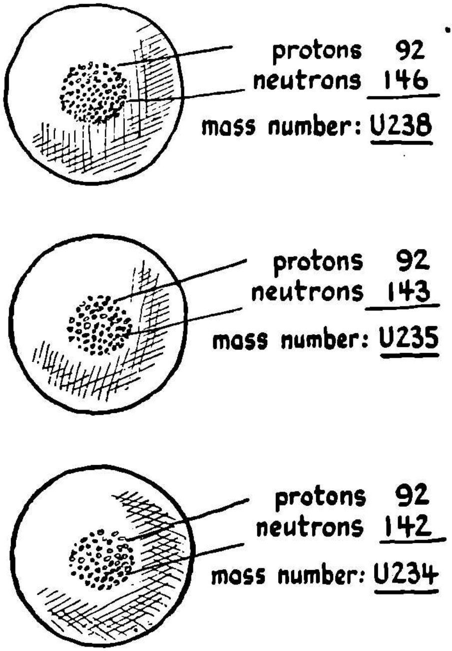
Whether or not an explosion will result when a neutron is added to an atomic nucleus depends on two factors. How much further excitation energy can the crowded nucleus stand? And how much excitation energy is added by the neutron? Bohr's calculations for the five most promising nuclei, assuming that the simple addition of the neutron itself, not the kinetic energy it carries, is the exciting factor, gave the following information:

Nucleus	*Excitation energy required to cause fission (in Mev)*	*Energy added by introduction of neutron (in Mev)*
U-234	5.0	5.4
U-235	5.2	6.4
U-238	5.9	5.2
Protoactinium	5.5	5.4
Thorium	6.9	5.2

The energy added by a neutron exceeds that necessary to cause fission only in U-234 and U-235; these two, then, were probably responsible for the fissions, with slow neutrons, that had been observed. Evidently, too, U-238 would fission if the neutron had a kinetic energy of more than 0.7 Mev when the nucleus captured it. Similarly, protoactinium would fission if a neutron carrying more than 0.1 Mev entered it, and thorium would fission with a 1.7-Mev neutron.

What would happen if a U-238 nucleus captured a neutron with less than 0.7 Mev of kinetic energy? Evidently it wouldn't fission—but it would certainly be in a dangerously excited state. Part of the excess energy could be discharged by throwing out a gamma ray—a bolt of pure energy. Stability could be achieved, too, by releasing an electron and rearranging the balance of the structure so that the new neutron would be converted into a proton. Actually, that is what happens: the U-238 nucleus discharges a beta-ray electron, and converts itself into element 93.

The next step in checking Bohr's calculations was to separate U-235 from U-238 and experiment with both substances. The mass spectrograph, an instrument for the separation of atoms differing in atomic weight, but identical in nuclear charge, was brought into use. It was a laborious task to separate even the small quantities of U-235 and U-238 needed for the experiment, but it was successfully accomplished, and tests proved that Bohr had been correct. The U-235 could be fissioned by slow neutrons as well as by fast neutrons. U-238 fissioned under fast-neutron bombardment, but did not react to slow neutrons.



All uranium atoms have 92 protons (atomic number 92). There are three types of uranium atoms—three uranium isotopes—each having a different number of protons.

The only hope of establishing a self-sustaining chain reaction, the physicists immediately saw, rested on U-235. U-234 would have been all right, except for the unfortunate fact that there was only 0.006 per cent of it in natural uranium—a hopelessly small quantity. U-238, thorium, and protoactinium were ruled out because they would sustain a chain reaction only in the presence of fast neutrons. A consideration of two points will show why this made U-238 ineligible.

First, atomic power can be practicable only if the necessary reacting atomic particles are supplied by the reaction itself. Cyclotrons can produce neutrons, but not in numbers sufficient to provide even a weak source of atomic power—that calls for neutrons by the gram or kilogram, not by the microampere.

Second, the reaction, to be practicable, had to be self-starting or able to start under conditions obtainable on Earth.

This second point ruled out the fast-neutron chain-reaction nuclei. U-238 would react satisfactorily under conditions providing an adequate supply of fast neutrons or under conditions in which the fast neutrons expelled by the fission products were not slowed down by encountering slow-moving atoms and losing energy to them. If all the atoms the neutrons encountered were moving with just half the necessary energy, or 0.35 Mev, they would react properly with U-238 to maintain a chain reaction.

One, and only one, condition is possible under which all the atoms would be moving with 0.35 Mev energy. If the mass of reacting material were heated to the necessary temperature, the thermal energy thus given the atoms would make them move at the required speed. Heated to the necessary temperature, U-238 will automatically maintain the chain reaction, just as U-235 does. There is just one difficulty. That temperature has to be in the *tens of billions of degrees.* Such a temperature is not only unearthly; it does not exist even in the core of the hottest star. If matter here on Earth is heated to such a temperature, the conditions can't properly be described as "obtainable on Earth"—because Earth in that vicinity ceases to exist. Yet this fantastic temperature has existed on five occasions: once in New Mexico, twice in Japan, and twice at Bikini. For an immeasurable and infinitesimal fraction of an instant, at the peak of the atomic explosion, precisely those conditions do obtain at the center of the exploding mass.

This whole series of interconnected facts was clear to physicists from the beginning of the uranium fission experiments. No fast-neutron fission reaction could be used as a source of power, and no such reaction could be made to detonate a bomb, since it could not be started. The slow-neutron fission was possible, however, because at normal room temperatures all the atoms of matter are moving at just such slow speeds as a slow-neutron reaction requires.* Thus, U-235, and only U-235, at that time appeared to have the necessary qualities. That was the atomic story as of mid-1940.

In March, 1939, Enrico Fermi, now an American citizen, had approached the United States Navy Department and pointed out the possibilities of uranium both as a source of power—the Navy would like warships of unlimited cruising radius—and as a source of explosive reactions. On February 20, 1940, the first funds were transferred from the Army and Navy Departments to purchase materials for experimenting with atomic power. On the same day some of the world's most eminent nuclear physicists became, by that fact, the world's first nuclear engineers. From that point on, their work was directed not merely at obtaining facts, but also at fitting such facts into a practical scheme for the construction of an atomic engine. At the same time the atomic story was barred from circulation. It disappeared from the technical magazines. At first the secrecy was such that the very secrecy was kept secret. Later, newspapers, magazines, news services, and radio broadcasters were requested to make no mention of atomic power, cyclotrons, betatrons, atomic fission, atom smashing, or atomic research. They were also asked not to discuss certain elements, including uranium, deuterium (heavy hydrogen), protoactinium, and thorium.

In the quiet seclusion of the laboratory, where the heavy artillery pieces were cyclotrons that operated without so much as a hum, the war for the world was being fought. What follows here is the story of that war. The atomic weapon from the laboratory quickly forced Japan to yield, and it is already hard to remember the anxiety of headlines that told of an army captured on Bataan, of Allied armies in retreat, of ships sunk off the Atlantic coast, of German tanks before Moscow, and of Japanese armies sweeping across South Pacific islands. But that is the background against which this battle of the laboratories must be pictured. The situation of the physicists would have been quite different if there had not been such pressure from the battlefields. An engineer in peacetime doesn't ordinarily build three manufacturing plants simultaneously because he *hopes* one of them may work. A white,

* Normal temperatures correspond to particle energies of about 1/40 of an electron volt of kinetic energy.

brittle, and unworkable metal that corrodes when exposed to air isn't ordinarily regarded as a bargain at $7,200 a pound.

As soon as the government contributed funds for atomic research, the job became a vast engineering project. But the first assignment of these atomic engineers was to settle the theoretical question: Could U-235 maintain a chain reaction? They needed U-235 for their experiments, and the situation with respect to uranium of any isotope type was deplorable. There simply wasn't any to be had. The largest amount of U-235 that had ever been prepared was measured in billionths of an ounce; now pounds of it were wanted.

Some ordinary uranium, at least, was required, so that methods for separating the desired isotope could be developed. But ordinary uranium metal of high purity was unavailable. The largest quantities of that pure metal that had been prepared were a few pounds each year from the Westinghouse Research Laboratories for research departments of several universities. The Westinghouse Company had fallen into this curious business more or less accidentally. Several years earlier, in the course of testing various metals as possible materials for making electric lamp filaments, they had decided to try uranium. So little was known about uranium metal—the metal separated from the relatively common oxide ore—that even the melting point was unknown. So Westinghouse laboratory workers set out to test it. Before the tests were possible, they had to work out a practicable process for producing pure uranium metal—something no one had ever bothered about. They finally developed a method, made some pure uranium, tried it in a lamp, and found it useless. But they had learned how to get high-purity uranium, and since there was some slight demand for it, they had continued to extract a bit for scientists throughout the country.

That was the nation's largest source of reasonably pure uranium in 1940. Uranium ore, on the other hand, was available in quantity. The Great Bear Lake deposits in Canada had been opened a decade or so earlier, and there are large deposits in Colorado. The Belgian Congo was accessible to American ships, and the greatest deposits known lay deep in that area. Uranium oxide had been a commercial material for many years. It was comparatively inexpensive, since it was obtained as more or less of a by-product of radium refineries. It had long been used for producing black ceramic glazes and was also widely used for coloring that peculiar yellow-green fluorescent glassware that you used to see in the dime stores. As a matter of fact, the consumption of uranium oxide as a ceramic coloring material was so high that in 1939 nearly 2 *tons* of U-235 was on display in United States gift shops and five-and-tens; this U-235 was, of course, mixed with a much greater proportion of U-238. The atomic engineers had to get pure uranium from the commercial ore. They would need to start with huge quantities of uranium oxide.

Since U-235 was neither available nor likely to be so within a short time, the basic problem would have to be attacked from another angle while the chemical engineering problems of obtaining purified uranium were being coped with. There was another approach to setting up a nuclear chain reaction, and this did not involve starting with pure U-235. The chain reaction does not take place in ordinary uranium because U-238 has a tendency to absorb neutrons without fissioning. Let's see what can happen to the neutrons produced when an atom of U-235 fissions. There are four ways in which the neutrons can vanish:

1. The neutron can simply flee the scene of action—shoot out of the lump of uranium and go somewhere else.
2. The neutron can be captured by a U-235 nucleus and produce a new fission. This is the one reaction that will cause further reactions, and the one, therefore, that the scientists wanted.
3. The neutron can be captured and absorbed by a U-238 nucleus, to produce U-239, a radioactive nucleus that emits a beta-ray electron, but no neutrons.
4. The neutron can be captured by the nucleus of an atom of some impurity present.

Items 3 and 4, above, can be eliminated directly if we use pure U-235, and only the first item remains to be disposed of, since the second is what we want. Mere escape of the neutron from the scene of action can be prevented by an application of simple geometry. Imagine for a moment that all space is filled to infinity with pure U-235. Then, obviously, there won't be any place for a neutron to escape to that isn't still in the scene of action. If, on the other hand, there were only two U-235 atoms in the Universe and one exploded, the chance that one of the expelled neutrons would hit the only U-235 atom left would be practically zero. A small mass of U-235 won't develop a chain reaction, for neutron escape is too easy. A larger mass will react, because most of the neutrons produced will be trapped by U-235 atoms before they can get away.

A familiar example of this sort of thing is found in a coal fire. Coal will burn only if it is kept hot. It produces heat in burning, but hot coal throws off heat by radiating it from all surfaces. You simply can't make one walnut-size lump of anthracite really burn; even if you heat it white hot, it will burn only briefly, for it loses heat faster than it generates it, and it quickly falls below burning temperature. But two dozen lumps of the same size will burn evenly if they are in a pile. Here you have increased the volume of the coal and decreased the area of exposed outer surface. Since the coal generates heat throughout the pile and loses it only at the exposed outer surfaces, it will now be able to generate heat faster than it loses it; consequently it will burn.

In a mass of uranium the fission reaction occurs throughout the volume, but loss of neutrons can occur only at the outer surfaces. As you increase the size of a cube or a sphere, the surfaces increase, but the volume increases more rapidly. If you have a cube $1 \times 1 \times 1$ foot, it has a surface area of 6 square feet. The volume is, of course, 1 cubic foot. If you double each dimension, making the cube $2 \times 2 \times 2$ feet, the area not only doubles, but quadruples—the surface area becomes 24 square feet. But the volume *octuples*—it becomes 8 cubic feet. This basic geometrical law is extremely important for the whole business of atomic power. It is one of the principal reasons for the detonation of the atomic bomb and the working of an atomic furnace.

If the mass of the reacting material is large enough, the escape of neutrons from the scene of action can be reduced to a point where it ceases to matter. Theoretical calculations early in 1940 indicated that a mass of U-235 somewhere between 1 and 100 kilograms—2 and 200 pounds, roughly—would be needed to form a self-starting, self-sustaining explosive chain reaction. A more accurate estimate could be made with pure samples of U-235. Since no pure U-235 was immediately available, perhaps some way of preventing the loss of neutrons by the methods of items 3 and 4 could be found.

The impurities could, theoretically, be eliminated by chemical processes. The point was theoretical, because absolute purity in a chemical material had never been attained. Getting the last trace of impurity out of a material is next to impossible—but for atomic work certain impurities had to be completely eliminated. A slight trace of boron—even one part in several millions—would ruin the experiment, for boron soaks up neutrons. Cadmium also captures neutrons and would upset all plans. Other substances, however, could be present in large quantities without detectable effect. Lead, for instance, pays not the slightest attention to neutrons; it leaves them alone, and they leave it alone. There was a better than even chance that chemical processes could be worked out that would eliminate the most harmful impurities.

Chemical processes could not, however, eliminate U-238 from U-235. All chemical reactions depend on the behavior of the outermost shell of electrons. When a nucleus has 92 positive charges it attracts 92 electrons, which settle problems of arrangement among themselves; how the electrons are arranged determines the chemical properties. The arrangement is dictated solely by the number of positive charges on the nucleus; whether there happen to be 234, 235, or 238 nucleons in the nucleus is of no concern to the outer electrons. Chemically, U-234, U-235, and U-238 are identical and no chemical process could ever isolate those chemically identical triplets. U-238 simply could not be eliminated from the scene of reaction by any method known in 1940. But there was another possible line of attack.

U-235 will fission in the presence of slow neutrons—that is the factor that makes U-235 so invaluable—but U-238 will not. Slow neutrons—those just drifting along at ordinary room temperature—merely wander up to U-238 nuclei and bounce off them. Therefore there can be no loss of *slow* neutrons by U-238 absorption. When U-238 is struck by a very fast neutron, it fissions just as U-235 does; hence fast neutrons absorbed by U-238 aren't lost to the reaction, since they will produce the desired result—more fissions.

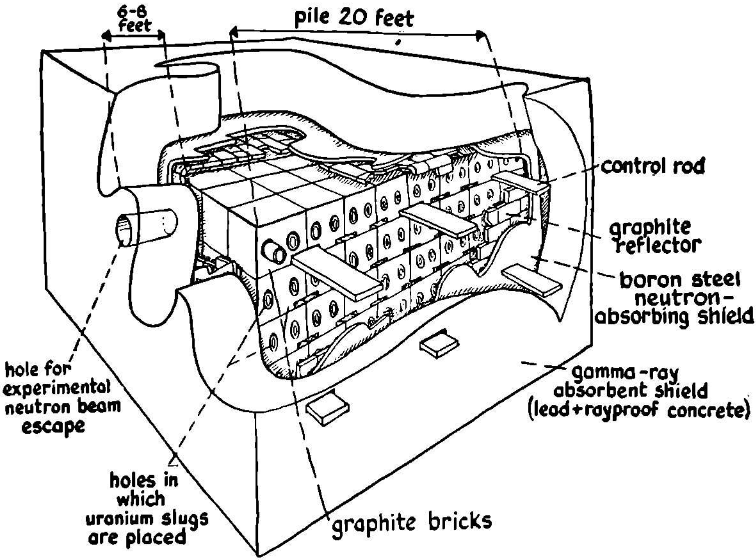
The trouble with U-238 is that it also absorbs neutrons going at a moderate speed and has a particular fondness for 25-volt neutrons.

U-235 will absorb 25-volt neutrons and will fission as a result, but there are so many more U-238 nuclei that the 25-volt neutrons are almost certain to be captured by U-238 rather than by U-235. U-238 will absorb 1,000-volt neutrons, too, and simply form U-239, which changes to element 93 with emission of a useless beta-ray electron and no neutrons. If there were just some way to keep the U-238 from absorbing moderate-speed neutrons, the presence of the heavy isotope would be no handicap. It could have all the fast neutrons it wanted: they cause fissions, which is what the physicists were after. If only the newly released neutrons could be carried off somewhere, immediately after the fission products expelled them, until they cooled down—that is, quite accurately, slowed down—and could then be returned to the mass of uranium after they had *dropped to so low a speed that U-238 wouldn't accept them,* maybe then the scientists could use ordinary uranium.

That reasoning eventually bore fruit in a device that does precisely what we have suggested and does it with magnificent simplicity. Everybody has become familiar with the term "uranium pile" for the arrangement by which atomic energy is released; to be accurate, we should say "moderated uranium pile." Slugs of uranium are inserted into blocks of some different material, the "moderator." This forms what is called a "lattice." The blocks are then combined so that they literally form a pile. The arrangement is shown on page 129.

Neutrons expelled from fission products move extremely fast. They have high speed plus high penetrating power. When a fission takes place in the center of a mass of uranium, the fission products are driven off in opposite directions with incredible violence and speed. The two products immediately eject excess parts with terrific force; several successive beta-ray electrons are driven out, and on the average each fission product blasts out one neutron. Each of the fission products has an enormous excess of energy, which it is dissipating as quickly and violently as possible in order to reach a stable condition. The fission-product atoms themselves are too big and too heavily charged to travel far through dense uranium metal. They stop within, at most, a centimeter of their point of origin. But the uncharged neutrons, shot out with enormous speed, streak away; unless they make a direct hit on some near-by uranium atom, they may penetrate several inches of uranium. If they do make a direct hit on a near-by uranium atom, there will immediately be another fission. If they don't . . . Suppose we let them escape entirely from the mass of uranium, while still traveling at terrific speed, into a mass of something else—something that doesn't absorb neutrons at all, whether slow, medium, or fast.

In this outer material, the moderator, the fast neutrons will strike various electrons and nuclei, bounce around a while, and simply



General arrangement of a uranium pile.

dissipate their energy until they have slowed down to the normal drift of gas atoms at that temperature. The moderator will not absorb them; they can only continue to wander, orphans looking for a home, until eventually they find an atom that will absorb them. If all impurities have been eliminated, the only material that can absorb them is U-235. The neutrons are drifting idly in every direction, and they will either escape entirely or be absorbed in U-235.

Perhaps it will be easier to understand the chain reaction if we take an atomic viewpoint. To a man's-eye view uranium is a hard white metal, almost exactly as dense and heavy as gold and much heavier than lead—an extremely solid material indeed. To an atom's-eye view a mass of uranium metal consists of tiny, compact nuclei set in enormous systems of electrons; in each of these systems 92 electrons are stationed in shell after shell, at greater and greater distances from the nucleus. These complex atoms are distributed according to a precise, ordered system, in ranks and files and cadres, each holding all its neighbors, and in turn being held by its neighbors, in a rigid pattern. The rigidity of the pattern is what gives the metal we know the property we call hardness.

The atoms aren't touching—not by any means. There are great distances between them. Most of the crystal of metallic uranium is empty space. Most of the atom of uranium that makes up the crystal is, in turn, empty space. Into this empty space an extremely minute particle, even smaller than the minute nuclei of the atoms, comes drifting. It gently nudges the nucleus of a uranium atom and bounces away to wander on. It approaches another nucleus in the same leisurely fashion—and bounces in a new direction. It's a very slow neutron, and these are U-238 atoms. It wanders to another and another and yet another atom in the crystal lattice of the metallic uranium, and each time it is rebuffed. Then it moves toward another uranium atom, an atom with exactly the same sort of electron rings, with a nucleus of exactly the same diameter, but with 3 parts less weight than 238—an atom of U-235.

The slow-moving neutron nudges at the U-235 atom's barrier of atomic forces—and abruptly vanishes; it's inside. For a short time the nucleus, now an atom of uranium isotope U-236, appears to be quiescent—then, abruptly, it bursts with a violence that is cataclysmic. The nucleus ruptures and disgorges a flash of radiant energy that streaks out at 186,000 miles a second. The strong and elastic membrane that could withstand the impact of a helium atom traveling thousand of miles a second has split wide open. A furiously churning mass of neutrons, protons, and beta particles is exposed to the strange realm of interatomic space. The remnants of the atomic force barrier have somehow destroyed themselves, vanishing in an explosion of terrific violence. The seething neutrons and protons are trying to establish a new barrier. With the violent annihilation of the old barrier the mass of neutrons and protons separates into two smaller masses, and each envelops itself in a new and tighter sphere of atomic force.

Just before that new force closes in, the disrupting violence has allowed the normal electrostatic forces to gain ascendancy, for an instant of time, over the barrier forces. The two newly created nuclei are driving away from each other so violently and so rapidly that the distant outer electrons discover that the positively charged nucleus they were circling has abruptly vanished. A complex structure of 92 electrons was gathered about a nucleus that suddenly isn't there. Now that the electrons are no longer held together by the attraction of the nucleus and are repelled violently by their negative charges, the entire electron system explodes outward. The inner electrons, most powerfully bound before, are most powerfully repelled now; they drive out with such violence that the first atom they hit reverberates with a blast of hard, penetrative X-rays.

Meanwhile, the two newly-formed nuclei are speeding away in opposite directions at rapidly diminishing speeds. They have been crashing into other uranium atoms and testing to the limit the toughness of the barrier walls in which they have wrapped themselves. With the speed and energy they acquired in that violent cataclysm of the fission, they can drive immense distances through even the closely packed uranium crystals. Finally, however, they slow down and begin to pick up electrons that build up new inner and outer layers of electron shells around them.

One of the nuclei quivers, and its barrier wall blows a bubble, which bursts to discharge an electron, streaking away at nearly the speed of light. Another bubble forms, and another electron streaks away—then a larger bubble, and a neutron shoots out. This is not just a drifting neutron, but one driving with enormous speed and violence. It is out of the uranium slug in the shortest fraction of a second and collides with a nucleus in the other material, the moderator, that is beyond. The neutron and the nucleus both recoil and fly off in opposite directions. The neutron strikes another nucleus and again recoils, but it has by this time given up much of its energy to the two nuclei with which it has collided. Collisions follow with enormous rapidity until finally the neutron has surrendered all of its original kinetic energy and simply drifts gently, pushing at one atom of the moderator after another. Then it drifts into another uranium slug, where the nuclei are arranged in rigidly organized rows and files and cadres. These nuclei are surrounded by shell upon shell of electrons, many more layers of electrons than surrounded the nuclei of the moderator. Drifting easily, the neutron nudges a nucleus, bounces, and wanders off to bump another. Each time it is repelled. It may try 100 or 200 nuclei before it suddenly vanishes inside another U-235 nucleus and precipitates another atomic cataclysm.

The essence of a chain reaction is that it is self-sustaining. Theoretical calculations indicated that it could be secured with a moderated uranium pile. From blueprint to finished building is, however, a long and sometimes perilous step.

9. CONSTRUCTING THE PILE

ONCE the theory of the pile had been worked out, the engineers had two clear-cut jobs before them. First, they had to make theoretical determinations of the proper size for the slugs of uranium, how far apart they were to be placed, and what material could be used as a moderator. Second, they had to get the necessary quantities of the chosen moderator in the required purity.

The selection of a moderator raised a number of problems. Of course it had to be something that would not absorb neutrons under any condition. Several elements would fill that prescription—lead has already been mentioned, but bismuth, tin, aluminum, carbon, and many others were also suitable on this score. The moderator would also have to force neutrons to reduce their speed abruptly, for only thin layers of it could be used. Why this was so can be best understood if we consider two extreme cases.

Let's suppose we find a paint that does not absorb neutrons at all, but slows them to a crawl in a layer a thousandth-inch thick. Blocks of uranium painted with this miraculous stuff can be put together in a practically solid mass and will work as a moderated pile. There would be no more chance of a neutron's escaping from the moderated pile than from a mass of ordinary uranium, and it would take only a relatively small amount of uranium to make such a pile. On the other hand, suppose we use a moderator that will absorb no neutrons, but must be 10 feet thick in order to slow the neutrons sufficiently. Each uranium slug, then, will have to be 10 feet from its nearest neighbors. The slugs themselves will have to be small, so that the neutrons will not slow down before they escape from the uranium. If these small slugs are scattered at 10-foot intervals, there will have to be an enormous number of them in a huge mountain of moderator before there will be a reasonable certainty that a neutron heading out in any direction will be captured by a U-235 atom before it leaves the scene of action.

Now we can propose the general specifications for the moderator:

1. It had to have zero, or very nearly zero, neutron absorption.
2. It had to be something that could be obtained with reasonable ease in highly purified form.
3. It had to be something that would slow neutrons abruptly.

Lead was the old stand-by for stopping radiations. Many people have a general impression that lead will stop any and all kinds of dangerous rays. But lead is just about the world's worst neutron stopper. It does not absorb neutrons, and it doesn't particularly slow them down either. If you want to get rid of neutrons, you can use cadmium; but what sort of thing can you use to slow them down? Evidently, you want a material that will absorb the enormous kinetic energy of the newly released neutrons—something like the sandpit used to stop artillery shells when they are to be recovered for examination—or something that won't bounce them off again as in a collision between highly elastic balls. Unfortunately, if the neutron doesn't bounce with a perfectly elastic rebound, it is absorbed. It has no other choice.

Let's consider for a moment the collision of elastic balls. Imagine a dance floor covered at two-foot intervals with big bowling balls. Now we will drive a golf ball onto the floor, so that it is rolling at a speed equal to that of a good 300-yard drive. The first time it hits a bowling ball it rebounds with violence, ricochets off at full speed to crash into another, bounces from that to a third, and so on with scarcely diminished speed. The bowling balls recoil slightly as they are hit, roll a foot or two, and come to rest again. When a small, light ball hits a large, heavy ball, the little one does practically all the bouncing.

Now replace the bowling balls with golf balls, similarly scattered about the floor, and drive the test golf ball onto the floor again. The first time the driven golf ball hits one of the scattered balls, *both* rebound with almost equal speeds. The driven golf ball has, in the bouncing process, shared its speed and energy with the ball it struck. Since both balls are equal in mass, each, after the collision, bounces to the same extent. The driven ball, after this first collision, has lost about half its energy. The second time it collides, it loses another half. The third collision dissipates another half of the remaining energy. This leaves the ball with one-eighth of its original energy after only three collisions.

These collisions are perfectly elastic, just the sort we find in the atomic world. We can see now why lead will not function as a moderator for the speed of neutrons: the neutrons rebound from the massive lead atoms, 208 times heavier than themselves, with practically no loss of energy. And we can also see why the atomic engineers decided to look for a moderator at the low-weight end of the table of elements.

Calculations made by the researchers as they considered energy loss per collision, density of materials, and practical limitations on the size of the lattice of uranium slugs and moderator, indicated that the moderator had to be an element not more than a dozen times heavier than a neutron. The perfect moderator might have been hydrogen, which has the same mass as the neutron, since the hydrogen nucleus is a single proton. Unfortunately, the neutron absorption of hydrogen is appreciable; when hydrogen is bombarded with high-speed neutrons, some will be absorbed in nonelastic collisions to form a new nucleus—deuterium, or heavy hydrogen. Hydrogen, therefore, fails to meet the very first requirement—that the moderator must have zero, or nearly zero, neutron absorption.

If hydrogen absorbs neutrons to produce heavy hydrogen, why not use heavy hydrogen as the moderator? It would be nearly as good at slowing down neutrons as hydrogen itself, but it would not absorb neutrons, because it has already absorbed one. Tests confirmed this immediately. Heavy hydrogen met the first requirement easily; neutron absorption was so close to zero that instrument errors made it uncertain whether it was slightly above zero or slightly *below* zero! The latter condition was possible, because if a deuteron—a heavy-hydrogen nucleus—is hit hard enough, the proton and neutron may break apart. This would leave the original neutron that struck the blow and make a new free neutron available. It would also, incidentally, stop the striking neutron completely; all of its energy could be used up in breaking the powerful binding-energy seal between the neutron and proton of the deuterium. The same tests also showed that heavy hydrogen met the third requirement. It slowed neutrons very quickly indeed, when used either as the heavy hydrogen in heavy water or combined in the form of paraffin containing heavy hydrogen.

The second requirement was the stumbling block. Certainly, heavy hydrogen was free of impurities; the process that separated ordinary hydrogen from heavy hydrogen was in itself so rigorous a process of purification that the product was heavy hydrogen and nothing but heavy hydrogen. In all the United Nations, however, there was no satisfactory source of supply of heavy water. Before this time heavy water had been a commodity of interest solely to pure science, something that was needed only in quantities of a few pints a year for the whole country. Although it was Harold C. Urey of Columbia University who had done the first work in separating heavy hydrogen, the world's supply had come from Norway. The easiest process of heavy-hydrogen production then known involved a differential electrolysis of ordinary water. Enormous quantities of water were passed through electrochemical tanks and broken down into hydrogen and oxygen by electric current to produce a small quantity of heavy water. This process required the use of huge amounts of expensive electricity and would have been most impracticable if it had been carried out for the production of heavy hydrogen alone. But in Norway, where many mountain streams make hydroelectric power plentiful, while coal is rather scarce, industrial hydrogen gas for oxyhydrogen cutting flames and similar uses was produced in large quantities by electrolysis of water. It was fairly simple for one of the big Norwegian hydrogen plants to install the special apparatus needed to separate the heavy hydrogen, since this plant was already in the course of mass production of electrolytic hydrogen and oxygen. Because the world demand for heavy hydrogen was relatively small, this one plant had produced nearly all that was made.

Shortly after Norway was overrun by the Nazis, British and Norwegian underground agents revealed that Germany was getting several kilograms of heavy water every day from the Norwegian plant and that the Germans had also ordered large quantities of paraffin made with heavy hydrogen. The only conceivable use for heavy-hydrogen paraffin in the quantities ordered was in conjunction with uranium experiments. The German scientists were quite capable of developing the idea of the moderated uranium pile, and they were also fully aware that they had exclusive possession of the world's heavy-hydrogen supply. The men in the laboratories of America called for help from the military. British Commandos and Norwegian patriots launched an almost suicidal raid on the heavy-water plant. It took three tries to get it, for the Germans were acutely aware of its value. And destruction of the Norwegian plant simply put the Nazi laboratories on a par with the Allied laboratories. The scientists on both sides sought another answer to the problem of the moderator until heavy water could again be made available.

The next heavier element is helium. In all the efforts to use heavy hydrogen the intention had been to use it in the form of heavy water or some other compound, because hydrogen gas has so low a density that a huge volume would have been required to contain any great number of hydrogen atoms—and the atomic engineers were trying to hold down size. The United States has a world monopoly of helium. It is a light atom, with extremely low neutron absorption. It is very easy to obtain it in highly purified form. It would have been perfect as a moderator in either solid or liquid form, or as a compound. But helium forms no compounds whatsoever. It is liquid only when chilled within half a dozen degrees of absolute zero—the lowest temperatures men have attained have been produced by the use of liquid helium. No amount of chilling has ever frozen it solid. So helium had to be ruled out.

Lithium, Element No. 3, absorbs neutrons, so it's out.

Beryllium metal, next on the periodic table, seemed to offer some promise. The possible choices were running out rapidly. Boron, next element up, was the element the scientists did *not* want in the pile. The next element is carbon, the heaviest element they could use and get the necessary effect of an abrupt reduction in the speed of the neutrons. Beryllium has a negative neutron absorption. When struck by a fast neutron, beryllium nuclei can absorb it, and then discharge *two* neutrons. The disadvantages of beryllium, however, were many. It is not a common material, its ore is hard to obtain, and the metal itself is extremely difficult to refine into a highly purified condition. The physicists reluctantly decided to reject it.

The moderator would have to be carbon. Carbon is element 6, has an atomic weight of 12, is extremely plentiful and cheap, and has a very low neutron absorption. It is readily available as a solid. It could be obtained in extremely high purity by difficult but practicable methods, because the raw material could be obtained in a fairly pure condition and in immense quantities. Carbon is the major constituent of coal, gasoline, oil, and charcoal. In dense and solid form it is known as graphite; in a still denser crystalline form it is diamond. Graphite, then, would be the moderator.

The moment the theoretical question had been decided, the researchers turned their attention to a tough practical world. They had to develop workable methods of producing sufficiently pure graphite and uranium in large enough quantities. There was no commercial need for the quality of graphite they demanded, just as there had been no commercial need for pure uranium metal. Consequently, while one team of researchers sought a technique for uranium production, another team was assigned the task of developing methods for the production of high-purity graphite. Meanwhile the other nuclear physicists were not marking time. The exact spacing of uranium slugs in a graphite moderator had to be determined, and for this, more accurate information was needed about the absorption characteristics of U-238, U-234, U-235, graphite, and their probable impurities.

Most of the nation's prominent nuclear physicists had been pressed into service in the early stages of organizing the great project. Ernest Lawrence, the man who invented the cyclotron, made a highly useful suggestion regarding the moderated uranium pile. The original plan had been to set up a research tool—something with which to study the chain reaction of U-235, if the reaction were possible under nonexplosive conditions; the uranium-graphite pile would have been of superlative value for that reason alone. Lawrence's suggestion gave it still greater significance.

When U-238 absorbed a moderately fast neutron, it was known, a series of radioactive changes was initiated. U-238 became U-239 by absorbing the neutron, and U-239 was a radioactive isotope, with a 23-minute half-life, emitting a beta ray (electron). The loss of a negative charge from the nucleus converted it to the next element in the scale—neptunium, Np-239. This was a beta-ray emitter, too, changing, with a half-life of 2.3 days, to element 94, plutonium, and becoming isotope Pu-239.

Calculations about nuclear stability, similar to those Bohr had made with U-234, U-235, U-238, protoactinium, and thorium, showed that Pu-239, like U-235, would fission in the presence of either slow or fast neutrons. Pu-239, to all intents and purposes, was a perfect equivalent for U-235. And Pu-239 could be made from U-238 in a moderated uranium pile. Most important, Pu-239 is an isotope of *plutonium;* it is *not* an isotope of uranium. It can, therefore, be separated from the uranium isotopes by *purely chemical methods.*

Lawrence proposed, in effect, that if none of the efforts to separate the uranium isotopes worked satisfactorily, U-238 could be transmuted on a commercial scale, with the atomic energy of U-235 driving the reaction, and thus a synthetic element that didn't exist on Earth could be produced for use in atomic bombs.* Lawrence's suggestion forced the moderated-pile research program into a different perspective. To produce an experimental laboratory-sized moderated pile, the physicists would require tons of graphite and uranium. If a system for such transmutation to produce Pu-239 as

* Plutonium has since been found to exist in nature in exceedingly minute quantities. Accidental fission of uranium naturally occurring in the rocks produces a few neutrons, which are absorbed by U-238, with resultant production of plutonium. The plutonium so formed has a half-life of about 10,000 years; it discharges alpha particles and reverts to U-235. It is noteworthy that U-234 fissions when a neutron is added, converting it to U-235. The U-235 nucleus produced in this way fissions immediately because it is highly excited, having been formed by an increase in energy. The U-235 formed by the radioactive decay of plutonium, on the other hand, is the result of a *loss* of energy and is stable.

The amount of plutonium present in natural uranium ores is so minute, however, that it could be found only by someone who already knew what chemical reactions to employ in seeking it. In other words, it was necessary to know all about plutonium before it could be found for study!

an atomic explosive were to be undertaken, several piles of much greater size would be needed. The scope of the project would be greatly enlarged, and many hundreds of tons of highly purified graphite and uranium would have to be produced.

When the Japanese attack on Pearl Harbor precipitated the United States into war, the atomic project was already under way. The direct involvement of the United States spurred the work. To summarize the lines of attack on the various problems that were being pursued at that time:

1. The basic problem remained that of determining, by use of a moderated uranium pile, whether a self-sustaining chain reaction was possible.
2. In connection with this problem one team of research chemists was engaged in developing methods for producing high-purity uranium metal.
3. Another group of research chemists was engaged in the development of commercial-scale methods for producing high-purity graphite.
4. Other research teams in nuclear physics laboratories throughout the country were making precision measurements of the neutron-absorbing characteristics of various elements, to determine how damaging they would be if present as impurities in the pile.
5. A series of teams was engaged in separate researches on various possible methods for separating the isotopes of uranium.

All these problems had to be attacked simultaneously, not one at a time. The outcome of the war depended not on who got the atomic weapons, but on who got them *first*. Long before high-purity graphite and uranium became available in quantities sufficient to make a reliable test of the great problem, the engineers had set up a sample section of an atomic pile, with the inferior uranium and impure graphite that was all they could get. The mathematical physicists could make theoretical calculations of the best spacing for the uranium slugs in the graphite moderator, but the calculations allowed wide margins for error. These wide tolerances were made necessary by lack of information; the purpose of this model section of a pile was partly to collect information. Even with impure graphite and uranium the results should be of inestimable value.

The first lattice structure of graphite and uranium was set up at Columbia University in July, 1941. It was a graphite cube 8 feet on a side, with some 7 tons of uranium oxide, in iron containers, distributed at equal intervals throughout the graphite. A series of preliminary measurements was made with this arrangement in August, 1941. Enrico Fermi was in charge of the experiment. He was assisted by H. L. Anderson, B. Feld, G. Weil, and W. H. Zinn. Simultaneously, more accurate measurements of the absorption of 25-volt neutrons in U-238 were being made by a staff of assistants working at Princeton University under Dr. H. D. Smyth, and the exact energies required for this type of absorption were determined. Dr. Smyth was to be the official biographer of the project, author of one of the most important documents in the history of mankind—the Smyth report.

Almost a year had passed in the first stages of organizing, theorizing, and working with minute amounts of stuff. No supply of the necessary materials had existed; it had taken time, precious time, to gather them. In the last quarter of 1941—while the Nazi armies were rolling across Russia and driving to the gates of Moscow—the atomic project was gathering momentum. The tool had at last been forged, and the first section of the uranium pile was ready for testing. The problem to be solved contained a factor to which the atomic engineers referred as *k*, the multiplication or reproduction factor. The success or failure of the chain reaction depended on this multiplication factor. If *k* could be made greater than 1.00 in a uranium pile, the project was certain of success. If not, the chain reaction would be impossible.

This *k* factor is somewhat hard to define. It might be called the ratio of the neutron birth rate to the neutron death rate. Suppose that at any one instant there are a hundred free neutrons loose in the uranium-graphite lattice. In the next moments some of these hundred neutrons will be involved in fission reactions with U-235 atoms and will give rise to fission products, which will in turn give off new neutrons. Some of the hundred original neutrons will have escaped from the pile; others will have been absorbed in impurities in the graphite, in the uranium metal, in the containers, and even in the air atoms inevitably present.

If enough of the hundred neutrons are absorbed in fission reactions and the resulting fissions produce enough new neutrons to make up for all other losses, with a slight margin over and above losses, the number of free neutrons will increase. After a few moments the original hundred neutrons will have been absorbed or escaped, but they will have been replaced by new ones. If there are 105 new ones, the reproduction factor *k* is 1.05, and the chain reaction will spread. But if the number of new ones is 99, then the reproduction factor is .99, and no chain reaction can maintain itself.

That *k* factor is similar to the ratio of deaths to births in a nation's population. People are dying continuously, but human life is a chain reaction, too; new people are continuously being born. If 100 people are lost to a nation—by death or emigration—in the course of a day, but 105 are born or immigrate into it, the population is growing. But if there are only 99 newcomers for each 100 who die, the population will inevitably vanish unless something reverses that ratio. The *k* factor that ruled all the experiments on the chain reaction was simply the ratio of neutron births to neutron deaths.

The experimental lattice section set up at Columbia was known to be too small to precipitate a self-sustaining chain reaction. A nation can lose citizens by emigration as well as by death; the uranium pile could lose neutrons by escape. The small section of lattice could not maintain a chain reaction for the reason that emigration from its boundaries would be too great. The only way to get measurements on a chain reaction would be to give the birth rate an artificial boost; the small lattice section needed immigrants to balance the emigrants. Calculations could then be made on the basis of the readings taken. Immigrant neutrons were obtained by placing an artificial neutron source at the bottom of the pile. Either a cyclotron or a radium-beryllium source could be used for this purpose. With the Columbia lattice section, the value of *k* was measured and found to be about 0.87—definitely below 1.00. All the scientists agreed that the value would have been considerably increased if pure grades of graphite and uranium oxide or uranium metal had been available. But still no one knew definitely that *k* could ever be made greater than 1.00.

Meanwhile Lawrence was at work on the plutonium problem.

It had not been determined that plutonium would actually fission. Nuclear physicists had a theory that it would, but no man at that time had ever seen or worked with plutonium. The element hadn't even been named, but was still spoken of simply as element 94. Lawrence had the largest cyclotron in the world in the University of California nuclear physics laboratory, and with it he could bombard uranium with neutrons in sufficient mass to produce an extremely small, but still useful experimental sample of plutonium. The results he obtained showed conclusively that plutonium would fission with slow neutrons, just as U-235 would, and that it would also fission when struck by fast neutrons.

The potential significance of the uranium pile now became even greater. It would permit the quantity production of a material that definitely could be separated to make a superbomb—*if* the pile could be made to work! There were still an enormous number of things to be done. Among the questions unanswered at the end of 1941 were these:

1. The problem of producing a quantity of high-purity uranium had not been solved. It was not even known that it could be solved.
2. The entire chemistry of an unknown element had to be determined. No one had worked with plutonium, and no one knew its properties.
3. There remained the problem of getting enough graphite of the required degree of purity.
4. When U-235 nuclei fission, they produce energy in vast quantities; for the uranium transmutation to plutonium, only 25-volt neutron energies were needed. The difference between the 200,000,000-volt energies of the uranium fission and the 25-volt energy required for the transmutation of U-238 to produce plutonium—199,999,975 electron volts of energy—would appear as heat in the uranium-graphite pile. In running the uranium pile to produce the precious plutonium atoms this energy would be a by-product and a problem. When the atomic bomb was finally produced, the energy would be the desired product. But for the pile—what could be done to carry away the enormous amount of heat? Water cooling? Cooling by air blast? By helium gas, which would help as a moderator as well as a cooling agent?
5. There was the great danger of radioactivity in the by-products

of the reaction. Almost any element in the chemical table can be made radioactive by intense neutron bombardment, and this was going to be an enormous instrument for just such bombardment. Furthermore, every uranium atom split would produce a pair of fragments that would be active sources of radiations; electrons, neutrons, and gamma rays would all come from these fission products. Certain impurities in the graphite and uranium were permissible so far as neutron absorption went—but they would nevertheless absorb enough neutrons to become deadly raido poisons. How much of a menace would that be? Was it a minor annoyance, or did it require treatment as a major problem?

Without instituting any special research program, the atomic physicists knew the answer. Radiation effects were going to be among the greatest of all the problems. In the years since Roentgen discovered X-rays and Becquerel discovered the strange rays from uranium ore science had learned that gamma rays are pure poison. The atomic physicists knew something even more disturbing. It might be that the atomic bomb couldn't be made, that the whole project would fail because the U-235 or the plutonium couldn't be made to detonate. But if the moderated uranium pile could be made to work, it would provide a potential weapon even more horrible and more powerful than any possible atomic bomb.

In all the subsequent atomic work—at Chicago; at Oak Ridge, Tennessee; at Hanford, Washington; at Los Alamos, New Mexico, where the bomb laboratory was to be set up—the menace of gamma radiation was to be ever present. Gamma rays are to nuclear physics what heat is to chemical reactions. Practically speaking, every atomic reaction produces gamma rays. They are a true radiation, but far shorter in wave length than radio waves, and far more penetrative. The great things to remember about gamma rays are these: They kill. They penetrate any material. Any nuclear reaction is practically certain to produce them.

The use of lead shielding to stop gamma and X-rays is well known and has given many people the false impression that lead is opaque to the rays in the same sense that a piece of cast iron is opaque to light. Nothing—absolutely nothing—can stop these rays completely. Remember that the solidity of matter is actually an illusion. Light is about the only kind of radiation that does not go through matter; both radio waves and gamma waves do. Matter is just about pure emptiness. The atom is made of a few minute electrons enclosing vast stretches of empty space—and an infinitesimal nucleus. The nucleus, in turn, encloses a great emptiness. The nucleus of a carbon atom—the atom that is found in a diamond, the hardest, most "solid" substance known—is the same in diameter as a lead atom. But the carbon atom has only 12 nucleons, the lead atom 208. The impenetrability of matter is like the impenetrability of a fast-spinning electric fan. The disc of the fan seems solid. You can't push your finger through it. Yet the finer structure of light shines through this apparently solid disc. In the same way gamma rays shine through the emptiness of matter.

Light is somewhat dimmed, however, in shining through a fan—some of it is actually stopped by hitting the fan blades—and gamma rays are somewhat dimmed in shining through matter by hitting the tiny amount of matter—electrons or the nucleus itself—present in the otherwise empty space. Lead is like a fan with many blades set close together. It has a great dimming power, and half an inch of lead will stop enough of the ordinary X-rays to make them relatively harmless. It takes about 36 times as much lead to stop the rays from some of the radioactives created in the uranium pile. Lead blocks 18 inches thick lined the walls of the "caves" in which laboratory workers in nuclear research kept their solutions, in order to protect themselves from the invisible death pouring from the radioactive atoms. A chemist in one of these laboratories couldn't leave his solution on the table while some reaction was taking place; it would have killed him. The solution had to be put back in the "cave," as the lead-walled boxes were called. It takes not less than 3 feet of solid steel to stop the rays from those "hot" radioactives, or a dozen feet of solid, specially compounded ray-absorbing concrete.

These deadly radioactive elements were produced as by-products of the atomic piles. Even before the piles were built, every nuclear physicist knew that such by-products were inevitable, no matter how they tried to minimize the effect. With the terrific concentrations of neutrons sure to be present in such a high-activity pile as they would need for mass transmutation to produce plutonium, every element would be made radioactive. And the hottest of all would be the violently unstable fission-product nuclei. One of the ways in which neutrons would be lost from the piles would be by escape from the outer surfaces. Neutrons can penetrate anything. But one can trap them with neutron-absorbing atoms, which are thereby made radioactive.

The nuclear engineers planned to build a uranium pile as a neutron source. The neutrons produced by the atomic fission reaction would be used to produce plutonium. But the engineers could, if they chose, use the escaping neutrons to create more synthetic radioactives. The atomic bomb might not work as a weapon at all; in 1942 they could only guess at its probability, but they knew very well of another atomic weapon: synthetic radioactives, which could be scattered as a death dust from a plane. A city sprinkled with synthetic radioactives from an atomic pile would soon be a city of death.

Gamma rays don't kill instantly. Only in the central explosion area of an atomic bomb is the concentration of gamma rays high enough to cause instant death. The less concentrated rays are more subtle than that. They kill by destroying the blood-making machinery of the body so that in a few days the blood becomes thin, won't carry oxygen to the tissues, and begins to ooze out of the veins and arteries into the tissues of the body. The blood loses its power to fight infection. A man exposed to the rays of a death dust would be able to leave the city easily enough, but his corpse would be found along some country road. Artificial radioactives have widely varying properties. All give off gamma rays, some of them extremely penetrative rays, others rays that can be stopped by a few inches of steel or a foot or so of concrete. Some give off a searing intensity of radiation for a very short time; others yield less radiation per gram of material, but will continue that radiation for thousands of years. There is one isotope of ordinary carbon, for instance, that loses only half its original strength in 1,000 years. If a dust of this carbon isotope were dropped on a city, no human being could enter the city for at least *5,000 years*. One beryllium isotope and one chlorine isotope are equally powerful.

On the other hand, there is a sodium isotope that is half gone in 23 seconds, another sodium isotope that has a half-life of about 15 hours, and a third sodium isotope that lasts 3 years. A certain phosphorus isotope has a half-life of 14.3 days, and physicists know of a sulphur isotope with an 88-day half-life. A cobalt isotope with a 5.3-year half-life has been discovered. A great number of synthetic radioactive isotopes are known; the total is something over 400, and undoubtedly the Manhattan Project discovered many new ones.

As a weapon death dusts would far surpass the atomic bomb in their adaptability to military purposes. Consider, for instance, the problem Hitler faced at Warsaw in September, 1939. He was not interested—as the murder factories of the Nazis later proved—in capturing Poles and Jews; he wanted to capture their land and their property. But the Germans were forced to destroy most of Warsaw in order to get rid of the Poles who were defending it. If Hitler had had radioactive weapons, he could have accomplished precisely what he wanted by dusting Warsaw. He could have killed every person in the city without damaging any of the useful buildings. His armies could have moved in as soon as the radioactive decay of the dust permitted. By using a dust with a half-life of, say, 10 hours, the city would have been in perfect condition for occupancy in little more than two weeks. If he had been in a hurry, a one-hour dust might have been concocted that would leave the city ready for use in a few days.

The mine fields of this war were intended to prevent the passage of an enemy force. How much more effective it would have been to sow a band of synthetic radioactives! Troops could cross the line in apparent safety, but the 100 per cent death rate a few days later would discourage further efforts to cross the impalpable mine field.

When the Allies landed on the Continent, the Germans left strong detachments behind in many of the important coastal cities. These forces were completely surrounded, but they were able to hold their isolated positions for months and were a serious threat to the whole Allied plan. They had been left behind by the German High Command for the single purpose of denying to American and British forces the use of important harbor facilities. If Hitler had had death dusts, he could have withdrawn his men and sprayed the cities with a five-year dust after the Allies had moved in. This would have disposed of the occupying forces and simultaneously put the ports out of use until perhaps 1995.

Gamma rays have effects other than destroying the blood-making machinery of the body. They can cause cancer. In lesser concentrations they can cause sterility, making it forever impossible for a man or woman so exposed to have children. A still lighter dose has an even more terrible effect: it doesn't quite cause sterility, but the children of persons exposed to the rays aren't always human. They are apt to be monsters with four arms and no legs, or perhaps no bones at all—just lumps of cartilage. This characteristic would be useful to a Nazi governor in controlling uprisings. If a town proved difficult to govern, it might be dusted very lightly, by way of an example to others, so that the people of the town were forever denied the possibility of children. Or the Nazis might have dusted a town or two with the low concentration of dust needed to cause a series of monstrous births. They would undoubtedly have been greatly interested in seeing what variations could be produced. Such an experiment would have been even more effective psychologically than Lidice.

The atomic bomb is only one of the atomic weapons in the arsenal of the United States today. In 1942 scientists were uncertain that the bomb could be made at all. They were sure, however, that if the Nazi scientists succeeded in establishing a self-sustaining uranium chain reaction in a moderated pile, they would have death dusts as a weapon. It was also quite evident that they would not hesitate to use such a weapon. That raised another question for the Manhattan Project to consider in 1942: What defensive measures are possible against a shower of radioactive material? The Smyth report does not state that a defense was found. It is probable that none is possible, just as there is no defense against the atomic bomb. The Smyth report says only this:

> . . . the fragments resulting from fission are in most cases unstable nuclei, that is, artificially radioactive materials. It is common knowledge that the radiations from radioactive materials have deadly effects akin to the effects of X-rays.
>
> In a chain-reacting pile these radioactive fission products build up as the reaction proceeds. (They have, in practice, turned out to be the most

troublesome feature of a reacting pile.) Since they differ chemically from the uranium, it should be possible to extract them and use them like a particularly vicious form of poison gas. This idea was mentioned in the National Academy report . . . and was developed in a report written December 10, 1941, by E. Wigner and H. D. Smyth, who concluded that the fission products produced in one day's run of a 100,000 kw chain-reacting pile might be sufficient to make a large area uninhabitable.

Wigner and Smyth did not recommend the use of radioactive poisons nor has such use been seriously proposed since by the responsible authorities, but serious consideration was given to the possibility that the Germans might make surprise use of radioactive poisons, and accordingly defensive measures were planned.

The race for atomic energy took on more and more desperate urgency.

10. *ATOMIC FIRE IS KINDLED—DECEMBER 2, 1942*

LAWRENCE and his team in California continued to wrestle with the problem of plutonium chemistry. The situation seemed hopeless, for they were out to discover the chemical properties of an element that didn't exist and that could not yet be created in the atomic pile. The fissionable isotope of plutonium that the uranium pile would produce was Pu-239; what the cyclotron produced was an entirely different isotope.

Neutrons can be derived from a cyclotron beam, but this involves bombarding some element with a kind of ion that a cyclotron can handle. The neutron, having no electrical charge, can't be accelerated in a cyclotron; so either deuterium or helium ions would have to be fired into an appropriate material to release neutrons.* This indirect method of approach would result in a considerable loss in over-all efficiency unless very large masses of material were used. Therefore, since the scientists were trying to get a substantial yield of plutonium, they did not use neutron bombardment of U-238 to produce the new element. Instead uranium was bombarded with deuterons—heavy-hydrogen nuclei. This process does not produce U-239, and thus indirectly Np-239 and Pu-239, but produces a different neptunium isotope, Np-238, which changes to Pu-238 by beta-ray electron emission. Though the Pu-238 atom is, from the viewpoint of nuclear physics, totally different from the Pu-239 that was eventually to be produced, the problem being studied at that time was the *chemistry* of plutonium; and just as the chemistry of U-235 is inseparable from that

* Although heavy hydrogen, or deuterium, was not available in the quantities needed for the uranium pile, there was an adequate supply of heavy water in the United States for the usual small-quantity needs such as cyclotron work.

of U-238, so the chemistry of Pu-238 was bound to be identical with that of the Pu-239 that was to be produced later.

The first studies of plutonium chemistry were made, and the results obtained with the minute sample that had been produced were satisfactory. Now a still larger sample was wanted. One of the early experimental findings was that plutonium bore a strong chemical resemblance to uranium—so strong that some very careful chemical tests were called for. In preparing the larger sample it was decided to use indirect production of neutrons and large masses of uranium. This time the cyclotron bombardment was made to cause neutron emission from one of the light elements, and the neutrons so produced transmuted U-238 to Pu-239. Many hours of prolonged bombardment at the highest possible intensities and several hundred pounds of uranium nitrate were necessary for this job. The experiments took time. By the end of 1942 the work had yielded 500 micrograms of plutonium salts—and 500 micrograms is considerably less than the amount of material in the head of a small pin. Nearly a year's work by many highly skilled men—nuclear physicists, chemists, and electronics experts—had gone into its making. Still, the amount was quite enough for those specialists of chemistry, the microchemists. For them a single microgram—about a five-millionth as much metal as in a five-cent piece—is adequate for many experiments. The plutonium sample was turned over to such men. The chemistry of plutonium could now be tried out even before the uranium pile was making it.

The extraction of pure uranium from crude uranium ores had been undertaken meanwhile by a group of industries. The Westinghouse Electric Company had made one attack on that problem and succeeded in producing a sample of extreme purity. The method was most complicated, however, and the sample weighed only a few grams. The Metal Hydrides Company had produced a few pounds of an impure powdered uranium metal. The only considerable quantity of raw material available in the country in 1941 was a commercial grade of black uranium oxide, used chiefly as a coloring material in ceramic work. This had come from the Canadian Radium and Uranium Company. It had an impurity content of 2 to 5 per cent, but it had been used satisfactorily in the first experimental uranium-graphite pile section and gave the *k* factor of 0.87.

By May, 1942, the supply of crude uranium had been increased, and purification experiments were beginning to show results. Fifteen tons a month could be counted on. The boron impurities had been almost eliminated and all other impurities reduced to less than 1 per cent. The *k* factor was up to 0.98—only 0.02 short of the crucial 1.00. By September, 1942, a ton of crude uranium a day was coming through. Purification processes had been developed to such an extent by mid-July, 1942, that, with the co-operation of the Mallinckrodt Chemical Works in St. Louis and of J. I. Hoffman of the National Bureau of Standards, a ton of high-purity uranium oxide was being processed each day from the impure black oxide. Material of a purity that hadn't previously been obtained on a laboratory scale was now being produced on a full-scale commercial basis.

The program of an all-out attack on the atom had expanded far beyond the laboratories. More and more of the country's great industrial plants were being called on for help. The Harshaw Chemical Company and the Du Pont plant at Penns Grove, New Jersey, were at work on production of uranium metal from the oxide by fall of 1942. Together the two plants produced 1,000 pounds of uranium a day, most of it at the Harshaw Chemical plant. Westinghouse and Metal Hydrides were also working on the problem, and Westinghouse had more than 6,000 pounds of the purified uranium metal by November, 1942. New and better processes were still being sought. Dr. F. H. Spedding and his associates were busy in their laboratories at Iowa State College. Dr. C. J. Rodden at the National Bureau of Standards was experimenting independently. The Union Carbide and Carbon Corporation was brought into the program before the end of 1942. By that time the chemistry of plutonium had been worked out in some detail.

These advances met the first two difficulties of the program—uranium metal and plutonium chemistry. The third problem, production of high-purity graphite, was considerably less complex. Graphite production has long been a major industry. This substance, which is a common crystalline form of ordinary carbon, is used for many purposes—for lead pencils, special greases and lubricants, arc-light electrodes, and electric furnaces and in the making of the nearest thing we have to an infusible, uncorrodible chemical crucible. The National Carbon Company and the Speer Carbon Company undertook the production of the superpurified graphite and were able, with the aid of experts at the National Bureau of Standards, to manufacture a highly purified material. The neutron absorption of this new product was more than 20 per cent lower than that of any other type of graphite. The graphite problem was, to all intents and purposes, completely solved by mid-1942.

In July, 1942, there was enough purified uranium and high-purity graphite to build a new test lattice. As in the earlier lattice, radium and beryllium, to serve as a source of neutrons, were put at the bottom. The density of the neutrons at various points was measured by means of special indicators.* For the first time experimental results indicated that if the lattice structure had been of full size, more neutrons would have been produced than were lost; loss of neutrons by escape still exceeded production in the small lattice section, but a full-scale pile would suffer less from that cause. The value the physicists assigned to the large pile was 1.007—very little better than 1.00, but sufficient to indicate that the uranium pile would be a success. The nuclear physicists had calculated that the vital *k* factor, now hovering so slightly above 1.00, could be increased further if air were kept out of the pile, for nitrogen has a small, but definitely noticeable, neutron absorption.

While these basic experiments were being made, other scientists, in laboratories all over this country and in Britain and Canada, were performing other experiments, each investigating some special but vital little question that might mean success or failure—

* There are several ways to measure the density and the relative velocities (energies) of the neutrons. Many experiments in laboratories over the last decade have shown that silver absorbs neutrons of low velocity and produces a radioactive isotope. If silver is placed in an experimental pile for a known length of time, the intensity of radioactivity of the silver on being withdrawn from the pile is a measure of the density of low-speed neutrons present in the pile at the point where the silver was. Other elements react with neutrons of higher speeds. By a series of such tests it is possible to determine the density of neutrons of all speeds.

even disaster. A seemingly minor point was being examined at the University of Chicago. Technicians there were trying to determine how long after the fission of a uranium atom the neutrons were released that were to fission new atoms. The point at first seems an obscure, esoteric bit of nuclear curiosa, rather trivial as compared to the great work that was being pushed forward with all possible speed. Actually, if that experiment had given the wrong answer, it might have been necessary to call off the entire program.

Suppose a uranium pile were set up and its natural *k* factor proved to be 1.01. This would mean that for every 100 neutrons consumed, 101 were produced. Such a pile would be not only self-sustaining, but self-accelerating. The speed of reaction, the number of uranium atoms fissioned at each instant, would increase steadily. Atomic reactions are the fastest things in the universe; when a uranium atom fissions, the two fragments drive away at a speed very close to the speed of light—hundreds of millions of miles an hour. Since these are atoms, they have to move only interatomic distances before encountering other atoms. Suppose the new neutrons are released instantly after fission, expelled from the atom fragments at speeds of millions of miles per hour. They have to travel only millionths of an inch before reaching other atoms and only a few centimeters at most before they have been slowed and have reached another uranium lump in the graphite pile. The cycle from neutron-caused fission through expulsion of new neutrons, slowing of these neutrons, and reaction of the new neutrons with other uranium atoms—all of this will occur in an instant so infinitesimal that even the enormous speed of electronic circuits that react in a ten-millionth of a second seems slow by comparison.

If all the newly created neutrons were instantly expelled—or were actually belched out at the time of fission of the uranium atom—it would be possible for billions of complete cycles to occur in a single second. If each cycle were just 1 per cent more violent than the last, *the reaction would increase in violence 1,000,000,000 per cent per second.* In two seconds it would be 1,000,000,000,000,000,000 times more violent than at the start; in three seconds, 1,000,000,000,000,000,000,000,000,000,000,000,000 times. Obviously, any reaction that could, within a tiny fraction of a second, increase from a useful working intensity to something a million times more violent could never be trusted. If that were the case, if the neutrons were produced at the very instant of fissioning, there would be no possible way to keep the uranium pile under control, no way to keep it from becoming a titanic uranium bomb!

On the other hand, suppose that just 1 per cent of the neutrons produced were delayed as much as 10 seconds after fissioning. Then if the pile were run with a *k* factor equal to 1.005, it would be increasing slightly with each cycle—but if those 10-second neutrons were absorbed, it would be *decreasing* with each cycle. For, if the 1 per cent of delayed neutrons were absorbed, the *k* factor would drop from 1.005 to 0.995. If there was even a 10-second delay, the pile could be kept under control by the simple expedient of absorbing the delayed neutrons to slow it up or by permitting them to increase the action if a higher operational level were wanted.

The technological resources of the entire nation had been required to get the *k* factor up to 1.007, and forcing it down would be no trouble at all. Any neutron-absorbing material thrust into the atomic pile would immediately lower the *k* factor. If a few rods of cadmium, the metal that soaks up neutrons like a sponge, or a boron material such as boron steel were pushed into the pile, they would instantly bring the *k* factor down as low as the scientists might wish. It was vital to know whether any appreciable percentage of the neutrons actually was delayed, and if so, exactly what percentage. That percentage could mean the difference between atomic fire and atomic dynamite. The test made at the University of Chicago showed that 1 per cent of the neutrons emitted are delayed a hundredth of a second or more, and about .07 per cent are delayed as much as a minute. If the pile were so designed that the value of *k* was only 1.01, the number of delayed neutrons would make controlled operation easy.

The design of the mechanical system of controlling and moving the damper rods presented a unique problem in engineering. Should they be moved by electric motors? What about the effects of radioactivity on the insulation in the motors? They might be short-circuited, and then the rods couldn't be moved! Hydraulic control, perhaps? Suppose some accident caused a failure of pressure in the hydraulic system—a puncture, or corrosion due to an unknown radiation? The system of cadmium and boron-steel damper rods actually used now in controlling the piles is such that no possible failure of electric power or anything else can interfere with their functioning. In addition to automatic electric and hydraulic power-driven damper rods a separate set of manually operated rods is always ready.

All of this was a journey into unknown territory where there was no light—only deadly gamma rays and exploding atoms. It was danger such as man had never faced before. A mistake on the part of a general might lose a city, a province, or even, if it were bad enough, a war. But a serious mistake on the part of the men in the laboratories could do damage that would make all the wars in history insignificant. A mistake in this research might conceivably destroy the planet Earth and leave simply a ring of broken rock and metal circling the Sun, like the ring of asteroids that circles farther out, between Mars and Jupiter. A thousand experiments had to be made and checked so that their results could be integrated into the accumulating body of knowledge about uranium, fission reactions, graphite, and moderators. The experiments are too many to describe, too many even to mention. Two thousand years of history had not produced any such amount of atomic engineering knowledge as came out of American laboratories between January, 1941, and July, 1945.

In the fall of 1942 the climax of the uranium-lattice experiments was near. The supply of high-purity graphite was adequate, and there was enough good-quality uranium metal and uranium oxide to justify an attempt to build a self-sustaining uranium-graphite pile. There was still not enough of the metal or oxide to make possible the best theoretical distribution of the uranium in the lattice; available materials rather than design theory had to be the controlling factor in the choice of the design. This first attempt might well fail for lack of enough pure metal, but the physicists and engineers decided to go on with what they had. Meanwhile the plutonium project—its code name was Metallurgical Laboratory—had been put under the control of a group at the University of Chicago, with Enrico Fermi, the man who had first, but unknowingly, brought about uranium fission, as chief of operations.

Since uranium is forever giving off alpha particles, and since cosmic rays from outer space are forever bombarding the Earth and everything on it, both alpha particles and cosmic rays would be constantly at work in the pile as it was built up. It was expected that natural accidental atom-smashing reactions brought about by these ever-present forces would cause a very slow continuous production of neutrons. There would therefore be no need to start the uranium reaction; when the pile reached the critical size, the reaction would begin of its own accord. Control devices had to be built into the pile from the start and set in a position to damp out the reaction at any time.

Layer by layer the graphite blocks, with the nuggets of uranium set into them, were built up. Each layer had cadmium-rod dampers built in, so that the self-starting reaction could not take the engineers unaware. The scores of recording instruments were watched constantly. Slowly, as the pile grew, the curve of reaction began to rise. Meter needles joggled slightly against their zero pins and seemed to lift a little. Suddenly the needles swooped upward! On December 2, 1942, the uranium pile went into self-sustaining operation. The first atomic fire in all human history, the first self-maintaining nuclear chain reaction ever initiated by human beings, was generating power! December 2, 1942—the date should be recorded in all the future histories of mankind. Only one other date in history is of equal importance, and that was never recorded, for the men who might have engraved it on the rock walls of a forgotten cave knew nothing of writing. They had built the first fire that human beings could control. We will never know where, or when, or by whom fire was first tamed.

The first nuclear chain reaction occurred—anomalously enough—on a squash court under the stands of the University of Chicago's football field. It began while the pile was still well below the size that calculations indicated would be critical. The uranium and graphite were of better quality than the engineers had expected, and the impurities less damaging than they had feared. The cadmium damper rods operated smoothly, and the pile was under perfect control.

For the first day the pile was held under the most rigid restraint. The power output was reduced to half a watt, about the power consumption of a flashlight bulb, for the first ten days. This output was not electrical, of course; it was heat, and so small an amount of it that even delicate instruments could not measure the rise in temperature of the tons of uranium and graphite in the pile. The power output was determined by measuring the number of neutrons produced per second, calculating the number of fissions per second this number represented, and estimating from that the energy released. On December 12, after ten days of study, the power output was cautiously increased to 200 watts. The procedure of withdrawing the cadmium rods a little, so that fewer neutrons were absorbed without producing fissions, and allowing more to become available for the reaction, increased the rate of reaction.

The reaction had proved beyond any possibility of doubt that a self-maintaining reaction was possible with normal uranium. Separating the U-235 isotope from the U-238 had not been an essential first step.

Who deserves the credit for this achievement?

No one man can claim it, nor is it likely that any man wants to claim it. Fermi was the directing chief, but co-operating groups in nearly all the important universities, industries, and technical centers in the nation had done work that made it possible for Fermi to collect the necessary material. Electrical engineers, chemists, and machine-tool experts had been needed to handle the hard, metallic uranium—it is so easy to forget that uranium is something more than a nucleus capable of fission; that it is a silvery, easily corroded, hard metal and must be handled, shaped, and turned into a workable substance. Groups of medical specialists had the highly important job of devising defensive measures to protect the workers against deadly radiations. The whole credit cannot be given to any one person or even to a dozen persons. Rutherford and Bohr, Einstein and Fermi, Hahn and Strassmann, Meitner, Urey, Lawrence—a thousand others—each had contributed. At any rate the first atomic power plant had been built. It was a small plant, producing only 200 watts of power, but it had at last tapped the ultimate power source of the universe. The power that lights the Sun and fires the stars had been harnessed by man and was under his control.

Medical experts were constantly on hand at the uranium pile to prevent the dangerous radioactive by-products of the reaction from killing or burning the men at work. Radioactive burns are strange and terrible things. The victim feels nothing at first—no sensation of heat or anything else that might warn him. Only weeks or months afterward the effects become apparent. In December, 1942, the medical staff was encountering the dangers of synthetic radioactives in mass production in Chicago. By late 1943, if the United States had so decided, we could have manufactured such isotopes on a large scale, loaded them in special lead-walled bombs, and scattered them over German and Japanese cities. We could have seared Berlin and left it an area of death, an area to be shunned by all living things for two millenniums. But this ghastly atomic weapon was never considered for use. Though the atomic bomb was still two and a half years away, its production remained the goal of all the research.

The great thing about the first successful self-sustaining, chain-reacting pile was that it had proved a chain reaction in uranium possible. Eagerness to finish the job rose as the reacting pile proved the goal was real, not a fantastic dream. The pile proved, moreover, that the danger of atomic weapons was also real. Before December 2, 1942, it had been possible to believe that no nuclear chain reaction would occur. The first atomic fire forever put an end to such optimism.

11. PLUTONIUM PRODUCTION

THE URANIUM pile had been built and put into operation. Now the Metallurgical Laboratory, in Chicago, had a research tool of surpassing power. Here was an enormously prolific source of atomic bombardment particles, a source of plutonium, and a supply of uranium, which, after its use in the reacting pile, could be studied for the effects of unknown radiations. The next step was to determine what size of pile and what power level were needed to produce a kilogram of plutonium per day. The pile was essentially an atomic furnace in which U-235 was burned as the fuel, while U-238 was present as a contaminant. The U-238 absorbed some of the by-products of the atomic reaction—the neutrons—underwent a change, and became plutonium. The more U-235 and U-238 was consumed, the more plutonium would be produced. The small, 200-watt pile built under the football stands would have had to operate for perhaps 70,000 years to produce enough plutonium for a bomb. Obviously, what was needed was a pile or a series of piles operating at a level that would consume U-235 at least 70,000 times as rapidly as the original engine. Instead of a 200-watt pile a 14,000,000-watt pile would be needed if even one bomb a year were to be produced. For practical purposes something like 100 times this, or 1,400,000,000 watts of atomic energy, would have to be given off by a uranium pile before any decisive quantity of plutonium could be produced.

This enormous amount of energy *would not be used up* in producing plutonium; it would be a by-product of the reaction. Neutrons of only 25-volt energies would be needed for the reaction, but energies of 200,000,000 volts would be produced. The 199,999,975-volt difference would appear as heat. Since this vast flood of heat would have to be dissipated, the site of the plutonium plant intended for bomb production must be in an area where an enormous amount of cold water was available. The water might be run directly into the piles. Or an indirect heat-exchange method of cooling might be used, with some other heat-transfer medium as the agent carrying the heat from the piles themselves; but eventually a river of cold water would be needed to cool off the cooling agent.

Although the nuclear chemists had been able to learn a good deal from the 500 micrograms of plutonium the cyclotron workers had succeeded in producing, knowledge of plutonium chemistry was far from complete. For one thing the product of the plutonium-producing piles would not be clean, pure plutonium; it would be a slug of metallic uranium in which a very small percentage of plutonium had been created. These slugs would, moreover, be saturated with a more deadly radioactive poison than man had ever encountered. The poisons that boiled out of those uranium slugs weren't simply radioactive; they were the tortured and violently battered products expelled by the processes of atomic transmutation on a mass-production scale—the ashes of an atomic furnace!

The atomic pile and the materials freshly extracted from it gave off not only gamma rays, but also several other types of dangerous radiation. Electrons, positrons, protons, neutrons, and alpha particles were discharged by the freshly extracted material. All of these emissions except the gamma rays and the neutrons are easily stopped by even a few inches of concrete or metal. The gamma rays we have already mentioned. Neutrons are similar to gamma rays in their ability to penetrate almost any matter; lead doesn't stop them at all, and once they have been slowed down to the low speed of ordinary gas molecules, they can drift in air without hindrance. Their range may be even greater than that of gamma rays.

The neutron isn't particularly dangerous in itself. It is quite correct to regard it as the atom of the first of all elements—the element of atomic weight 1 and atomic number zero. The neutron is slightly radioactive, since it breaks up, after approximately 20 minutes, into a proton and an electron and settles down as an ordinary hydrogen atom. The real threat from the neutron is that it can react with so many different kinds of ordinary atoms. When that happens, the neutron is absorbed, and the atom usually discharges a high-speed electron and becomes an isotope of the next heavier element, whatever that may be. If the atom with which the neutron happens to react is a sodium atom in the blood stream of a human being, a gamma ray is generated in the body.

Ordinary radioactive materials give off positrons and electrons, or alpha particles and gamma rays. Only the unstable, freshly created fission products of the atomic piles are neutron emitters, and even they emit neutrons for only a short time—perhaps a few hours. Neutron-emitting radioactives couldn't be used as a weapon, but they constitute a major menace to health, like all the radioactives in uranium slugs fresh from the piles. The radioactivity in those slugs is of such a degree that it is a menace to health, and it seemed quite possible that chemical reactions would take unpredictable directions in the face of such an atomic fury. Chemical processes that worked very nicely with the cyclotron's plutonium and with natural uranium might quite possibly be unable to do anything in the presence of those radiations. The problem was difficult.

Investigation of plutonium's chemistry had shown that Fermi's original guess back in 1933 was wrong; element 93 was *not* like manganese and masurium. It resembled the chemistry of uranium more closely than that of any other chemical element! And plutonium, element 94, was more like uranium than like any other element! Instead of getting into an ordinary group of elements at the heavy end of the periodic table, the researchers had discovered, as it turned out, a new set of elements, which had much in common with the "rare-earth" elements. These rare-earth elements are a group of 15 about the middle of the table—elements 57 through 71, with atomic weights from 138 through 175—with almost identical chemical properties. The similarity of their properties is due to the fact that chemical properties are determined by the electron arrangement in the orbital electrons. The rare-earth elements have a curious habit of hiding the changes in the electron arrangements that come with increasing numbers of positive charges on the nucleus, deep within the inner electron rings, where the changes have almost no effect on chemical properties. The first of the well-known rare-earth elements is lanthanum. All those that follow it—strange-sounding elements like cerium, which is used in cigarette-lighter flints, praesodymium, neodymium, illinium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutecium, and hafnium—are practically identical in chemical properties. It took several decades of chemical research to show that the group did consist of different elements.

Separating U-235 from U-238 by chemical processes is impossible. To complicate matters further, the physicists discovered that uranium is the first of a new group of rare-earth metals. Neptunium and plutonium have chemical properties so similar to those of uranium that separating them, even under the best of conditions, would be a most difficult laboratory process. Nevertheless, it was going to be necessary to carry out that difficult and delicate separation on a large scale. Scientists are persistent people. It was evident that they would need a large uranium pile to produce enough plutonium for working purposes. An intermediate-size plant was in order now—a pile with a productive capacity midway between the small model in Chicago and the giant piles that would be demanded by mass production of plutonium. The original plans worked up for the giant piles provided for the use of helium gas as a cooling agent; blast fans would blow the helium through the graphite and uranium pile, would pick up the heat, and would pass the hot gas on through a water-cooling system.

The medium-size pile was constructed at the Clinton Engineer Works, in Oak Ridge, Tennessee. Simultaneously under construction was the main Oak Ridge plant, which was to be devoted to the other half of the great Manhattan Project—the separation of U-235 from U-238, a part of the master plan we have not yet discussed. The Clinton pile was designed to handle 1,000 kilowatts of heat, with powerful air blowers dissipating the heat directly into the atmosphere, instead of using the helium gas as an intermediary. The essential effects would be the same, it was believed, for though the nitrogen in the air tended to lower the neutron efficiency somewhat, by absorbing neutrons, this could be compensated for by a partial withdrawal of the cadmium-rod dampers.

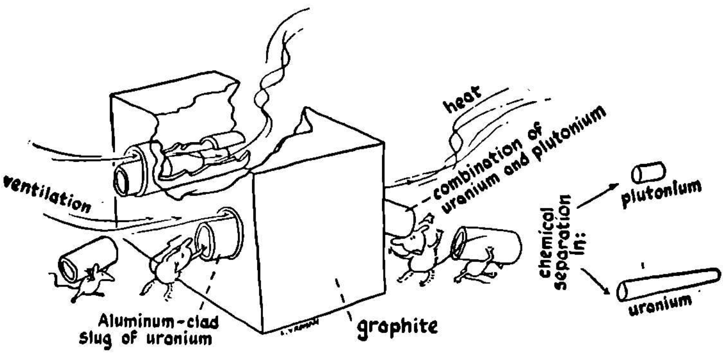
The Clinton plant was intended as a sort of pilot plant, a tryout mechanism to give experience in building and operating the great plutonium production equipment that would have to be built, as well as to produce enough plutonium to test the separation methods that had been developed by using the minute cyclotron-produced quantities. But things did not work out that way. Urgent wartime pressures made it impossible to proceed according to a progressive, step-by-step plan. The great plant at Hanford, Washington, was launched before the Clinton plant was really in operation. And the Hanford piles were ultimately made water-cooled instead of helium-cooled, so that the Clinton pile never did function as a pilot plant for the final piles. The result was that the Hanford piles were constructed from a theory reinforced only by the relatively scant experience the engineers and physicists had gained at the Chicago pile and the entirely different air-cooled Clinton pile. It was as though the Wright brothers, immediately after their successful Kitty Hawk experiment, had started to build a plane of the type used by the airlines in 1940, and, halfway through the job, deciding that they needed something better, had immediately begun work on a gigantic Martin Mars flying boat—not only a vastly larger plane, but one designed for an entirely different sort of service.

The story cannot be told in chronological order; too much happened in too many places in too short a time. In Chicago, specialists were working on characteristics of neutron absorption with the mighty neutron beams they could tap out of their uranium pile. At Columbia University, groups were working on the separation of isotopes. In California, Lawrence and his group had started another investigation, using an entirely different system of isotope separation, while J. R. Oppenheimer of the University of California had gathered a group for theoretical investigation of the problems connected with manufacture of the atomic bomb itself. In November, 1942, the Oppenheimer group had selected a site for their first laboratory work—at Los Alamos, New Mexico, about 20 miles from Santa Fe. The Stone and Webster Engineering Corporation and the Tennessee Eastman Corporation were working at top speed on the immense construction job at Oak Ridge, Tennessee. The Du Pont Company was called on to build the great Hanford plant, where plutonium was to be produced and separated. No one had ever imagined such a chemical engineering project. The Du Pont contract with the government assured a total profit of $1.00. No one could guess what the actual cost would be. No one knew what chemical processes would be involved or what the nuclear processes would be after a considerable amount of the fission products had accumulated. Those nuclear fission products might conceivably wreck the whole enterprise. Most of them were so short-lived and so violently unstable that they could not be produced artificially to permit studies of neutron absorption. They might even break up the chain reaction before it had proceeded far enough to produce a usable concentration of plutonium.

Nevertheless, the production of plutonium was to be attempted, and the plant was started at Hanford, Washington. The site was chosen for three principal reasons. There were no large settlements near by that might be menaced by radioactive products escaping from the great piles when they were in operation. The Columbia River, which would be used to carry away the enormous amounts of heat produced, is one of the greatest sources of clear cold water in the country. The clearness was a great point, for while the water itself could not be rendered radioactive by the terrific bombardment in the piles, impurities in it might have been transmuted into powerfully radioactive isotopes. Finally, the immense power plants at Grand Coulee were within easy reach, and they could supply all the electrical power needed for the plant.

In Oak Ridge, Tennessee, another plant was under construction, and a medium-size uranium pile went into operation. The big question it had to answer was whether the plutonium produced could actually be separated from the mass of unreacted uranium by the processes that had been worked out on a microchemical scale. The separation had to go even further than that. Fission products were present, together with the plutonium and uranium, and the fission products included practically all the elements in the middle part of the chemical table. In the form they had in the uranium slugs, however, these fission-product elements were violently radioactive, so that they were a highly undesirable admixture for material that was intended to be an atomic explosive. The separated plutonium had to be purified of these radioactives.

One of the services performed by the Clinton plant was research on the biological effects of the radiations. A large laboratory was set up for chemical analysis, for research on purification methods, and for fission-product studies, and extensive facilities were prepared for medical research. The health problem was becoming major all through the enterprise. No human being, no living thing, can approach a uranium pile in full operation, nor can any man work near newly activated slugs of uranium. Slugs that have been used in the piles and contain the precious plutonium must be removed from the pile by remote control. This meant that the pile had to be designed with the uranium placed in cylindrical channels so that the slugs could be pushed in at one end and out at the other. Other holes in the pile allowed admittance of control rods



Operation of an atomic pile. In science, what is done, not who does it, is important.

and instruments. The control rods used on this pile were made of boron steel, an alloy with a very high boron content that would reduce the *k* factor, the factor of neutron reproduction, below 1.00 and so would put the reaction under control.

The uranium slugs, after reaction in the pile, were removed by machinery, carried mechanically to processing vats, and processed by automatic devices. The plutonium was delivered in a semi-refined state for final purification in an adjacent laboratory. The separation processes were carried out in a series of cells that were placed end to end and buried in the ground to form what was known as the "canyon." The walls of these cells were made of extremely thick, specially treated concrete to minimize escape of radiation. Uranium slugs that had been activated were transferred under water to the first of these immense vats, and every subsequent operation was carried out by pumping solutions or precipitated muds from one tank or centrifuge to another.

This separation plant had been designed and laid out on the basis of experiments performed with microchemical methods on millionths of an ounce of plutonium—not in the presence of any such violent radioactive rays as were present in the Clinton plant. Nevertheless, the process worked. The Clinton pile went into operation on November 4, 1943, and the first batch of uranium slugs went into the processing mechanisms after little more than a month of nearly continuous transmutation activity at 700,000 watts. By January, 1944, metal from the pile was going to the separation plant at the rate of a third of a ton a day, and by March 1, 1944, several grams of purified plutonium had been delivered. Further improvements in the separation methods were worked out, and the percentage of recovery rose from about 50 per cent at the start until by June, 1944, between 80 and 90 percent of the plutonium was being recovered.

Radioactive fission products were also recovered for experimental use. Some of these products gave off neutrons; nearly all gave off positrons and gamma radiation. The gamma radiation of some of these materials was more powerful than any radiation from natural radioactives, and the quantities of the materials available were huge by comparison. Furthermore, since most of them had relatively short half-lives—half-lives of days or weeks rather than of the millennium and a half of natural radium—the output of one milligram of these materials was correspondingly more intense. Radium might be compared to coal, which gives a slow, steady, reddish fire; these new materials were more like the magnesium foil used in photographic flash bulbs. It doesn't last long, but while it does, the outpouring of radiation is enormous.

The solutions were deadly. In a dark room they would give off an eerie blue glow, making the air itself glow around them. In a lighted room the solution of barium nitrate looked just like any other barium nitrate and acted like it chemically. No human sense could give any warning of the death rays pouring out of the clear watery solution. But Geiger counters and ionization chambers in physics laboratories hundreds of feet away, beyond thick concrete walls, would rattle like castanets under the rain of hard, penetrative rays driving through many feet of dense concrete and steel. The solutions had to be kept constantly in curious cabinets that looked like safes, with thick doors swung on massive hinges and with walls made of solid lead.

Every worker in the laboratories carried a small instrument, resembling a fountain pen, that reacted to radiation, and somewhere on his person he had slips of photographic film that would darken if he were exposed to too much radiation during the course of the day. The air of the rooms was tested regularly with a gadget the workers nicknamed "Sneezy." This device would clack busily in the presence of radioactive dusts. And "Pluto" was sensitive to alpha-emitting radioactive elements that might accumulate on desks, in drawers, cabinets, and the like. Pluto sniffed out minute particles of plutonium dust. Geiger counters watched over the laundry to check on radioactivity in coats and clothing before and after laundering. At the exit gates of some of the laboratories concealed Geiger counters sounded the alarm if someone whose clothing, skin, or hair was contaminated tried to pass. These were the detectives constantly on the lookout for the stealthy killer, radiation. Fortunately, its very nature made it easy to detect before it became dangerously concentrated.

Plenty of other hazards to health had to be safeguarded against. Plutonium, for example, not only is an alpha-ray emitter, but becomes, if the dust is inhaled or ingested in any way, a deadly chemical poison. As might be expected, since the chemical reactions are so similar, uranium also is a poison. The fission products include elements that are poisonous chemically as well as radioactively. Barium is highly poisonous except in the form of the extremely insoluble, and hence inert, barium sulphate.

The Clinton plant was immensely valuable as a large-scale research tool. Besides chemical and medical research, some physical research was carried out with the high-intensity neutron beam that could be obtained by simply opening the massive shielding around the Clinton pile. For most work the neutrons available from the Chicago pile were adequate, but the Clinton pile, operating at a level of nearly 2,000,000 watts by mid-1944, provided an even heavier neutron flow for research with higher-intensity beams.

The Nazis were falling back in June, 1944, hard pressed now. They had lost Africa, much of Italy, all of Russia. The Nazi leaders were searching still more desperately for the atomic weapon. Time and again Hitler's promise of a secret weapon cheered his men. Most people were sure that Hitler was making a sheer bluff. The men of the Manhattan Project, the chiefs of staff, and many scientists who, though not actually connected with the project, knew something of atomic physics, were sure that he was not. It was clear from the terms in which he referred to what would happen when he launched his secret weapon that he hoped soon to have the atomic bomb.

The Führer and his high command must have been convinced that they were very near a solution. If they could just hold out a few more months—perhaps a few more weeks—they would have a weapon so terrible that a tiny fragment of Germany would be base enough from which to launch a successful attack on the rest of the world. Prepare a redoubt in the mountains of southern Germany and Austria, and perhaps, in the months such a maneuver would gain, the problem would be solved, the weapon could be made ready, and the Nazis could yet triumph.

The activities of the Nazi government seemed to make little sense at that time. What real point could there be in holding an isolated redoubt in central Europe? They couldn't hope to defeat the Allied power with a fragment of an army holding a few mountain bases and a few small cities when all the power of Germany had failed. The power of Germany had failed, but the power of the atom, if they could once get it, would not fail.

The German scientists, however, did not get very close to the answer. Great flights of British and American bombers, droning overhead, blasted important laboratories and chemical plants out of existence. Peenemunde, where the rocket carrier for the atomic bomb-to-be was being developed, was destroyed, and nearly 5,000 German technicians were killed. If the laboratories didn't blow up of their own accord, TNT dropped from flight after flight of giant bombers exploded them into shreds and snarls of wire and steel.

During 1943 and 1944 large uranium piles and chemical separation mechanisms were being built at Hanford, Washington. They were the same in principle as the pile at the Clinton plant, with uranium slugs dropped automatically into chemical equipment that processed the material to extract the plutonium. The same elaborate safety precautions had to be taken, but on a larger scale, for these immense piles at Hanford were almost 1,000 times greater than the Clinton pile.

The Hanford piles were water-cooled. Water is a most satisfactory cooling agent, because a relatively small volume can soak up such a large quantity of heat. Moreover, water is cheap and easily available. But water has one unfortunate characteristic so far as uranium cooling goes. Uranium is an active metal chemically, and it corrodes rapidly in contact with water. Most of the familiar heavy metals are remarkable for their resistance to corrosion—lead, gold, platinum, and silver are all highly resistant. There is a tendency to think that heavy metals are naturally resistant to corrosion. That is not the case, as the scientists at Hanford discovered.

The uranium slugs had to be canned. They had to be protected by some kind of coating that would meet several stringent requirements. The requirements fell into three general classes—chemical, mechanical, and nuclear. The cans obviously had to be made of some material that would not absorb neutrons. They had to be of some material that could be removed automatically in the processing of the finished slugs, but would not corrode in the cooling water. The mechanical requirements were especially tough. The cans had to form a watertight and gastight seal and establish a uniform, heat-conducting bond with the uranium.

Aluminum seemed the best bet so far as material went. It has a low neutron absorption and does not corrode in fresh water. But aluminum does not weld easily, and getting that heat-conducting bond proved an infuriating problem. The whole atomic bomb project seemed in danger of serious delay because a little container for wrapping up the uranium couldn't be produced—it may have been an accumulation of just such small details that kept the Nazis from attaining the secret weapon Hitler so desperately wanted. The problem was solved only a few weeks before the Hanford piles were due to go into operation. A further improvement was made in October, 1944, after the first of the giant piles had begun experimental operation.

Of course there were other problems, too, in the building of those piles—the pipes that carried the cooling water, for instance. What material should be used for those? The choice, like the choice of all the materials to be used in the pile, was limited by considerations of nuclear physics. The material of the pipes should not lower the *k* factor of the pile by absorbing neutrons; furthermore, the pipes must not disintegrate under the high intensity of neutron bombardment and gamma radiation that would inevitably be present in the pile. Of course the pipes also had to meet all the ordinary requirements—they must not leak, corrode, or warp.

From the viewpoint of nuclear physics seven different elements were usable—beryllium, magnesium, aluminum, zinc, tin, lead, and bismuth. No beryllium tubing was to be had; pure beryllium metal is extremely hard, strong, and light—but it is also brittle as glass, and tubing could not be fabricated. Of the remaining elements only aluminum seemed to fulfill all the other requirements. But it was impossible to know what the corrosion resistance of aluminum would be in contact with water and under high-density neutron and gamma-ray bombardment. Aluminum metal is very easily corroded, and contact with water will dissolve it into a white powder in a short time; normally, aluminum is coated with a very thin waterproof layer of aluminum oxide, which protects it, and if that coating were broken away by neutron bombardment, the aluminum would soon dissolve. Only after the piles had been in actual operation for some time could the scientists be sure that aluminum had been a sound choice.

Besides pipes certain other things had to go into the pile—recording instruments, for instance, which needed electrical connections. This meant that an insulating material meeting all the demands of nuclear physics for low neutron absorption and resistance to extreme radiation intensities had to be found. Experimental and control probes, which for various reasons had to be inserted into the pile and removed, had to be made of a material that met other requirements. Any material thrust into that atomic violence was certain to be made intensely radioactive. How long the radioactivity lasted would depend on the material chosen for the probe, and so would the degree of radioactivity induced.

There was still a question about the behavior of graphite and uranium under the high intensities of reaction planned for the giant piles. The smaller piles had not approached the high intensity needed for real production of plutonium, so that information on this question was still unavailable. It was found that the graphite suffered a definite alteration of properties, which, fortunately, was not dangerous. Its mechanical strength and its heat and electrical conductivity were altered by the intense neutron radiation.

The final problem was the flood of death-dealing radiation generated by the nuclear reactions in the pile. These had called for a good deal of thought at Clinton, but at Hanford, where the uranium piles were to be operated at intensities a thousand times greater, the problem was so magnified that it was really different in nature. There were five different kinds of radiation: alpha, beta, and gamma rays, the usual concomitants of natural radioactivity, plus positron and neutron radiation, which is not encountered in natural radioactivity. Alpha rays—helium nuclei—are easily stopped by a thin layer of shielding; an inch or so of iron would be adequate. Beta rays—high-velocity electrons—would also be easy to stop, and the positron radiation would destroy itself in an attack on electrons before it ever left the graphite of the pile. These three types of radiation presented no real difficulty. But gamma rays and neutrons were something else. Gamma rays are an electromagnetic radiation similar to light and radio waves, but of very short wave length and great penetrative power. The gamma rays produced in an active uranium pile can penetrate astonishing distances through dense shielding material. However, they do travel, like light, in straight lines, and they can therefore be reduced to a safe intensity by massive barriers of dense concrete and steel or by many feet of earth. As for neutrons, they are particles, uncharged particles, that can wander like a gas. They behave like a gas in one respect, anyway; they spread out. But unlike a real gas, they have no bulky orbital electrons, and so they can push through any solid material—unless it contains nuclei that can absorb neutrons. Gamma rays can't turn corners, but neutrons can, and they delight in escaping from unsuspected cracks.

The piles had to be loaded and unloaded, the uranium slugs moved in and out. Water for cooling had to get in and leave. There had to be exits. These could be effectively blocked, so far as gamma rays were concerned, by simply turning a corner. Neutrons, however, just turn the corner and keep right on going. Designing shielding that would stop all the dangerous neutrons was a real problem. To make it tougher, the shielding had to be airtight. Air that passed through the pile while it was in action became dangerously radioactive. It is true that air cannot undergo a self-sustaining chain reaction, just as a rock cannot burn in a fire. But the rock can come out heated burning hot by the coal, which can burn. Similarly, the air can be "heated" by the uranium "fire" and give off radioactive rays afterward.

The radiation dangers of the uranium pile itselt continued into much of the separation plant, since the uranium slugs contained quantities of highly radioactive fission products. The Hanford plant required great quantities of high-density concrete for the construction of the various concentration cells and for shielding the uranium piles. One interesting result of the radioactivity problem is pointed out by the Smyth report:

> The problem of maintenance is very simply stated. There could not be any maintenance inside a shield or pile once the pile had operated. The same remark applies to a somewhat lesser extent to the separation unit, where it was probable that a shut-down for servicing could be effected provided, of course, that adequate remote-controlled decontamination processes were carried out in order to reduce the radiation intensity below the level dangerous to personnel. The maintenance problem for the auxiliary parts of the plant was normal except for the extreme importance of having stand-by pumping and power equipment to prevent a sudden accidental breakdown of the cooling system.

The first large pile at Hanford went into operation in September, 1944, and the other piles soon afterward. By the summer of 1945 all the chain-reacting piles and the entire separation plant were in full operation. Plutonium was being produced in quantities adequate for making the bomb. The problem of producing the necessary material for the superweapon had been solved. At Hanford atomic power was harnessed, and heat energy was produced in such enormous quantities that the waters of the Columbia River, normally cold, bubbled and steamed when they left the plant. The world's first commercial transmutation factory had been established. An element that could not be found ready-made on the planet was being fabricated to meet the demands of mankind. The ancient dream of the alchemists seemed prosaic now that men were transmuting one element into another that was far more precious than gold, since it was an element that Nature did not provide. Here at Hanford was a complete, working solution to the question posed in 1940: Can we concentrate enough of a fissionable material to make an atomic bomb?

The battle of the laboratory had been won almost simultaneously with the winning of the battle of the armies in Europe. And, because the battle of the laboratories had been won by the same nations that won the battle of the armies, it would stay won. If Germany had won the battle of the laboratories even after losing the battlefields, she could still have won the world.

12. SEPARATION OF U-235

WHEN the atomic project was first getting under way in 1940, the setting up of a moderated chain reaction in an ordinary uranium and graphite pile had seemed important for only two reasons: it would be a most convincing proof of the theory that a chain reaction was possible, and it would permit a study of a self-sustaining chain reaction under nonexplosive conditions. Only after the pile project was well under way did the possibility of manufacturing plutonium appear; in 1940 the interest of the physicists was still focused exclusively on the problem of separating U-235 from U-238 in natural uranium. The Metallurgical Laboratory group at the University of Chicago had originally been on the side line, investigating one of the secondary problems connected with atomic fission.

The main line of work was investigation of the dismaying task of separating U-235 from the natural uranium mixture in quantities needed for the atomic bomb. The physicists did not then know what quantities would be needed. They knew only that an amount somewhere between 1 and 100 kilograms per bomb seemed essential. We have traced the Chicago project rather fully, because the work done there advanced the whole field of atomic knowledge, as well as accomplishing the immediate end—the production of atomic fuel for the bomb. That work was spectacular; it was dangerous; it broke into new and unknown fields of nuclear physics at practically every step. Even such little things as the electrical insulation on the instrument cables had to be considered from the viewpoint of nuclear physics and the resistance of ordinary matter to the attack of violent atomic radiation. But the approach was circuitous. What was actually wanted was U-235. The men on the plutonium project said in effect: "Well, we don't know how to separate it, but we can burn it away atomically and use the neutrons released in that process to transmute the uranium isotope we don't want into an isotope of a new element, plutonium, that is just as good as the U-235 we don't know how to get."

The real problem remained: Could U-235 be separated directly? Until plutonium was produced and the separated metal was laid down on the table in adequate quantities for actual use, the plutonium idea remained a fine theory. And the plutonium was not laid down on the table until early in 1945. Until that date the effort to get it might have been proved impossible at any one of many stages. Thousands of steps had to be taken from the knowledge as of 1940 to the finished product—and every one of them was a halting pace into the absolute dark of an unknown corner of the physical Universe. The fate of the United States could not be allowed to rest on a possibility so highly theoretical. The attack on the problem of separating isotopes of heavy elements remained imperative.

The isotopes of uranium are all different. Only by understanding fully the minute differences and by devising means to make those small differences produce large effects could the separation be made. Consider these points:

1. There is no chemical difference between U-235 and U-238 that can be used in separation.
2. The two isotopes, since they are both isotopes of uranium, have the same number of positive charges.
3. The two isotopes *do* differ in total mass—but only to the extent of 3 units in 238.
4. This difference in mass means that the U-235 isotope will be only slightly more mobile.

The first and last of these statements may seem to conflict. In a chemical reaction in which atoms are changing partners—an exchange reaction—the U-235, being very slightly more mobile, has a tendency to make the exchange somewhat faster than the heavier isotope. This type of preferential chemical reaction of a lighter isotope is of real and useful significance with isotopes of such extreme difference in mobility as the light and heavy hydrogen atoms. If water and hydrogen gas are passed through a catalyst in such a way that the hydrogen of the H_2O exchanges places with the free hydrogen gas, it will be found that three to four times as much heavy hydrogen will be trapped in the water as remains free in the gas. This was one of the ways developed for producing heavy water as a possible moderator in the uranium pile. But that sort of method isn't practicable with uranium isotopes; the difference in their atomic weights is too slight.

With the massive isotopes of uranium some method that depended on physical properties rather than on chemical exchange seemed essential. Obviously, there was no way of applying mechanical forces to individual atoms. You can't tie a string on a uranium atom and pull it out; you can't push it with a stick. The forces applied would have to be of another nature—something like the force of gravity, which would pull at every atom. For instance, although all things fall with the same speed in a complete vacuum, a stone and a feather falling the same distance in the same time, there is a difference when air or some other resisting medium is present. Then a stone falls much faster than a feather. Conceivably, a system might be worked out in which uranium atoms would fall through a long tube having some resisting medium—a trace of hydrogen gas, perhaps—and the slightly heavier U-238 would arrive at the bottom first and could then be trapped and discarded.

This method won't work in practice, but it indicates how mechanical separation might be accomplished—by making the force of gravity much more intense, so that greater differences existed. Gravity can't actually be changed—yet. We haven't learned how to increase or diminish gravity, though the knowledge of the atomic nucleus we now have may give us some clues. But we can get the equivalent of a many-times-greater gravity by using a centrifuge. The familiar cream separator, or a bucket of water swinging from the end of a string, represent devices that take advantage of the fact that the effect of gravity can be secured by making something move swiftly and turn a corner. Whereas it takes many hours for the cream to float to the top in milk which is simply standing in a natural gravitational field, it rises in the cream separator in a matter of minutes. In the swiftly spinning bowl of the separator the denser milk falls outward under the effect of a pseudo gravity many times increased. A centrifuge capable of separating U-235 from U-238 and skimming off the lighter U-235 atoms as a cream separator skims off the lighter cream globules might conceivably be satisfactory. The centrifuge separator that the nuclear engineers had in mind would be an immense thing, a giant steel cylinder spinning at terrific speed on massive precision-made bearings.

A team of research men under J. W. Beams, with suggestions and help from Dr. Urey, who had first isolated heavy hydrogen, went to work on the centrifuge. A test model was built. The "model" had to be a full-sized unit; a large rotor going at full speed was needed for the test. The machine was set up at the Standard Oil Development Company's plant at Bayonne, N. J. Although some separation of the isotopes was effected, the project was abandoned. The manufacture of the giant rotors was an extremely difficult, high-precision job because of their huge size and the tremendous speed at which they had to spin. Moreover, the machines capable of manufacturing them were urgently needed for the manufacture of naval rifles, marine turbines, and similar heavy equipment. But the conclusive consideration was that, during the months that had been spent in developing the centrifuge system, other methods of separation had been found equally promising.

Another method of separating isotopes depended on what is known as "thermal diffusion." The theory of this operation is in many respects more complicated than the theory of nuclear stability; it is completely beyond explanation in any but mathematical formulae, save in the most general terms. Basically, it depends on the fact that while the molecules that make up solid matter are locked in rigid rows and files, like soldiers on dress parade, the molecules in a liquid are like the same soldiers after the order "Dismiss!"—a milling mob, with each individual wandering off in the direction he chooses. A gas, on the other hand, is comparable to the same soldiers after an enemy plane has made a diving, strafing attack on the field—each individual is heading in a different direction at high speed and paying no attention to where he's going, except that he wants to get as far away from all the others as possible. In such a mob scene as matter in the gaseous state presents, the lighter molecules, understandably, move faster. When there is a source of local heating, such as a hot wire, the general drift of the molecules is disturbed. Instead of a uniform distribution there are local concentrations and dispersions. And whenever there is a difference in distribution, there is a chance for intermolecular forces to operate differently on isotopes of different weights.

In practical work there is an advantage in using a liquid rather than a gas, simply because there is more matter in a cubic foot of liquid than in a cubic foot of gas, so that smaller apparatus can handle more material. In theoretical work, however, there is a terrific difference between the liquid and gas problems. A few mathematical experts can handle most of the theory of thermal diffusion in gas. Yet the problem of thermal diffusion in liquids is something to give the most expert manipulator of mathematical symbols a severe workout. Nevertheless, a separation method for uranium isotopes was perfected on the principle of thermal diffusion in liquids. In this instance the light and heavy isotopes of uranium could be separated by separating uranium hexafluoride, a uranium compound of great importance in the process of uranium separation. It is a compound that is liquid at room temperature, but boils at a relatively low temperature—about 134° F. It was available, therefore, as either a liquid or a gas without much departure from ordinary temperatures, and it was used in nearly all the uranium work.

Apart from its useful physical properties uranium hexafluoride has a certain chemical property that makes it bad stuff to work with. All uranium salts are deadly poisons. Most fluorine compounds are also deadly poisons. The roach poison that people have, with fatal results, often mistaken for flour, baking powder, or some other kitchen commodity, is sodium fluoride. Uranium hexafluoride contains six times as much fluorine and is poisonous as a liquid, as a solid, or as a gas—and that gas seems most anxious to find leaks. Working with uranium hexafluoride is as dangerous as working with the poisonous gases used in warfare.

One other method of isotope separation that had been used before offered possibilities. It depended on the general proposition that a lighter, more agile particle can thread its way through a complicated maze more quickly than a heavy particle can. If you've ever watched a small boy getting into a football field through a crowd of adults you'll have a rough idea of the process. The maze must be a semiporous solid material, or barrier, and the particles must be gaseous; liquids will not work satisfactorily. Since uranium itself melts at a temperature above that of molten iron and does not boil short of impossibly high temperatures, it is necessary to use the uranium hexafluoride compound. The fluorine atoms have 19 units of weight apiece, and 6 fluorine atoms are combined with each uranium atom in the hexafluoride compound; for each uranium atom, that is, we have 114 weight units of fluorine. Separating two particles of weight 235 and 238 is difficult, but now, instead of separating uranium atoms, we must separate two particles that are molecules of uranium hexafluoride—particles, respectively, of weight 235 plus 114, or 349, and of weight 238 plus 114, or 352. Instead of 3 parts in 238, the difference is only 3 parts in 352. But uranium, unfortunately, isn't a gas.

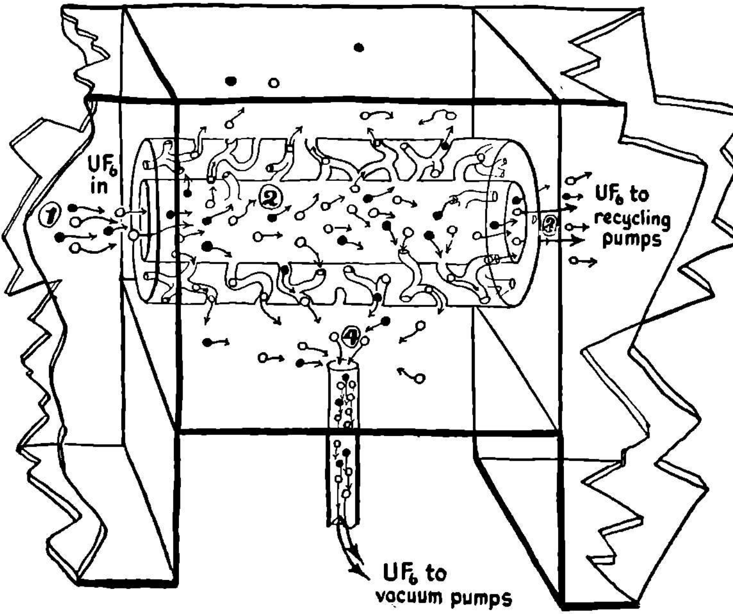
The problem for this method is to find a suitable barrier—a semiporous material that will serve as the maze. The original discovery and isolation of argon from the nitrogen in the air had been carried out by a diffusion method based on this principle, with clay pipestems as the barrier. Other barrier materials had been developed, and the most pressing item in the program of uranium isotope separation was discovery of the best barrier material. The material finally adopted is *not* mentioned in the Smyth report. It's one of the things the United States paid $2,000,000,000 to learn.

The important—and highly unfortunate—thing about this separation by submicroscopic mazes is that it can never be complete. The *average* particle—the molecule—containing the lighter isotope, *tends* to get through the barrier a *little* faster. But occasionally a molecule of uranium hexafluoride containing U-238 will get through before one that contains U-235.

Suppose we start with a mixture of uranium containing 99 per cent U-238 and 1 per cent U-235; this is a mixture slightly richer in U-235 than occurs in nature, but the proportions are easier for our figuring. Let this material, converted to the hexafluoride, flow through a tube made of our porous barrier, while we keep pumping the evacuated space outside the tube. The diagram on page 181 shows the process roughly.

The uranium hexafluoride, UF_6, comes in at *1* and flows along the porous-walled tube at *2,* and most of it goes out into the collector box at *3.* A certain percentage, however, leaks through the porous barrier, because the chamber surrounding the tube is kept pumped out so that there is a low pressure. This material that leaks through is collected and leaves at *4* on the way to the vacuum pumps.

Since the lighter U-235 molecules of UF_6 will usually get through the barrier a little faster, there should be more in the gases



Operation of a diffusion isotope separator.

leaving at *4* than were present in the input gases at *1*, while the exhaust at *3* should have been stripped—made "leaner"—by that amount. Assuming a theoretically perfect barrier, the best possible enrichment factor can be worked out mathematically. It turns out that the "enriched" gases at *4* will contain 1.0043 per cent U-235 if we started with 1.0000 per cent at *1*.

What we want is to raise the concentration of U-235 to at least 90 per cent. It seems quite hopeless by that method. But it isn't, actually. The gases from *4* can be passed into another similar tube system, and the enriched output of that system will contain a little more than 1.008 per cent U-235. The next time it is passed through a filter system, it will be 1.012 per cent, then 1.016, then 1.020—and so on. If you're patient and make enough passes through enough filters, you can, very gradually, build up the concentration of U-235.

In 1940 they knew that method would work. It wasn't a neat, easy, or clever method, but it would work. There were tremendous obstacles in the way. It would require enormous plants, and the enrichment per stage couldn't be so high as that ideal figure of 1.0043; that is the enrichment secured if only small quantities of the gases entering at *1* are allowed to diffuse through to *4*. If a large percentage—say 50 per cent—of the quantity going in at *1* emerges at *4*, the enrichment is considerably lower. The gas that does *not* pass through is progressively lowered in U-235 content, and the more chance it has to diffuse through, the more lean gas gets through to dilute the enriched material.

Although allowing a large portion to diffuse through reduces the concentration effected in each stage, it gives a greater amount of material to work with in the next stage. If only 1 per cent of the original gas were allowed to pass the first filter, and 1 per cent of that allowed through the second filter, only 10 pounds would be available at the third stage, if we started with 100,000 pounds of gas. That is too extreme a cutdown. The best, most practical degree of separation per stage had to be determined. The number of stages required had to be figured out. A thousand purely technical details represented ten thousand different researches.

The final stages would be working with gas composed of nearly pure U-235 hexafluoride. They would be small, because if all of the original U-235 were recovered, for each 140 pounds of input material only 1 pound of purified U-235 could be obtained. But the input stages would have to be huge; they would have to handle not only 140 times as much gas, but nearly 140,000 times as much!

The reason for this is that only a small fraction of the U-235 present in a given volume of gas is concentrated in the part that gets through the barrier; the part that does not pass the barrier still has almost as much U-235 as it had at the start. Suppose we have a quantity of gas that is just entering a stage well down the line. It has already passed through so many earlier stages that the U-235 content has been enriched to 10 per cent. It passes through a new stage, and half of the quantity is allowed to diffuse through and pass on to a still higher stage; it is now enriched to something slightly above 10 per cent U-235. The other half that does *not* diffuse has been stripped of part of its U-235 and is now down to 9.998 per cent U-235. We certainly don't want to discard that! It must be passed back down the chain to a point where the gas entering the filter contains only 9.998 per cent, and it must be allowed to work its way up the chain of filters again. Thus each of the earlier stages handles not only all the new input, but a great deal of material that is being returned as the discard from still higher stages. The whole process is exceedingly laborious, involving enormous numbers of pressure pumps and vacuum pumps, heaters and porous barriers, valves and pipes in huge quantities. It's an intricate maze of piping, but eventually you get the desired answer, and the average molecule of the gas is U-235 hexafluoride.

Problems of mechanics remained to be solved after the theory was worked out. It was apparent that nearly 4,000 separate stages of filter barriers had to be set up. To get enough gas through the not very porous barrier—if it were really porous, the enrichment effect wouldn't take place—an enormous area of barrier surface would be needed. The calculations indicated that many *acres* of barrier surface would be necessary, even if the maximum safe pressure differences on the two sides of the barrier were used—full atmospheric pressure on one side and a vacuum on the other. It wouldn't be wise to use higher pressures; uranium hexafluoride is too dangerously poisonous and corrosive. If that much pressure were used, the barrier had to have sufficient mechanical strength to stand it without bursting. Moreover, the material in the barrier had to be something that could be produced in great quantities, something that wouldn't corrode despite the highly corrosive nature of the uranium hexafluoride. By January, 1942, a number of different barrier materials had been investigated in the laboratories, but no large-scale plant tests had been made.

The United States was trying to get the arsenal of democracy into full production. This meant that there was an acute call for machine tools, pumps, electric motors—almost every kind of mechanical aid—for war production. And the diffusion separation of uranium isotopes called for 4,000 stages, each stage fed by pumps, each pump driven by electric motors. The gas that diffused through the barrier was at very low pressure and had to be pumped up to atmospheric pressure before entering the next stage. Each of the successively higher stages handled less gas, so that a different-sized pump was needed at each stage. Every time you compress gas, moreover, you inevitably heat it, so that a cooling system capable of dissipating all that heat had to be provided. Electric power running into thousands of kilowatts would obviously be imperative. Stainless steel and high-strength, noncorroding alloys were necessary in huge quantities for the building of the new Navy. Uranium hexafluoride is violently corrosive, and only the most resistant metal alloys can withstand its attack—stainless steel, inconel, and a few other high-nickel alloys. Because of the deadliness of the gas the pumps would have to be made of those tough, noncorroding metals, which are also very difficult to machine.

Finally, there was the problem, the major problem, of getting enough uranium to start operations. This was 1942, and the Metallurgical Laboratory was trying to get metallic uranium for its uranium pile. The gas diffusion plant wanted uranium hexafluoride in large quantities and would always have to have a very large quantity in use in its process. With 4,000 stages to be filled with gas, and with all the associated pumps and pipes, an enormous amount of uranium hexafluoride would be needed just to fill the system before anything started.

When the process was finally put into operation, the researchers realized, another kind of problem would arise. The successive stages were supposed to have successively richer gases, but there would be no enriched gases with which to begin. After the system was filled, the recycling processes would have to continue undisturbed for a long while, gradually building up the concentration of U-235 in each stage. In effect there were two filling-up problems: First, the whole system had to be filled with uranium hexafluoride. Second, the higher stages had to be filled with U-235 hexafluoride.

The Manhattan Project group had to make one of the great gambles of history at this point—one of the series of great gambles in the whole atomic undertaking. Theoretically, isotope separation would work. Experimentally, it did work on a laboratory scale, with laboratory technicians nursing it at every stage. The normal procedure of chemical engineering at this point would be to construct a pilot plant—a plant in size midway between their laboratory equipment and the full-size plant intended as the final operating equipment. But there simply wasn't time to do it. The problem was not only to get the atomic weapon—the Allies had to get the atomic weapon *first*. People who have not had the disheartening experience of seeing highly plausible laboratory ideas collapse when tried out on a plant scale cannot appreciate the magnitude of the gamble that now had to be undertaken.

The trouble with laboratory demonstrations is that quite unsuspected effects all too frequently help the process along—effects that may not continue to operate to an appreciable extent in the full-sized plant. An example of the trickiness of multiplying the size of a process is the familiar parlor stunt of floating a bar of solid steel on water. Common knowledge says that steel does not float on water, but steel will float on water if the bar is small enough. A needle can be floated on the surface tension of water. You can *not*, however, multiply everything 10,000 times and get the same effect. The effects in this instance are easy to see. Sometimes far more subtle things are at work to help the small-scale test. Generations of engineering experience have demonstrated time and again that it isn't wise to go from the laboratory directly to the full-scale plant.

Still another danger overhung a full-scale plant, and this was superlative. The idea was for the plant to produce purified U-235 for use in atomic bombs. In the final stages of the isotope separation the tubes, filters, and pumps would be working with pure U-235. But a certain mass of pure U-235 deposited in one place is all that is needed to induce the most colossal explosion man has ever seen! No one at this time, the end of 1942, even knew exactly what that "certain mass" of U-235 might be. The design of the plant would have to be such that the mass of purified isotope was always far below the lowest possible critical size.

In January, 1943, the laboratory work had been carried as far as it could be. It was time to start building the plant. Authorizations were signed that month, and soon the immense structures at Oak

Ridge, Tennessee, began to rise. At the Clinton Engineer Works in Oak Ridge a complete working solution had been reached to the problem posed in 1940: "Can we separate enough fissionable isotope to make an atomic bomb?" The battle of the laboratory had been won. The problem of the atomic bomb had been solved—solved not once, but twice. The researchers working with Fermi had solved it by producing fissionable plutonium, $_{94}Pu^{239}$. The researchers working with Dr. Dunning and Dr. Urey of Columbia University had also solved it; they had separated out the fissionable uranium isotope $_{92}U^{235}$.

Each of these solutions was complete in itself.

13. ELECTROMAGNETIC SEPARATION

WHILE the group at the University of Chicago was working on the problem of setting up the uranium pile and the Columbia University group was working on the separation of isotopes by the diffusion method, two other research teams were busy in other parts of the country. Dr. Oppenheimer and his associates were setting up their laboratory at Los Alamos, New Mexico, for research on the ultimate problem, the design and structure of the bomb itself. In Berkeley, at the University of California, Dr. Lawrence headed a busy and widely scattered research team, made up largely of cyclotron experts. These men were, necessarily, all over the country, for they stationed themselves wherever powerful cyclotrons were located. Part of Dr. Lawrence's team was at Columbia University, to work with the Columbia cyclotron. Another part worked in Cambridge, Massachusetts, at the Massachusetts Institute of Technology and at Harvard University; there are big cyclotrons at both these institutions. The headquarters of the group, however, remained in California, partly because Dr. Lawrence not only had invented the cyclotron, but maintained his leadership over its development and use. A highly respected school of nuclear physics had grown up around him. Anderson, who discovered the positron, was one of Lawrence's group in California.

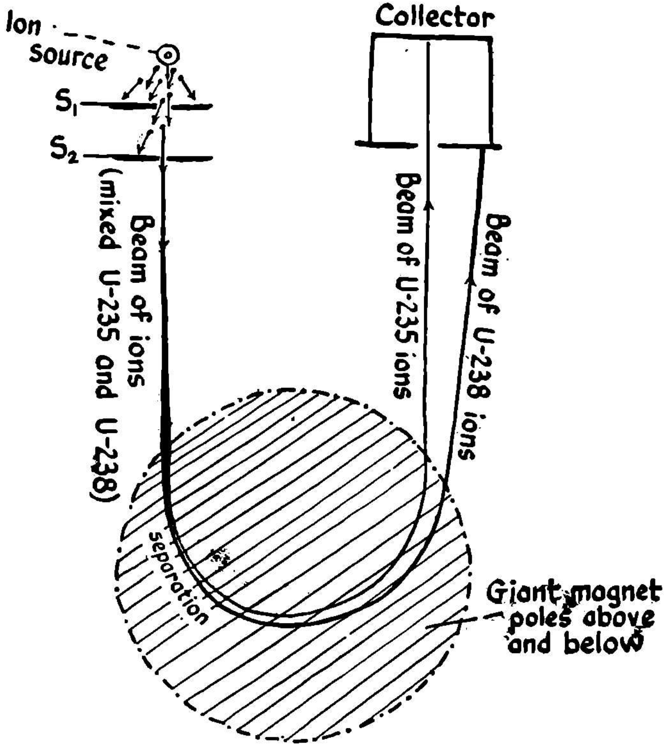
This team had originally been assigned only incidental duties, such as producing samples of isotopes for the other research groups as they were needed and making up new elements and rare radioactives on demand. It was this team of atom makers who prepared the first samples of plutonium so that the chemistry of the unknown element might be studied; the entire team, using all the cyclotrons available, had also produced the 500-microgram sample of plutonium with which the separation process, used to free plutonium from uranium residues, was worked out.

The men in Lawrence's team were not only nuclear physicists, but cyclotron specialists as well, men used to working with huge magnets, powerful electric fields, and the beams of ions that are part of the cyclotron's working forces. They, too, wanted to see the separation of isotopes accomplished, but their natural inclinations were toward electromagnetic methods of isotope separation. The Chicago group, under Fermi, had been charged originally with determining the possibility of a chain reaction; the outcome of their efforts was the world's first commercial-scale transmutation plant, in which they manufactured plutonium. Dr. Lawrence's group drifted into the business of separating isotopes electromagnetically on a commercial basis.

In 1939, when the theoretical calculations of Niels Bohr indicated U-235 as the isotope that fissioned with slow neutrons and U-238 as the isotope responsible for the production of element 93, the theory had been tested by working on a submicroscopic sample of pure U-235. The sample had been prepared by a young atomic physicist, A. O. Nier, who had separated it by the most accurate of all methods—the mass spectrograph. This was the instrument by which isotopes had first been detected.

In principle the mass spectrograph is a sort of second cousin to the cyclotron. Many of its parts are identical with those used in the cyclotron. It, too, requires a big magnet and a beam of ions. But it isn't out to get high voltages; so it needs no radio-frequency power supply. A good supply of moderately high-voltage direct current will do.

The material to be tested, or separated into its isotopes, is introduced in the form of a gas at the "ion source." The ion source is one of the secrets of the success eventually attained and, as such, is definitely on the military secrecy list. The type of ion source in common use before the war, however, was the one with which the work started. In spite of various modifications it consisted mainly of a hot filament, emitting electrons, and a strong positive voltage applied to a grid of wires around the filament. When a gas was introduced into this arrangement—a very slight amount of gas—it suddenly found itself in the midst of a violent rain of high-speed electrons. The electrons were escaping from the filament and heading for the positive grid with great rapidity. Any gas molecules that got in their way were hit violently; they usually lost a few chips from their atoms—perhaps an outer electron or two. The principle is diagramed below.



Electromagnetic isotope separators are production-line mass spectrographs.

When a neutral atom loses an outer electron, it becomes electrically unbalanced; with the loss of the negative electron, its charge becomes positive. Such an atom is called an ion. The ions in the mass spectrograph are attracted toward the negative charge that is applied to the slit plate S_1, and some of them go through the slit. Between S_1 and S_2 they are enormously accelerated by a very powerful electric field, and most of them will succeed in passing through the slit at S_2 and enter the magnetic field produced by the two big magnet poles above and below the plane of the ion beam.

When they enter the magnetic field, all the ions have practically the same speed. They all have the same charge—each has lost one electron and therefore has one positive charge—and all are acted on by the same magnetic field. Since a magnetic field tends to push aside a moving electric charge—remember how the pattern of light in the magic-eye tuning indicator in your radio writhes and twists in the field of a magnet—the course of the ions will be bent into an arc of a circle, looping around in the magnetic field.

If all the ions were the same, they would loop around in the same path and wind up at the same place. But if we have introduced mixed uranium isotopes, the ions aren't the same. The ions of U-238 are somewhat heavier. The magnetic field can't push them aside so easily or force them into quite as tight a loop as the U-235 ions. The U-238 ions, swinging wide on the turn, wind up at *B*—and are stopped by the baffle plate. The U-235, turning a somewhat tighter loop, will wind up at *A*, pass through the slit in the baffle, and finish their run in the collector.

If the slits at S_1 and S_2 are very narrow and intense magnetic and electric fields are used, separation by this method can be made almost absolutely perfect—the isotope collected in the collector will be 99.999 per cent pure U-235. The separation can be made so exact that the almost forgotten isotope U-234 is even separated out of the U-235. This method of separation is, in fact, the one used by nuclear physicists for determining what isotopes are present in a mixture. The mass spectrograph was, all through the experiments of the various research teams, the instrument of final recourse. If the mass spectrograph showed a concentration of 0.07 per cent U-235 after some process had been tried, that process hadn't worked. If it showed 1.0 per cent U-235, the process had worked.

The mass spectrograph is a magnificent instrument—a precision tool of utmost importance, as delicate as a chronometer, as precise as an astronomer's telescope. Lawrence and his team wanted to turn this precision instrument inside out, redesign its mechanism, and make it not only separate isotopes, but produce them as well.

It was like trying to redesign a ship's chronometer so it would still keep accurate time, but also supply power to run an elevator. The spectrograph used in 1941 was a wonderful gadget for separating isotopes. It really cleaned out the unwanted ones. But the yield of the desired isotope was almost incredibly small. A. O. Nier had used the mass spectrograph to get the first pure sample of U-235 the world had seen, but his method would have required hundreds of millenniums to produce enough U-235 for an atomic bomb. He was able to collect about a millionth of a gram per 16-hour working day. Since the atomic bomb requires several kilograms of U-235, it would have taken 1,000,000,000 such mass spectrographs several days to prepare enough for one bomb. And each mass spectrograph required a very large, massive electromagnet, as well as all the auxiliary electrical equipment.

Lawrence and his group were willing to agree that it was hopeless on the face of it, but they were convinced that a lot could be done to change the situation. The basic reason the device was so slow was that it was, in essence, a machine that picked up an atom, looked at it, weighed it, and put it in the right bin, then picked up another atom, tested it, and put it in the right bin. The mass spectrograph studied its material atom by atom, and it takes a lot of individual atoms to amount to anything. The number of ions produced by the ion source in one second was far too small. Simply making the apparatus bigger would not answer the problem. In the very small apparatus the physicists ordinarily used, they already had a nearly infinite number of gas atoms. Putting in more would not increase the number of ions produced. The trouble was that the ions weren't coming out. Of the ions that did come out of the source, only a very small proportion were used. Most of the ions headed in wrong directions and missed the small slit at S_1; of those that did pass through S_1, comparatively few were headed right to pass through S_2. Finally, of those that passed through both S_1 and S_2, only a very small percentage were U-235 ions. Of the U-235 ions that did get into the separation chamber, some would have been accidentally slowed down or accidentally given a little extra shove; consequently they were bent a little too much or too little by the magnetic force and missed the collector slit.

In December, 1941, no one was certain that the diffusion plant would work or that plutonium could be produced. The nation needed a third string to its bow in case the other two failed somewhere on the way between mathematical theory and engineering fact. Lawrence and his co-workers began work that month on the problem of converting a mass spectrograph into a mass-production spectrograph. They gave it a new name to fit its new status—the *calutron*, after the *Cali*fornia *U*niversity cyclo*tron*, from which most of its parts were to derive. The program of attack was divided into three subprograms:

1. An ion source that would produce more ions.
2. A more complete use of the ions produced.
3. A way to make the ion beams hold together, in tight beams that would go where they were directed and not spread loosely between the slit at S_2 and the collector slit.

By January, 1942, much stronger beams were being used, and the beams were being held together by an almost forgotten trick of electron and ion optics, used long ago in early cathode-ray tubes. By introducing a slight trace of gas instead of running them in a well-pumped vacuum, the experimenters made them hold together better, instead of spreading, as one would at first expect. The reason for this is that the ions in the beam, being similarly charged, repel one another strongly and tend to spread out. But they are extremely fast-moving ions, and if a very tiny amount of gas is present on their racecourse through the magnetic field, they will create thousands of ions along their path by collisions with the molecules of gas. These newly created ions will tend to overcome the mutual repulsions of the ions in the beam and hold the stragglers firmly in the stream. This effect made possible the use of much stronger ion currents, the transfer of many times more ions each second, and consequently the separation of more U-235 per day. This method of attack proved highly successful, the results indicating that Lawrence's hopes for a useful production tool were well founded.

The next problem was a more effective use of the ions available. The number of ions passed per second will be greatly increased if the slits at S_1 and S_2 and the collector slit are all made wider. The wider slits at S_1 and S_2 will permit a larger percentage of available ions to get into the ion beam, and the wider collector slit will utilize a greater percentage of those that go around the racetrack. But with wider slits at S_1 and S_2, the ion beam itself will be broad and fuzzy—it won't be a sharply defined ribbon around the invisible magnetic field. Ions going in quite different directions will be able to pass the broad slits, and they will tend to wander off in different directions, so that some U-238 ions that leave from one side of the slit will be landing precisely where U-235 ions from the other side of the wider slit should land. The use of wider slits will increase the total amount passed, but will decrease the sharpness of the separation.

Lawrence and his group started their work by taking the 37-inch-diameter magnet from the University of California cyclotron to produce their magnetic field. For ordinary mass-spectrograph work the magnetic field at the center of the huge pole should be as nearly equal to that at the edges as possible. But now the researchers varied the distribution of the magnetic field. They made it stronger here and weaker there, and in various and ingenious ways unbalanced the original carefully attained uniformity. Why? Because, by using nonuniform fields, the ions from those wider slits could be refocused. The ions from the outer edge of the wide slit met a different intensity of magnetic field and in the long run wound up exactly where equally massive ions from the inner edges of the slit did. The use of a wide slit gave them a sort of distortion, like the bad focus of a poor camera lens. By carefully skewing the magnetic field, a way was found to produce an equal but opposite bad focus of the magnetic field. This brought the ions back to a clean, sharp beam, many times stronger than before.

The result of the experiment with the ion source is still under wraps of secrecy. For many years researchers had been trying to get a better ion source. The lack of an adequate source had long been the main limitation in most work in nuclear physics. Finally, however, with the use of wide slits and a magnetic field to tighten the beam, more of the ions could be used. Letting just a little gas into the spectrograph chamber made it possible to get much stronger ion beams. A great advance had been made, because each of these factors multiplied—not merely added to—all the others. Suppose the wider slits allowed the experimenters to use 10 per cent of the ions instead of only 2 per cent; that multiplied the previous production fivefold. If the new ion sources were five times more productive, that meant a total improvement of not 5 + 5, but 5 × 5, or 25 times. And if the introduction of gas into the vacuum increased the efficiency of the beams five times, that meant a total improvement of 125 times. The final figures have not yet been released, but presumably the over-all factor of improvement was close to 1,000,000 times.

The device could be still further improved. The expensive part of the apparatus was the gigantic magnet. The ion source wasn't very complicated; it was rather like a radio tube, and it cost little more. Neither was the collector an especially complicated affair. But the huge electromagnet had immense iron pole pieces, an enormous frame, and expensive copper bus bars that made up the great magnet coils. Magnet coils drink electric power in great gulps; they're expensive to run. The ion source, then, is small, and so is the collector, but the magnet is huge. There is plenty of room between those big poles for more than one ion source, and the engineers and physicists studied several methods of arranging the ion sources and collectors for best use of the magnetic fields.

Most of the early work was done with the 37-inch cyclotron magnet. A gigantic cyclotron had been under construction before the war put an end to the building program—a machine of such size that its magnet poles measured 15 feet across. The project had been laid aside, but now the new and promising developments of mass spectrographs led to a decision to rush it to completion for experimental work on the calutron isotope separator. The original undertaking had been financed by private funds, supplied largely by the Rockefeller Foundation. Now, to finish the job quickly, it was necessary to do overtime work at additional expense, and the Foundation advanced the extra appropriation. By May, 1942, the giant machine was ready for use.

Multiple ion-beam systems were set up, and the investigations began. The ions themselves constitute a flowing electric current, and just as the magnetic field pushes them, they tend to push back at the magnetic field, so that when several beams are present there are marked interactions that must be taken into account. There were also limitations on the number of sources and receivers that could be used with one magnet. Nevertheless, the rate of production per magnet soared still higher. By the summer of 1942 the calutron was working well. It would take many units to separate enough U-235 for purposes of any military significance, but this mass-production version of the mass spectrograph worked. It was conclusively shown to be a practicable method of producing U-235.

A moment's glance at the rather confused chronology of the Manhattan Project at this point will make the importance of this success more apparent. The first atomic fire was not touched off until December 2, 1942. Research on diffusion separation of U-235 was not sufficiently advanced to authorize the start of the great Oak Ridge, Tennessee, plants until January, 1943. Even in January of 1943, however, both the diffusion process on a commercial scale and plutonium production on a similarly large scale remained untried and unproved hopes. The calutron separation process *had already proved itself*. The process differed basically in its industrial aspects from either the plutonium or the diffusion separation process for manufacturing atomic bomb material. The diffusion plant could not work at all until every part of it worked; as in a mass-production assembly line, everything had to work at once, or everything was completely stopped. The plutonium process required huge apparatus, and it became more efficient as the apparatus were made larger. Furthermore, the associated chemical processing plant had to be working properly. Every step in the procedure had to be carefully matched with every other step. It was not so with the calutron. One calutron magnet with its series of ion sources and collectors was a relatively small unit, but that single unit was quite capable of taking raw natural uranium and turning out highly purified U-235. Furthermore, a moderate degree of contamination in the uranium did not affect the result, for the calutron process that separated U-235 from U-238 would eliminate any ordinary impurity.

The calutron resembles a small local machine shop. It is infinitely more flexible in operation than the other systems for isotope separation. If it were decided that the production of U-235 should be increased, the gas-diffusion plant could not be expanded; a plant completely new from start to finish would have to be built. But if greater production with the calutron method were desired, the addition of one, two, or a hundred new units would meet the need. Many tons of purified uranium had to be accumulated before the first of the plutonium piles could be started. Many tons of purified uranium hexafluoride had to be prepared and fed into the gas-diffusion system before the apparatus could start, and then there had to be many days of recycling before any useful product could be withdrawn. But the first calutron, in its first day of operation, and using a few ounces of crude uranium, yielded an appreciable amount of U-235.

In every way the calutron had proved itself. The diffusion process had to be a gamble. The calutron process merely required the use of many units exactly like the full-scale unit already built and tested. Its production was not a gamble—it was simple arithmetic. If one calutron produced 100 milligrams of the U-235 a day, 1,000 calutrons would produce 100 grams a day, and 100,000 calutrons would produce 10 kilograms a day. If the group working on the structure of the bomb itself found that 10 kilograms were required for one bomb—in 1942 no one knew yet whether they would need 1 or 100 kilograms—and the chiefs of staff decided one bomb a day should be produced, then simple arithmetic would give the answer in terms of the number of calutron units required.

The advantages of the calutron were many and alluring. Its disadvantages were these: It took time to carve the massive magnets out of the iron blocks, time and precious copper for the coils, time and money for the installation. Moreover, demands of the calutron engineers for electrical control equipment would be competing with the demands of other engineers for such diversified military equipment as radar, gun-training motors, and battleship armor-plate. The calutron seemed to be expensive. But its results were known to be certain.

In September, 1942, construction of a plant using the electromagnetic process of separation was authorized, and building began in November at the Clinton Engineer Works at Oak Ridge, Tennessee. An indication of the extent to which this project competed with other essential war work is found in the list of companies that aided in the construction. The Westinghouse Electric Company manufactured the ion sources, receivers, pumps, tanks, and other mechanical parts; Westinghouse was also manufacturing ship's turbines, electric torpedoes, and radar equipment. The General

Electric Company manufactured the electrical control equipment; that company was also making radar, ship's turbines, and navy gun-control equipment, along with other items. The Allis-Chalmers Manufacturing Company produced the massive magnets; its other war work included production of heavy gearing, turbines, and motors for the Navy. The construction of the buildings and the installation of equipment were undertaken by Stone and Webster Engineering Corporation, also engaged at that time in building war plants throughout the country. The operation and maintenance of the whole plant was put in charge of the Tennessee Eastman Corporation, which had long been operating major chemical industries in the Tennessee Valley area.

From this viewpoint we can survey the uranium program as of the end of 1942.

The electromagnetic separation plant was under construction and would be in production in about nine months.

The authorization for the gas-diffusion plant at the Clinton Engineer Works had been granted, and construction work on that project would begin in January, 1943.

The first self-sustaining chain reaction had been initiated in December, 1942, and was already supplying information of great value.

Approval of the construction of the plutonium plant at the Hanford Engineer Works in the state of Washington had been made contingent on the successful operation of the uranium pile at Chicago.

Nineteen forty-one had been a year of research and discovery. The year that followed had been a year of laboratory activity, in which theories were tested and found wanting or were proved and translated into methods of practical engineering. The next year, 1943, was for most of the projects a year of cautious advance and construction, as 1944 was, too. All methods of producing fissionable isotopes were in full production early in the climactic year of 1945. The calutron separator method was in production long before any other process had reached the working stage; thanks to the completion of the first few units, some U-235 became available before the end of 1943.

Eight different methods of separating fissionable isotopes had been proposed. Six were developed sufficiently to prove themselves practical solutions to the basic problem. Five of these six were developed to or beyond the pilot-plant scale and actually produced concentrated fissionable material. These five were:

1. Plutonium production by the uranium pile.
2. Gas-diffusion separation of U-235.
3. Calutron separation of U-235.
4. Thermal diffusion concentration of U-235.
5. Centrifuge separation of U-235.

The first four of these methods were used for production at Hanford, and U-235 separation by calutron and gas diffusion was practiced at Oak Ridge.

Five separate teams of researchers in the course of 1941 and 1942 had devised five methods of producing the U-235 required for the atomic weapon. This should be proof enough that there is no atomic secret. The only secrets that exist are the secrets of chemical trade processes, on much the same level as the "secret" of successful manufacture of synthetic rubber. At this moment the Americans and the British are the only ones who know the chemistry of plutonium—unless someone else has taken the trouble to synthesize plutonium in one of the world's many cyclotrons, as Lawrence and his team did in 1942. Any good microchemist should be able to solve the problem in a few months. It is worth while to notice that the men who did the work, the atomic scientists themselves, have insisted that there are no secrets and that any group of intelligent engineers and nuclear physicists could duplicate their work in a very few years. There are secrets—trade-process secrets. But all the secrets of *science* are of one kind: they are Nature's secrets, and Nature has no favorites. She'll tell anyone at all who just asks the right questions.

The history of atomic fission demonstrates this. In 1932 Enrico Fermi first brought about the fission of uranium by bombardment with neutrons. It was not until seven years later, in 1939, that anyone offered the true explanation of what had occurred. Within a matter of days a dozen men had confirmed this new explanation. How, if it took seven years to figure out, could a dozen men confirm it within days?

Science is much like the game of Twenty Questions played with

Nature. Nature will always answer "Yes" or "No" if the right questions are propounded in the right way—that is, if the correct experiment is performed. Hahn and Strassmann, in working up to the uranium-fission explanation, had continued to ask, of one fraction of the radioactive product they got, such questions as "Is it radium?" They made an experiment; Nature said "No." "Then," asked Hahn and Strassmann by performing another experiment, "is it barium?" And Nature said "Yes." That answer narrowed things down to a point at which scientists could ask the critical question: "Does bombarding uranium with neutrons release 200,000,000 electron volts of energy?" Nature, in answering "Yes!" to that question, confirmed the theory of uranium fission.

The secret of the atomic bomb does not and never did belong to the United States, England, and Canada; it was always Nature's secret. If the successful solution discovered in the United States had been the result of a flash of genius on the part of one individual, then the process might be regarded as a secret possession of the United States. But that was not the case. Instead the solution represents the culmination of a steady and logically planned attack by many men—skilled, highly intelligent men—on a single problem.

The Smyth report contains a passage that powerfully supports this analysis. It quotes a National Academy report, made on November 6, 1941, to this effect:

> An estimate of the time required for development, engineering, and production of fission bombs can be made only roughly at this time.
>
> If all possible effort is spent on the program, one might however expect fission bombs to be available in significant quantity within three or four years.

Exactly three years and nine months later, the world's first atomic bomb flattened Hiroshima.

14. *FINISHING THE JOB*

ONE of the main research teams scattered across the country has not yet been discussed. This was the group organized in the summer of 1942 under J. R. Oppenheimer. The research problem assigned them was the design and structure of the bomb itself. The work obviously could not be undertaken until other phases of the general problem had been investigated sufficiently to determine the practicability of an atomic bomb, what type of material would probably be available, and in what quantities it could be secured.

The site chosen for the atomic bomb laboratory was a little place called Los Alamos in the desert of New Mexico, on a mesa about 20 miles from Santa Fe. When the bomb group moved in, a small boarding school moved out. Los Alamos had nothing to offer but nothing—no library, laboratory, power plant, or machine shop. Its "nothing" was a great asset for this particular group. The place was remote enough to draw little attention, though it was within easy plane distance of Chicago and the organizational headquarters of the Metallurgical Laboratory, under which the bomb group was originally placed; it was also within easy flight of the University of California's great nuclear research laboratories. To test the mighty weapon would take a lot of empty space, and the great, bare stretches of sand and rock were precisely what was needed.

Laboratories were built, libraries were organized, and the necessary research equipment was moved in. Men and women from all over the country were assigned to the project after signing stringent secrecy agreements; careful censorship of their mail was required. Nearly all these people were in their late twenties or early thirties; nuclear physics is a young man's game simply because the science hadn't developed sufficiently to attract many students before 1930 or 1935. Among younger scientists all over the nation there were tales of a Shangri-La before President Roosevelt made the name famous as the base of General Doolittle's Tokyo raid. To these young scientists Shangri-La was a secret place where the most fascinating—but utterly mysterious—projects in the world were being undertaken.

Those who came to Los Alamos had work, dangerous work, to do. The problems facing them could be divided roughly into three main categories:

1. How much fissionable material is necessary for a bomb?
2. What arming mechanism should the bomb have?
3. How can the bomb be controlled?

Problem No. 1—the quantity of fissionable material needed—had to be attacked first. To get at it the whole program had to go back to the fundamentals of nuclear fission by investigating what happened to the neutrons produced. As in the functioning of the atomic pile, neutrons could meet any of four fates:

1. Capture by U-235, with consequent fission.
2. Capture by U-238, without fission.
3. Capture by impurities, without fission.
4. Escape from the system.

For the reaction to be self-sustaining the first of these effects would have to produce more neutrons than were consumed in all four ways together. In the uranium pile the second effect had been minimized by the use of the graphite moderator, the third had been reduced by careful chemical purification, and the fourth had been overcome by making the pile large enough to reduce the relative importance of neutron loss from the surfaces.

In all the work on the moderated uranium pile the primary object had been to prevent the reaction from getting out of control and becoming explosive. Dr. Oppenheimer's group was now setting out to force a chain reaction of unlimited violence. It would not be an explosion in the usual sense of the word, for a normal chemical explosion is a relatively sudden release of energy that converts a small volume of a solid, liquid, or gaseous mixture or compound into a very much larger volume of hot gases; the hot gases immediately start to expand, and this expansion is the blast that does the damage. A chain reaction of unlimited violence is fundamentally different—more closely related to a bolt of lightning than to a chemical explosion.

Just consider the speed of reaction involved. Chemical explosions are slow enough so that electronic circuits have no difficulty at all in measuring the rate of change, microsecond by microsecond. An electron displaced from a quartz crystal by the stresses building up in the crystal because of an explosion wave can travel in a wire and send its signal along to a vacuum-tube amplifier many feet away; this tube responds, controlling electrons drifting across it with an energy of perhaps 150 electron volts, and affecting the next vacuum tube. This in turn may affect the beam of electrons in a cathode-ray oscilloscope by causing it to deflect easily and adjust to the new situation. In a properly designed setup this whole process will have taken perhaps a fifth of a microsecond—one five-millionth of a second.,

When a uranium nucleus fissions in an unlimited reaction, the disrupted atom flies apart with velocities upward of a quarter billion miles per hour. Neutrons are ejected from these parts with such impetus that they could cover the distance from the Earth to Mars in six minutes. But they have only to go distances measured in billionths of an inch before causing another fission; as soon as they reach the next atomic nucleus the disruption extends. Traveling at speeds far higher than those of electrons in vacuum-tube amplifiers, they need cover only the distance between atoms to produce their effect. The reaction spreads with utterly inconceivable speed.

By comparison with this, the apparently wild and uncontrollable reaction of a chemical explosion with the usual materials—TNT, gunpowder, nitroglycerine—is a mere polite change of partners. The explosion of nitroglycerine, for instance, is the result of a reaction in which oxygen atoms linked with nitrogen atoms shift over, desert the nitrogen atoms, and link up with carbon and hydrogen atoms. The temperature of a nitroglycerine explosion is quite limited. At 2800° C. water vapor begins to break down into hydrogen and oxygen; at 3500° water cannot exist. The energy of the nitroglycerine explosion comes from the formation of water vapor; hence nitroglycerine's "wild" explosion has a definite limit. It can't get much hotter than 3000° C.

The heat engendered by an unlimited uranium reaction is inconceivable in ordinary terms of temperature. The reaction is enormously more violent than those at the heart of a star. The matter at the very center of the Sun would cool the material given off by an unlimited uranium reaction, for the temperature of fissioning uranium is somewhere in the tens of billions of degrees. The atomic bomb itself does not produce blast; it has too little mass to do that. It simply releases energy in stupendous floods in an immeasurably short time. Everything in its immediate vicinity is instantaneously converted into gas atoms that are stripped of their electrons, the nuclei themselves hurtling out at speeds higher than those attained by the ion beams of a cyclotron. The furiously rushing ions from the bomb in turn strip electrons from other atoms to form one vast ball of terrific electric tensions and heat. It is the great release of raw energy and the expansion of the instantaneously heated matter in its immediate vicinity that give the uranium bomb its extreme effectiveness.

A prime point, to the bomb designers, was that the whole reaction would occur with a speed that is inexpressible except mathematically. That fact is very intimately related to the four types of neutron loss and has a bearing on the threat of too great neutron loss by direct escape. Since the scientists would be working with pure U-235, they would not have to think about loss of neutrons either to U-238 or to impurities. The only neutrons consumed would be those captured by U-235 nuclei and actually causing fission; all the rest would escape. Loss of neutrons by escape could be overcome by enlarging the mass sufficiently to make the surfaces through which neutrons could escape small in relation to the volume of U-235 in which they were generated. But the instant the unlimited fission reaction started, the whole mass of uranium would erupt into flying atom particles traveling in all directions at speeds approaching 150,000 miles per second. It was, in other words, going to expand at enormous speed, and expansion, by automatically increasing the extent of surface, would allow that much greater chance for neutrons to escape, while there would be no corresponding increase in the number of U-235 nuclei that might capture them for further fissions. Soon the loss of neutrons would exceed the rate of generation, and the chain reaction would die out.

The efficiency of the bomb, then, would depend on getting a high percentage of the U-235 to react and yield its energy before the system had expanded far enough to stop the reaction. The necessary size of the original mass would depend on the efficiency of the bomb—and that would depend on how fast the bomb expanded after the unlimited reaction was started. The laws of temperature rise, of expansion, and of neutron absorption were fairly well worked out by the end of 1942, and it was possible to calculate, on these bases, the time interval between the instant of the first fission reaction and the moment the energy release had exploded the unreacted atoms of uranium so far out as to break the chain reaction. Once an unlimited chain reaction begins, the speed of progression is unimaginable, and that time interval is incredibly short. *Almost all the technical difficulties of the bomb project came from the extraordinary brevity of this time interval,* the Smyth report said.

Some guesses can be made about the length of this interval, though the exact figures are, of course, secret. Suppose that in a mass of uranium 2 inches in diameter an atom near the center is struck by a fission-product nucleus moving at 100,000 miles a second. The two nuclei will simply bounce, for even such titanic shocks can't break the bonds of nuclear binding energy. The uranium atom, recoiling at something like 30,000 miles a second, can cover the inch of distance to the outer surface of the mass in somewhat less than a billionth of a second. If that U-235 nucleus is to react, a very high-speed neutron will have to start after it *very* soon in order to overtake it. In all calculations on the bomb, then, the researchers had to bear in mind that there would be only the minutest fraction of a second in which the reaction could be effected. They could never hope to make it complete or entirely efficient.

Neutron loss by escape was the process that would bring the unlimited chain reaction to an end. That same process could be used to keep the U-235 from detonating before detonation was desired. Natural uranium will not explode, thanks to the damping effect of capture of neutrons in U-238 without fission. The pure U-235 and pure Pu-239 that were to be used in the atomic bomb would not have any such inherent safety factor. The two fissionable materials could be safely kept only in small, isolated pieces, separated by considerable space, which would allow neutrons to escape without reaction, or within walls of some neutron-absorbing material such as boron steel or cadmium alloy. So long as the fissionable materials were in sufficiently small masses, they could not explode. Again there was the question: How small is "sufficiently small"? The materials could be safely stored in small one-gram or ten-gram units. That precaution suggested, by simple inversion, how to operate the arming mechanism that was to set the bomb off. If the materials were safe to handle in small pieces, then simply assembling them into one large piece would cause an explosion.

Suppose tiny U-235 cubes are gradually put together, like children's blocks slowly being built up into a single large cube. Each small cube has so much surface in relation to its volume that any stray neutron would simply cause a single fission, and the fission-product neutrons would escape from the tiny block before causing trouble. As more and more blocks are assembled, the chance for a fission-product neutron to escape from the whole mass becomes smaller—so small that most of the neutrons do not escape. The instant one neutron appears, it produces two more by fissioning a U-235 atom. These two will cause two new fissions and produce four neutrons. And the entire mass will go into an unlimited chain reaction. The point at which that unlimited chain reaction sets in is the critical point, and the mass of uranium at this point is the *critical mass.*

The detonation mechanism of an atomic bomb, therefore, need consist only of a device to bring two or more subcritical masses together so as to make up a single supercritical mass. If absolute assurance were desired that free neutrons would be available, each subcritical mass might have a bit of beryllium alloyed with the U-235 or Pu-239 used. Beryllium, when struck by alpha particles, emits neutrons, and both U-235 and Pu-239 are natural alpha-emitting radioactives. The instant the two subcritical masses were assembled, the unlimited chain reaction would begin.

The exact critical size of a uranium mass is one of the top military secrets. We may, however, make some general estimates. A sphere is probably used, since a sphere is the geometrical figure with the least surface in proportion to its volume. Apparently the critical mass is not more than 2 pounds. If we assume a 2-pound sphere as the active material of the atomic bomb, it will have a diameter of 1.8 inches. The critical mass, incidentally, depends on the shape of the piece. If, for instance, the U-235 were in the form of a flat plate ¼ inch thick and 3½ inches square, it would have the same total weight as the 1.8-inch sphere, but neutrons could escape so freely from the broad surfaces that nothing would happen. Furthermore, making the plate 3½ × 3½ feet would not change the situation appreciably; neutrons would still escape easily. The same effect occurs when we try to make coal burn; if the coal is spread out in a layer one lump thick, it will not burn even though there is plenty of coal. Pile it compactly, however, and a fire can be started easily.*

The original questions confronting the Los Alamos group had been these:

1. How much U-235 is needed?
2. How can the material be detonated?
3. How can the material be prevented from detonating until final preparations have been made?

Theoretical considerations could now give clear indications of the answers for the second and third of these questions. A mass of U-235 below the critical size would not detonate, nor would two such masses, so long as they were kept apart. But bringing the two subcritical masses together would cause them to detonate. The two masses, however, would have to be brought together extremely quickly. The first of the original questions was still open: How big *was* a critical mass? The problem was urgent. Both Hanford and

* Coal companies, coal-burning ocean steamers, and similar large-scale handlers of coal, incidentally, have trouble preventing a coal pile from starting its chain reaction spontaneously. When very large quantities of coal are piled compactly, the slow natural oxidation, or decay, of the coal in the center generates heat, which cannot escape through the huge mass. The inside of the pile gradually heats up and is finally hot enough to start the whole pile burning. This reaction can be controlled in the same way a uranium pile is controlled—by inserting something that will absorb the agent necessary for continuation of the chain reaction. In the case of uranium piles cadmium bars will absorb neutrons; in coal piles water poured into them will absorb the heat and carry it off.

Clinton were getting ready to produce the fissionable material. They weren't so much interested in how big a critical mass would be; they wanted to know how big a safe mass *couldn't* be. No one had the slightest desire to discover the critical size accidentally.

Calculating the critical size was a sticker. The reactions occurring just before the chain reaction got going would be chaotic. Much of the vitally needed data was still in the realm of what engineers call "guesstimates"—highly educated guesses, but still not much more than good hunches. Scientists could measure the neutron-absorption characteristics of a U-235 nucleus, but hardly the neutron absorption of a fission-product barium isotope traveling at a speed of 90,000 miles a second. A great deal of the data would have to be derived from such sources as the heavy neutron beams emitted from the experimental uranium pile at Clinton; the Clinton pile was then still under construction, and until it got going and one section of its shielding walls could be opened to get the needed beam of neutrons from the swarms that would be escaping from the pile as it operated, there was no way to make the necessary tests.

Working from what preliminary information was available in the spring of 1943, physicists made several estimates of the critical size. Unfortunately, the answers conflicted. Meanwhile more theoretical work was being done on the auxiliary problems. Besides the shape of the mass, the surrounding material affects critical size. Neutron loss from the surface of the mass is the factor that ultimately determines the critical size—but that neutron loss can be controlled in certain ways. If the uranium or plutonium is surrounded by cadmium, for instance, any neutron that wanders out will be absorbed by the cadmium and simply stay out of the reaction.

Suppose the cadmium envelope is replaced by beryllium. Beryllium has a nucleus capable of a rather unusual neutron reaction known as the $(n, 2n)$ reaction. This expression indicates that if one neutron goes in, the nucleus reacts by ejecting two neutrons. All neutrons that escape from the uranium mass are, of course, traveling outward; a neutron ejected from a beryllium atom may travel in any direction. There is no chance that a neutron escaping from the uranium will return to it of itself; there's an excellent chance that a neutron ejected by the beryllium will shoot right back into the uranium. Judging from the general effect, you might say that the beryllium "reflected" neutrons—and reflected more of them than actually struck it. Any material that does not absorb neutrons will bounce some of them back toward the uranium, and any neutrons bounced back will be pure gain for the uranium. In building the uranium piles a final outer layer of plain graphite, without uranium slugs in it, was used to reflect back as many neutrons as possible. A reflector layer around the atomic bomb not only helped to reduce the critical size, but also aided in another way.

Atomic force is so violent that no ordinary force can possibly bind or restrain it. The strongest, toughest steel is as so much tin foil in the path of that fury. As a matter of literal fact, thick layers of tin foil will resist the blast better than an equal thickness of hard steel. Ordinary strength has nothing to do with it, because no material has a strength that can even approach the power of the blast. Individual atoms have inertia, however, and tin atoms are heavier than iron atoms. It takes a more violent shove to get a tin atom moving than to get an iron atom into motion. Tin foil—or, better, lead foil—helps the reaction of an atomic bomb. Lead atoms reflect neutrons, with practically undiminished speed; that, incidentally, is why lead wouldn't serve as a moderator in the uranium pile, where the neutrons had to be slowed down. Also, because of the great inertia of lead, it would take time to get the massive lead atoms moving out of the way of the furiously expanding U-235. For that added infinitesimal bit of time the nuclear reaction would continue, and it would be just that much more nearly complete before its spreading out broke the chain.

At this point we may be able to form some picture of the bomb itself. It would consist of two subcritical masses of uranium or plutonium, assembled to produce a single supercritical mass at the moment of explosion. The assembled mass would be surrounded by a heavy layer of neutron-reflecting tamper material—lead or some similar massive, neutron-bouncing material.

How would the assembly be carried out? Because of the enormous speed with which the atomic reaction would proceed once it started, it was highly desirable that the assembly should be completed in the shortest possible time—in a minute fraction of a second. If the assembly were carried out slowly, an ineffective fractional explosion might take place and do no more than drive the semiassembled masses apart. For that to happen in actual use would have been a national disaster; it would have placed in the hands of the enemy a practically undamaged atomic bomb, together with an adequate supply of U-235 or plutonium to aid him in his own atomic researches, even if he didn't reassemble the device more efficiently and return it to us. The actual bomb was therefore well equipped with extremely powerful chemical explosives and most reliable detonating devices designed to assure that the U-235 or plutonium would be rendered thoroughly useless if for any reason it failed to function as an atomic bomb.

The most obvious way to achieve extremely rapid assembly was to fire one subcritical mass as a projectile into another subcritical mass as a target. But several considerations—such as portability, assurance of sudden and perfect contact between the two masses, and certain special secret devices for assuring action—complicated the problem beyond a simple gun-and-target arrangement. Some proposals were made for introduction of a neutron-absorbing substance that would tend to prevent any reaction until the maximum contact between the two masses had been established. This should ward off premature detonation and give greater assurance that when the bomb went off, it would *all* go off.

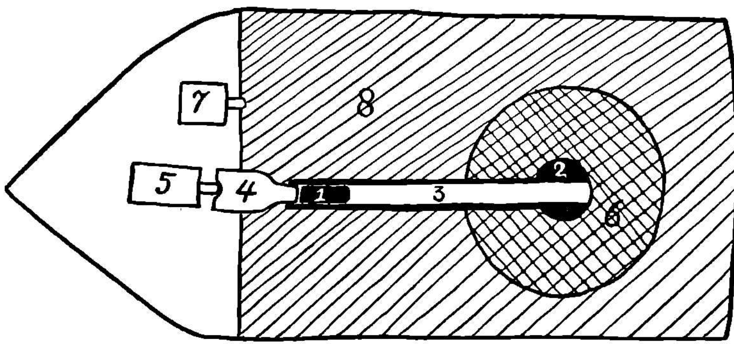
The experiments conducted at Los Alamos were of a very different order from those carried on at Chicago or at the Clinton experimental pile. At Chicago the experiments were all dedicated to studying slow-neutron reactions and how best to keep uranium under control. The Los Alamos experiments were of the general nature of that favorite small-boy experiment: How close to a window can you throw a stone without breaking it? The scientists wanted to investigate the reaction between fast neutrons and U-235, the type of reaction involved in the atomic bomb. The only possible source of the necessary quantities of fast neutrons was a self-sustaining uranium chain reaction. For a fast-neutron reaction the moderator had to be omitted or at least very greatly reduced. If the moderator was reduced, the presence of U-238, the natural curb on the reaction, was intolerable.

In other words, it was necessary to investigate the atomic bomb by working with something that didn't *quite* explode atomically. This was the final stage of the battle of the laboratories. It was no more dangerous than the job of a bomb-removal squad working with a delayed-action bomb. It makes very little difference whether a chemical bomb annihilates you molecule by molecule or an atomic explosion does it atom by atom. The workers *thought* they knew how to do the job and survive. Bomb-removal squads and the scientists at Los Alamos both were exploring unknown and exceedingly dangerous territory. The main difference is that the scientists at Los Alamos stayed on the job continuously for two years. There were casualties, of course, and it can be expected that there will be more. It is a real miracle that the job has been done with such an astonishingly good record. One of the factors that made the scientists cautious was the realization that it was not only their own lives that were endangered; they were charged with the safety of an entire nation.

Month by month the necessary data were gathered. The fast-neutron reactions were studied in a modified uranium pile. Heavy water was available now, and it facilitated the investigation somewhat, since it was infinitely easier to assemble and disassemble a uranium pile moderated with heavy water; it could all be done with a pump. In the latter part of 1944, as the first calutron units at Clinton went into operation, U-235 became available in useful quantities. Gradually, as the experiments progressed, less and less heavy-water moderator was used, and the slow-neutron reaction became less significant in sustaining the chain reaction. The fast-neutron reaction—the detonation reaction—became more and more important.

Different methods of calculating the critical size began to give similar results as the data accumulated. With the question of the actual size of a critical mass answered, the other two questions—how to fire the bomb and how to prevent its firing—were also disposed of. The mechanism for detonating the atomic bomb is one of the top engineering secrets of the entire project. It is one problem that cannot be worked out in usable detail from data that have appeared in the scientific journals; work with considerable masses of highly purified U-235 or plutonium would be necessary to duplicate the answer exactly. Any good nuclear physicist, however, could deduce from previously published material the general nature of the solution. On this page we give a sketch of a device that suggests the basic principles of the bomb mechanism.

The two subcritical masses, *1* and *2,* are of different shapes: one a cylinder longer than its diameter, the other a sphere with a hole through its center. Each mass allows relatively high neutron loss in proportion to its volume. When joined, the two form a single sphere, a shape most satisfactory for the utilization of neutrons. This is now a supercritical mass, and detonation occurs instantaneously. To bring the two together in the briefest possible time,



The general essentials of an atomic bomb.

the cylinder is a bullet in the gun barrel *3* that can be driven with tremendous speed by the powder charge *4*. Since the gun barrel will be used only once, it can be greatly overloaded. The powder to drive the two masses together could be detonated in almost any ordinary way—by a standard time fuse, a radio fuse controlled from the plane that drops the bomb, or a proximity fuse similar to those used in antiaircraft shells. Finally, just in case something goes wrong somewhere, the entire mechanism is fixed for emergency demolition. Probably several powerful demolition charges are arranged to destroy the bomb and scatter the parts beyond recovery. On the other hand it is quite conceivable that a thermite device is arranged with a heavy charge of ordinary U-238 in such fashion that, if the atomic bomb does not explode as it should, white-hot molten U-238 will deluge the mass. Probably no other arrangement could so effectively prevent enemy efforts either to study the mechanism of the bomb or to recover the U-235. Nothing is harder to separate from U-235 than U-238; if the enemy could do that, he could make his own atomic bombs. Plutonium might be a bit harder to conceal.

Whatever mechanism is used for emergency demolition, it is probably equipped with half a dozen or more independent detonators, and each of these detonators may be designed to go off with a different type of impulse. Shock of landing, ground-level air pressure, a second radio signal, a time bomb, or any one of a number of forces could be made to trip the emergency demolition system.

The atomic age began on December 2, 1942, when the uranium pile in Chicago began its self-sustaining chain reaction. The age of atomic weapons began on July 16, 1945, a short distance from the Los Alamos laboratories, with the test firing of the world's first atomic bomb. The world was notified on August 6, 1945, that the great $2,000,000,000 atomic project had opened the atomic age. The news was formally given out by President Truman, but the real announcement had been made at Hiroshima, Japan.

15. TRYING OUT THE PRODUCT

THE FIRST TEST of the atomic bomb was made by placing it on a 150-foot steel tower, somewhat like a high-voltage transmission-line tower, at a place called Alamogordo, situated in a natural bowl in the New Mexico desert. The test was successful. The event is far more of a definition of the place than anything else about it. The area has since been proposed as a national monument.

Recording instruments were set up at intervals out to a distance of 6 miles, though instruments all over the country served as part of the data-collecting machinery even when they were not specifically linked into the test. Seismographs for hundreds of miles around recorded the event. Types of seismic waves never before recorded were discovered. Never before in man's experience had a blow powerful enough to disturb the vast dead mass of the Earth struck the planet from directly above.

From a distance of 6 miles, in a deep and heavily buttressed observation station, the scientists who had had most to do with this great project watched. Enrico Fermi, Dr. Oppenheimer, who had directed the bomb team, and other leading workers were assembled there. In the very early morning of July 16, 1945, near dawn, an automatic mechanism detonated the bomb. All the observers reported two things that impressed and awed them—the intensity of the light that burst forth, beyond anything recorded on Earth before, and the beauty of the stark, barren mountains ringing the natural bowl as that awful light beat against them. At 6 miles the sound was a prolonged, terrible roaring. In an instant a vast cloud of dust was shooting toward the sky in a strange and terrible pattern that is as characteristic of the detonation of an atomic bomb as the awful blast of light. Several minor explosions followed the great primary blast. Theory cannot begin to handle all that goes on when the unlimited chain reaction of pure U-235 breaks loose. What the minor explosions are or why strange and beautiful colors appear is not clear. A general outline of the theory of the actual blast will help, however, toward an understanding of what the atomic weapon means.

In the instant of the detonation the immense energy of a considerable portion of U-235 is released. In that instant a certain quantity of matter is heated to a temperature beyond the meaning of the word. In the same instant the reaction is completed, and the temperature has fallen. Perhaps ten-billionths of a second has passed. The atomic reaction has ceased to release energy; now the tortured atoms are attempting to dissipate the impossible surplus of violence. Much of the energy is blasting out as gamma radiation of unique intensity and penetrative power. This is energy, energy traveling at the speed of light; it is mass with momentum. Air atoms struck by this energy are hurled forward at enormous speeds —in effect they are instantaneously raised to millions of degrees of heat. But the terrific energy of these gamma rays is too concentrated to permit them to exist long in the neighborhood of matter. Nearly all the energy is being dissipated in blasting electrons and positrons into existence; matter is being created from raw energy. The electrons and positrons so created will, by the violence of their collisions with air atoms, generate new gamma radiation of somewhat lesser intensity, radiation that will drive outward and in its turn create more electrons and positrons.

With the passage of time, measured in fractions of a microsecond, the positrons will collide with electrons, and their mutual destruction will give rise to two new gouts of gamma radiation. All atoms in the vicinity of the detonation will be bombarded by flying particles of fissioned U-235 atoms, by unreacted U-235 atoms escaping at enormous speed, and by the floods of neutrons blasting outward. These atoms will take up the great exodus—and the great temperature. Blasted away with such enormous suddenness, the outer electron rings are not able to keep up with the rapidly driven atoms and are left behind or stripped away themselves by a passing U-235 or fission-product nucleus.

The steel tower on which the test bomb was placed simply vanished, converted instantaneously into stripped iron nuclei swept before the terrible fury of exploding atoms. Only the lowermost girders and the base of the tower were far enough from the center of explosion to depart as simple boiling steel vapors, still intact as atoms, with electron shells whole.

Detonation has two effects: first, the purely mechanical outward pressure of enormously heated and expanded gases that once were the U-235, the bomb mechanism, and the heavy atoms of the tamper material plus immediately adjacent air atoms; second, the effects of gamma radiation. The mechanical effects are essentially similar to those produced by the blast of an ordinary chemical bomb; they differ only in intensity and magnitude. The radiation effects are something new to this world, but because the test bomb was fired in an area where it could do no damage, they were scarcely demonstrable then. They appeared more clearly at Hiroshima and Nagasaki.

Photographs of the test firing do, however, show graphically some of the story of mechanical blast produced. The first photographs show an irregular cloud of expanding debris, mottled white, gray, and black, with curious black holes in the center of the whitest areas. These black holes are due to a photographic effect known as "solarization." They were not dark areas in fact, but areas of brilliance so terrific that the light sensitivity of the film's silver salts was totally exhausted. The maximum response was evoked from the film, but still more light burned into it, light in such vast floods of energy that the very nature of the material was inverted; instead of darkening, it began to bleach out again. In prints made from such negatives these areas show black.

The exposure settings of the cameras used have not been given out. Apparently a battery of cameras adjusted to several widely different settings was used in order to get proper exposure of some one of the many films at each stage of the process. But some indication of the exposures used can be gathered from the fact that the film failed to register the faintest trace of an image of the land around. The observers have reported that the flash, as they saw it, was many times brighter than daylight. This flash was not able to record any image of the ground on the film. Evidently superhigh-speed movie cameras were used; the lenses must have been stopped down to pinholes, with dense layers of nearly opaque glass before them.

The darkest areas of the cloudy mass shown, then, must have been enormously brighter than the brightest sunlight. The burns in the negative may have been caused by outflaring jets of the incredible, vastly heated stuff of the bomb itself, jets formed, perhaps, by unequal yielding of the atoms of the dense tamper metal with which the U-235 or plutonium was surrounded. At this stage the gassy stuff is turbulent, violently uneven in its distribution. The whole cloud is expanding at a speed far greater than the highest speed at which air molecules can move out of its way.

In successive later photographs, evidently taken with cameras set for greater exposures, the curious, evenly spherical shape of the expanding cloud develops. These later pictures begin to show traces of the ground around the explosion; the brilliance of the flash must, however, have diminished greatly, since the great expansion would have lowered the terrific temperatures. The film in the camera that took these pictures must have been allowed more exposure. The spherical shape of the expanding cloud of incandescent—and more than incandescent—gases is readily understandable. The photograph is actually a picture not of the atomic detonation, for that was over long before these pictures were taken—perhaps a hundred microseconds before—but of the sound wave that the detonation generated. The sound wave is of such terrific intensity that it has become a fearful quasisolid juggernaut advancing in all directions simultaneously. It is a photograph of the distance that a particle traveling at the speed of sound could cover during the time that had elapsed since the primary explosion itself ceased. And, naturally, it is a photograph of the particles that primary explosion drove out, slowed down to the speed of sound.

The curious skirt effect shown in some of the pictures is simply that same spherical sound-wave front, which has struck the ground and is echoing back upward, half broken and distorted by the primary sound wave, which was still advancing. The quasisolid nature of this sound wave is clearly and terribly demonstrated by three facts. These pictures show it as something real and visible—a sound so awful in its intensity that a photograph taken from a distance of 6 miles shows it clearly. Where that sound wave struck the solid, packed sand of the desert, a huge depression appeared, a rounded, gently sloping pit, as though some Titan's ball-peen hammer had struck a blow; the pressures and temperatures in that sound-wave front were of such magnitude that the surface sands of the desert fused into a brittle greenish glass at the instant of contact. Finally, seismographs hundreds and even thousands of miles away recorded the shock that traveled through the vast mass of the planet when that terrific sound wave struck.

The official War Department release describing the test detonation says: "At the appointed time, there was a blinding flash lighting up the whole area brighter than the brightest daylight. A mountain range three miles away stood out in bold relief. Then came a tremendous sustained roar and a heavy pressure wave that knocked down two men outside the control center"—which, you will remember, was 6 miles from the steel tower on which the bomb had been set. The mathematical physics of sound propagation in air shows that any extremely intense sound tends to cause local compressions of air of such magnitude that the air does not act like a perfectly elastic medium. This imperfection of elasticity causes the pitch of the sound to fall lower and lower with distance, and at a considerable distance a sound that started as an extremely sharp crack will be reduced in pitch to a deep roaring noise. Ordinary lightning furnishes an example; a near-by stroke has a characteristic crack—a sharp, high-pitched, extremely abrupt noise—but distant lightning produces the long, low bass, rolling sounds of thunder. The final degradation of the sound takes the pitch too low for human ears.

The sound wave from the atomic bomb, at 6 miles, had degraded through the range of human hearing to a pitch far below audibility, save for a small remaining fraction that had originally started out as supersonic tones too shrill for human ears. That small fraction produced the "tremendous sustained roar." The main sound energy had been transformed into a single tremendous wave of air that registered as a heavy pressure wave, powerful enough to knock men off their feet. Long before the sound wave reached the 6-mile observation point, the terrific intensity had been diluted down to more appreciable values.

The smooth, brilliant luminosity of the spherical shell that had leaped into being when the bomb exploded was due to a familiar phenomenon—but one so distorted by sheer violence that it was unrecognizable. When air is compressed, it gets hot. When the bomb went off, the air in its immediate vicinity, the steel of the tower, the metal of the tamper in the bomb, in fact everything near it, was instantaneously converted into gas hotter than the stuff of the Sun itself. The expansion outward was violent and sudden beyond description in any meaningful terms.

The air 500 feet from the bomb could not be "warned" to get out of the way faster than the sound wave starting out could travel. So the enormously hot masses of gas from the bomb's immediate neighborhood started pushing outward, and the inert molecules of air simply piled up before them. Water does not resist the push of a hand—but if your hand slaps the water fast enough, the water acts like a rigid, immovable solid. The speed at which the expanding bomb stuff was moving out was so great that the air, like water, couldn't get out of the way. It simply piled up in front of the advancing wave as it was compressed more and more violently between the outward-driving masses and the motionless mass of the atmosphere. The compression heated the trapped air to incandescence—the smooth, luminous loom of the spherical wave front shows it. The temperature of that terrifically compressed air became so high that its instantaneous touch in bouncing from the ground fused the desert sand to a brittle greenish glass.

When the bombs were dropped over Hiroshima and Nagasaki, they were set off at an altitude the Japanese reported as about 1,500 feet. The United States Government has not yet released information on this point. Let us assume about half the Japs' guess, say 800 feet. The altitude, whatever it was, produced certain differences in the effects experienced. For instance, the fused sand around the New Mexico site was not duplicated, nor was the radioactivity found in the New Mexico sand found in the Japanese ruins. The intention of the bomb designers was to minimize the new, special characteristics of the weapon in every possible way—to make it as little an *atomic* bomb and as much just another, but more powerful, bomb as possible. By exploding it at a considerable altitude practically all the strange effects of the atomic nature of the weapon could be annulled; only the purely mechanical heave of the blast wave was applied against the Japanese cities. The same effect, so far as the structures in the cities below were concerned, could have been attained by detonating some 20,000 tons of TNT in the air.

The effort to minimize the effects of the atomic nature of the weapon was made for a number of reasons, primarily psychological. Human beings react in curious ways to murder, battle, and sudden death. When a new and untraditional weapon is introduced, there is often a violent reaction. The weapon is regarded as unfair. This feeling that the new is necessarily unfair is so strong that it will tend to cause condemnation of any novel weapon even by people of the nation that has used it. There is no strict logic in reaction to weapons. It's felt quite fair and proper to stick an enemy with a bayonet, punch holes in him with rifle or machine-gun bullets, maim him with shell fragments, bury him alive with a bomb blast, drown him in water, disembowel him with a land mine, or even convert him into a flaming, animated celluloid doll with a flame thrower. It is felt to be unethical, however, to drown him in gas or blister his skin with a chemical liquid that does not actually burst into flame. Poison gas is a horrid weapon, and we must not use it. It is not a traditional weapon. But people have been using all the other methods of slow or sudden death regularly for centuries, and so these have come to be accepted. The atomic bomb was a new weapon. So long as it was employed purely as a mechanical device—simply a supersuperexplosive bomb—it would be simply a development of a traditional and therefore accepted weapon. On the other hand, if the designers took full advantage of its special properties, the most extreme and violent objections could be expected.

Radioactivity has never been used in war. The Greeks didn't use it; the Romans didn't sanction its use; they had never heard of it. It had never been possible as a weapon of war before, and therefore it was certain that there would be a violent reaction if it was found that a new way of killing had been introduced. Radioactivity had to be avoided, and detonating the bomb high in the air was about the most convenient way to do that. The bomb might also have been designed to go off at a considerable distance underground. Setting the bomb off in the air exploited its mechanical effects almost exclusively. The enormous heat produced carried the radioactive dusts high into the stratosphere, and they came drifting down only after hours, days, or weeks. Since the more virulent radioactive isotopes have short half-lives, their dangerous period was expended where they could harm nothing but a few air-borne bacteria and chance grains of weed pollen.

The Army was quite correct in its analysis of the situation, of course. There *was* loud protest against the radioactive possibilities. No very violent protests were made—outside of Japan—at a military base city's having been annihilated by a single bomb. But considerable furor was built up at the thought that radioactivity might have caused some of the deaths. The Army attempted to quash the argument immediately by taking a number of news reporters to the New Mexico test site and allowing them to examine the crater. Since there was a considerable amount of radioactivity at Alamogordo, the reporters were required to wear protective shoe coverings. The Alamogordo site actually is radioactive to a mild degree. Nine months after the test explosion it still was not safe to carry on one's person pieces of the greenish glass formed from the desert sands. But the Alamogordo bomb was exploded only 150 feet in the air, and the ground received the direct impact of some of the bomb stuff and retained it in the crust of lava that formed; the radioactivity was not all or almost all dissipated in the upper atmosphere.

The best indication that the Army had not the slightest intention of causing severe radioactive damage by the use of the atomic weapon is the fact that they used the bomb at all. It would have been infinitely easier to pack some of the more furiously radioactive fission products of the Hanford piles in lead canisters and drop them with just enough explosive charge to scatter the material well. Such radioactivation was not intended by our government. It is quite certain that at this point in history no one else knows so much about the properties of atomic bombs and the radioactive isotopes formed by atomic fission as the scientists of the Manhattan Project, and they have stated that no important radioactivation occurred at Hiroshima or Nagasaki.

The scattering of radioactive isotopes in the Earth's atmosphere will have practically no effect whatever so long as only four or five bombs are set off in the course of a year. There are natural radioactives, too, an enormous quantity of them, in the Earth. Oceanographists, geologists, and others have made studies of the Earth's seas and the muds that settle to the bottom of them. These muds are detectably radioactive, and the tonnage of the muds is astronomical. With such huge tonnages even a barely detectable degree of radioactivity implies the presence of a startling amount of radioactive material. It has been calculated that the seas of the Earth contain approximately *20,000 tons of pure radium*. Atomic detritus from a few bombs will constitute only a tolerable addition to natural radioactives. The constant bombardment of cosmic rays from space probably produces many times greater effects, and the living things on this planet have got along with that for a couple of billion years.

Because of the psychological reactions expected, then, the bomb's action was arranged to be almost purely mechanical. So far we have discussed only the mechanical aspects of the atomic detonation. Radiation of pure energy could not be eliminated, however, and its effects were significant. Any radiant energy—light, ultraviolet rays, X-rays, or gamma rays—can be termed "heat rays." Normally, the term is used in connection with infrared rays such as are given off by hot stoves, electric irons, and the like, but any radiation will produce heating if there is enough of it. A lens made of ice will not pass infrared rays, but an ice lens can be used to concentrate the Sun's visible light rays and start a fire.

When gamma rays are produced in such enormous quantities as in the detonation of a pound or two of U-235, the most noticeable effect is heating—heating that is unearthly in its intensity. Radiation in the enormous quantities produced by that explosion exerts a terrific pressure—a mechanical pressure so violent that it is almost certain that the upper steelwork of the Alamogordo tower was destroyed by the *mechanical pressure of radiation* from the unlimited reaction of the U-235. The gamma rays, traveling outward at the speed of light, left everything else behind, for no material particle can attain that speed. It is a wind blowing at 670,000,000 miles an hour. Its impact is as violent, from sheer mechanical pressure, as the impact of a 16-inch shell. That is ordinary gamma radiation such as doctors familiarly use in cancer therapy and industrial technicians use in inspecting massive steel castings. The only difference is one of quantity.

The very violence of the outburst of gamma rays from the atomic bomb prevents any great penetration; most of it is destroyed in one way or another within the first hundred feet. In whatever way it may be absorbed, however—whether by electron-pair creation or by simple absorption into the atom it strikes—it causes heating. Ordinary words are intended for the experiences of everyday life; the scientists use the same words, but they have vastly different implications. "Heating" in this connection refers to the atomic cataclysm that results when a gout of gamma radiation, traveling at the speed of light, collides with the nucleus of an atom—of oxygen, for instance. The gamma ray has such terrific energy that it has the mass of a hundred electrons; the violence of its impact is so great that the oxygen nucleus abruptly starts moving at a speed representing a temperature of some 50,000,000° C. That is "heating" in the physicist's sense of the word. By the time the radiation has spread out 100 feet, however, the effective concentration has dropped to a more understandable level. It no longer acts as though it were something solid driving out with a billion tons of pressure behind it. The intensity has dropped to a degree that our minds can grasp.

The zone of the explosion itself is by now a foot or two in diameter. The bomb has been converted to the strange condition of a hollow shell of gas many times denser than the densest metal on Earth, and at a temperature such as exists only in the heart of a star. The radiation is so violent that the atoms of air that are being deluged with it are converted instantaneously into a radiation-opaque screen of electrons separated from their nuclei. To all intents and purposes the equivalent of the matter deep in the heart of a star has been created. It radiates away the excess energy. Those are the only English words that apply to the situation.

The diluted, thinned-out, visible part of the radiation was what made mountains 3 miles away from the test explosion stand out in bold relief, many times brighter than the brightest daylight. It was that same diluted 6-mile-distant radiation that produced temporary blindness in a man so rash as to look *toward* the bomb instead of away from it immediately after it exploded. The original blast of light was the radiant energy escaping from the reaction itself. The "ball of fire" visible through dark glasses afterward was the incandescent gas of that incomprehensible sound wave that dented the solid earth where it bounced and that fused sand to glass at its touch.

At Hiroshima the Japanese were not 6 miles away from the explosion. They were in a position to report on the effects of the blast of energy as it was experienced by human beings. There are some limitations on such reporting, however. At Nagasaki no person within 3,000 feet of the point on the ground directly below the bomb survived the explosion—not one individual. Those on the streets outside buildings were killed by the concussion wave that came some four seconds after the detonation, at the speed of sound; they were killed either directly or by buildings crashing down upon them.

The figures on exact distances are relatively meaningless, since the Nagasaki-model bomb was already obsolescent at the time it was dropped and is completely obsolete now. Present atomic bomb types are very much more powerful; the uranium atoms in the bomb are much more efficiently utilized, so that fewer escape detonation. As a guide to what the weakest and crudest atomic bombs the world will ever know could do, it is of interest that, in an area approximately 5 miles in diameter, any individual's chance of survival was about 50 per cent.

The effects of the bomb's radiant energy are direct indications of what can be expected. Any matter heated to the temperature of the atomic bomb gives out all types of radiant energy. The effect each kind will have depends on its relative intensity and the opacity of air to that particular type of radiation.

Air is transparent to visible light, of course; that's why we can see light. But "transparent" is a much trickier term than most laymen realize; you have to specify what part of the spectrum you're dealing with. Unlike fused quartz, glass is not transparent to the ultraviolet rays of sunlight. Air is as opaque as so much solid metal to part of the ultraviolet spectrum, while metallic silver is transparent to a certain band in the ultraviolet. Black hard rubber is quite transparent to infrared light; photographers sometimes use hard-rubber "lenses" for filtering out visible light when they want to photograph the invisible infrared. Air is opaque—or nearly so—to much of the infrared spectrum as well as to much of the ultraviolet spectrum. It is "dark gray" to the lower part of the X-ray spectrum, but quite transparent to the hard gamma rays representing 2,000,000- to 3,000,000-volt energies.

The result is that while every kind of radiation starts out from the bomb, only the infrared, visible light, the lower part of the ultraviolet, and the upper part of the gamma-ray spectrum get through any amount of air. Most of the radiation of the bomb is in the gamma-ray region, but much of that is absorbed and radiated again as visible light by air atoms in the immediate neighborhood of the bomb. Three kinds of radiation killed the Japanese. Because visible light can travel farthest and most easily through air, visible light—friendly, ordinary light!—was the greatest killer of the three. Ultraviolet co-operated with the visible light; the intensity was so tremendous that a fatal "sunburn" could be acquired in a few millionths of a second. Gamma rays didn't claim so many victims. Since even the hardest gamma radiation is to some extent absorbed by air, it could not be an effective killer at distances of, say, 2 miles or more. At shorter distances gamma rays had only corpses to work on; other effects had done the job.

Light and ultraviolet rays, in the intensity the atomic bomb produced, can cook a human being in a thousandth of a second. Since it takes much longer than that for a nerve impulse to travel from the skin to the brain, it must be a painless death. The light intensity directly below the bomb was so great that black or dark surfaces of buildings, the dark bark of trees, or dark hair or clothing on human beings were instantaneously charred. Japanese in dark clothing were burned far more severely than people in light-colored clothes. The bodies of women clad in dark-and-light striped materials were charred in stripes. Small dark patches on clothing were transferred to the flesh beneath as severe burns, tattoos branded into the skin in a fraction of a thousandth of a second. These effects were all caused by visible light and infrared and ultraviolet rays. The small Nagasaki bomb burned black clothing as much as 2,000 feet away from the explosion. Ripe wheat over a mile from the bombing point was instantaneously set afire. Gamma rays had little or nothing to do with these effects.

Japan has some buildings of inordinate strength and solidity, far more solidly constructed than any buildings in Chicago, St.

Louis, or New York, because they're designed to be earthquake-proof. A person sheltered in such a building might survive the concussion wave, be sheltered by the wall from the burning radiance, and emerge from the disaster seemingly unscathed—a scratch or two from falling concrete, perhaps, but no particularly painful injuries. Nevertheless, the man is already dead. Gamma rays shine through concrete walls to find the man behind. In the cells of his body the rays can work strange and frightening changes. If the intensity is high enough, it causes a three-dimensional sunburn all through him—his bones, his brain, his intestines, are all burned, and death follows very shortly. The burn can be severe enough to melt away the flesh in a matter of a few hours. One of the experimenters at Los Alamos—where they were trying to see "how close can you come without hitting it"—was killed by one of those horribly dangerous experiments; gamma radiation got him. His hand and arm were most severely exposed, and within a few hours the flesh sloughed away from the bone; in a few more hours the disintegration spread to the rest of his body.

Lower intensities work more subtly. The rays injure all the cells of the body, but some cells are resistant to their effects. The brain seems to be relatively little changed by quite severe doses. Strangely, it is the cells at the very center of the big bones of the legs, the breastbone, and the like that are most noticeably affected. These cells at the center of the great bones have a very special function—a case of Nature's tucking away a specialized organ in an available empty space; bones are hollow for lightness, and the blood-forming tissues are in them. At their center are organs that produce the blood cells and most of the highly complex mixture that is blood. The red cells that carry oxygen, the white cells that are the body's defense army, the various complex chemical substances that cause clotting, all seem to be concentrated there.

These blood-forming cells appear to be especially sensitive to gamma rays. Blood cells wear out rather rapidly and have to be replaced constantly. With these bone cells destroyed, the victim's blood continues to wear out, and there is no new supply to replace it. The red cells die off, and his blood becomes thin; breathing air does him no good, because there are no cells to carry it to his tissues. Usually he dies before that effect becomes very noticeable. The white cells, too, are not being replaced; the body's defense against invasion fails, and the slightest infection will be fatal. If he somehow avoids that, still he is doomed. The chemicals that cause blood-clotting aren't being produced. Only a hemophiliac—one who suffers from "bleeder's disease"—can fully realize what that means. It isn't cuts on the surface of the skin that worry a bleeder; those he can get at and stop. The trouble is that every bruise breaks tiny blood vessels; the blood clots and plugs the leak, and you are scarcely aware that anything happened—unless you are a bleeder. It doesn't take a big bruise; the jar your bones get when you come down the stairs rapidly breaks tiny blood vessels, but that's all right if your blood is normal; they're repaired again in a couple of hours, and no harm is done. If your blood does not clot, however, it will ooze into the joints, and the joints will swell as blood pressure forces them apart. The effect is precisely that produced by the ancient torture instrument, the rack. That is what the hemophiliac fears. It is those little, all-over leaks that kill the victim of gamma rays.

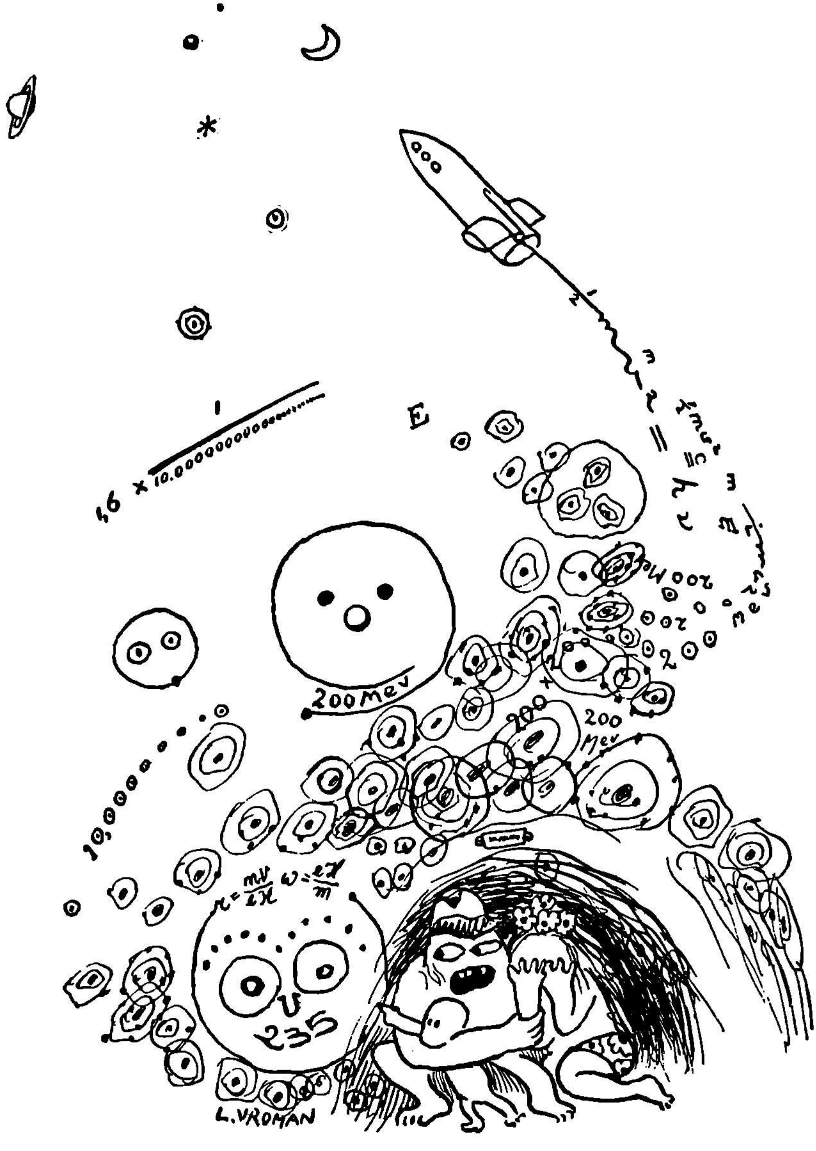
Gamma rays can be even more subtle if a still smaller dose is absorbed. Sometimes the victim isn't killed, merely sickened; surviving blood-making cells repair themselves and replace the destroyed cells. The victim lives, but another type of cell has suffered damage, those that produce the sex cells. If the damage is severe, these cells are so altered that the man or woman becomes sterile. If the dose of gamma rays is still lighter, the sex cells are not so extensively altered, and children are possible, but they will not be quite human children. They will be mutations, freaks. There may be four eyes, or no eyes, no arms and four legs, or an alteration that simply makes the child inhumanly susceptible to cancer. Hemophilia itself is one rather common type of mutation. If the gamma rays do not kill the mother by making her a bleeder, they can, and may, make all her male children and her female children's male children bleeders. With such mutations the blind force of the gamma rays mindlessly changes the blueprints for coming generations; a mutation will affect not only the immediate child, but the descendants of that child. Naturally, most of the changes will be for the worse.

But it is possible for such changes to be for the better. A change in pattern might call for elimination of the eyes, so that the baby would be not merely blind, but eyeless; but it might also do something useful like eliminating the appendix or ridding the body of the troublesome and useless wisdom teeth. Or it might effect a subtle shift in the metabolism of the child so that it would be born totally immune to all known diseases. Or it might create a new type of brain that was half again as competent as any previous human brain. It is possible that some affected Japanese might give birth to a genuinely superior, nonhuman type of child. The chances of a superman's being produced are remote, but it is almost certain that there will be a large number of freak human births in and around the Hiroshima and Nagasaki areas during the next forty years. The first wave of such cases must have come in the early summer of 1946. Medicine, biology, embryology, and most of the associated sciences are keeping a close watch; this is their chance to observe the effects of the atomic bomb.

The buildings will be rebuilt, the dead will be buried, trees will be replanted, the injured healed, and the scars of the bomb's immediate, visible effects wiped away. But not until the last child who was near enough to feel the effects of the gamma rays has passed the age of reproduction—sometime about the year 2000—will the last direct effect of the atomic bomb be known. By that time certain effects of the bomb will have been built into the race. With ordinary chemical bombs the effect is a simple matter of life or death. Atomic bombs are different; they can change the pattern of life.

PART THREE

THE ATOMIC FUTURE



E
200 Mev
200 Mev
U
235
L.VROMAN

16. POINTERS FROM HIROSHIMA AND NAGASAKI

THE ATOMIC BOMB is here to stay as long as men have an industrial civilization. Many think it should be outlawed, like poison gas. The ban on gas became effective—for much the same reason that laws against horse stealing did when automobiles took the place of horses. The conditions of the Second World War made the use of gas disadvantageous. In the First World War, a war of position, of fixed lines, gas was effective, and it was used then in spite of all pledges to the contrary.

Hiroshima and Nagasaki have invaluable lessons for us.

First, these atomic bombs were the *smallest and least damaging that human ingenuity can contrive.* Dr. Oppenheimer says that the cost of destruction per square mile by atomic bomb can probably be reduced by a factor of ten or more, but only with a "great increase in the unit power of the weapons." You can't hope to wipe out a town of 10,000 cheaply by atomic bombing, but a city of 10,000,000 can be destroyed economically. New York may be a seven-bomb city in terms of Nagasaki-type bombs, but it is an ideal target for a single new-style bargain-rate superbomb.

Second, since the bombs were set off high in the air, their special properties were minimized, and they were practically no more than powerful chemical bombs. When an atomic bomb is detonated in air, its force is practically all wasted—it should be detonated in the heart of a mass of dense, rigid material, say 500 or 1,000 feet deep in granite rock. The rock would be converted into the same kind of incandescent gaseous sound wave that appeared in the air of New Mexico. The atomic forces would thrust the rock out of their way with the same terrible indifference that they brushed the air aside, and the dense rock masses would take up that energy very quickly in the form of a terrifically intense shock wave comparable to that of the severest earthquake. Immediately above the detonation point the rock would probably be hurled upward, but this is an unimportant and unnecessary side effect. The shock wave, traveling through the rock at a speed far greater than that of sound in air, would demolish every man-made structure.

Major Alexander P. de Seversky, who believes that the only significant military power consists of huge fleets of bombing planes, has inspected the ruins of Hiroshima and Nagasaki and reports that the damage is the same in character and extent as could be expected from an ordinary raid of 200 Superforts carrying incendiary and explosive bombs of the usual sort. He makes a great deal of the fact that ordinary fires were started by overturned stoves and the like and that none of the lavalike fused sand or the terrific heat indications seen in New Mexico appeared in these cities. Concrete buildings, although burned out internally, were not knocked down. Seversky has declared that one 12-ton blockbuster of the ordinary chemical type would be as effective against the steel and concrete buildings of New York or Chicago as one of the atomic bombs used against Japan. Dr. Urey, in discussing atomic bombs and atomic warfare on the radio, commented: "A blockbuster do the same damage as a 20,000-ton-equivalent atomic bomb? That's plain foolishness."

General H. H. Arnold put it this way: The total cost of delivering the atomic bomb at Hiroshima might be set at $1,240,000, including a reasonable estimate of the cost of the bomb, the cost of the reconnaissance flights and the bomber actually used, and the ground-crew charges against the planes involved. It destroyed 4.1 square miles of Hiroshima. At that time the chemical-bomb attacks against Japan were destroying industrial cities at the rate of about a square mile for each $3,000,000 of the war budget. This rather forcefully suggests that, even if Superforts could have done the job, it would have cost approximately $12,400,000 instead of $1,240,000.

To evaluate the devastation at Hiroshima properly, two types of damage must be considered: first, the material and human injury to the city and its inhabitants, and second (more important in terms of warfare), the wound dealt the whole Japanese war economy. Let's look at the event from a Japanese military viewpoint; let's go back mentally to the early morning of August 6, 1945, and to headquarters in Tokyo.

About 7:15 Tokyo time that Monday morning the Japanese long-range early-warning radar sets picked up a flight of enemy planes coming in on a course that indicated a destination somewhere on the Inland Sea. The air-raid early alert was sent out at once, but about forty-five minutes later, or about eight o'clock, the shorter-range radars had determined that the flight was very small—not more than three planes or so—which meant that it was simply a reconnaissance flight or, at worst, a nuisance raid. The general alert was lifted, and a broadcast warning was sent out that a reconnaissance or nuisance flight was under way and that, if B-29's were seen overhead, precautions should be taken on a local scale. A photographic or weather observation mission was expected. The Japanese headquarters radar maps showed the steady progress of the mission, across a minor Inland Sea port, Hiroshima, and back out toward Guam and Saipan, its vague and undetermined mission apparently completed. No reports of trouble came in; so no particular attention was paid to what seemed to be just one flight among many.

About 8:15 A.M. the Tokyo control engineer in the Japanese Broadcasting Corporation found that the Hiroshima radio had gone off the air. He didn't succeed in finding out what the difficulty was; telephone connections to Hiroshima were blocked. A little later the Tokyo railroad telegraph control center realized that something was wrong with their lines into and out of Hiroshima—there seemed to be a break about 5 or 6 miles north of the city. Very confused unofficial reports of some sort of catastrophe were coming in from small places within 10 miles of the city. Hiroshima had suffered an explosion or—what probably seemed more likely to a Japanese—maybe a violent local earthquake shock.

Since the communication systems were government-owned and -operated and the army was the government of Japan, these events were reported to the army's air-raid defense division. The army started calling its own wireless station at Hiroshima, but there was no response. Headquarters was thoroughly mystified. Seismographs indicated no earth shock of major proportions; radar sets showed that there had been no large raid; army records gave evidence of no large stocks of explosives in Hiroshima. Some catastrophe had certainly occurred, however. The army had very complete control in Japan; if telephone and telegraph lines had been cut, some officer would have had the duty of reporting to headquarters, and immediately, what had happened, why, and how. There was some kind of irregularity that needed investigation.

A young Japanese staff major was ordered to fly down to the Hiroshima army airport, investigate, and radio back his report. Three hours later he was within sight of the cloud over Hiroshima. He was still about 100 miles away, and the world hadn't yet become familiar with the strange characteristic shape of an atomic bomb smoke-dust cloud. He didn't recognize it. But he did realize that something terrible had happened to Hiroshima.

When he reached the city, there was no army airport. There was no city either—simply a vast, flaming scar. He had to fly on to a navy base some 30 miles away. The men at the navy base had witnessed the explosion; they had attempted to send rescue missions into Hiroshima already, but the trucks had been turned back by the raging fires that enveloped every roadway. Under the major's orders several thousand men made a new assault on the problem, and about dusk that long July day—and dusk comes fairly late in that season—Hiroshima was at last in touch with the outside world again. Before that time only a few stragglers—burned, broken, confused—had come out. Their tales didn't make much sense; each said that there had been a great air raid and that one of the bombs had exploded directly over his house.

Back in Tokyo the thing didn't make much sense either. Do you remember waiting, that day, after President Truman's first announcement, to see what the Japanese would say—and wondering why they said nothing? The reason is clear enough now; when a city is hit by an atomic bomb, it doesn't call for help, it doesn't send out stories of its plight, it doesn't warn the rest of the nation. The bomb is rather like a very old trick that was used during the recent war. A scout out on night patrol through enemy lines creeps up to a place where two of the enemy are sharing their blankets in sleep and very quietly slits the throat of one of the two, then steals away, leaving the other sleeping. Only when the second wakes in the morning to find his bedmate's throat slit, his body cold in death, does he know what happened in the dark. . . . Only many hours later, when men from outside got in, did Tokyo know that one of its cities was dead, its throat slit.

The little throat-slitting trick was devised long, long ago as a grimly practical method of psychological warfare. A soldier is willing to face battle and danger; it takes the heart and the courage out of him to know that somewhere in the night there is a raider so silent, so deadly, that he can slit the throat of a man and not have that man's companion know he sleeps with a corpse! It takes the heart, the morale, out of a nation to know that any single plane, floating invisibly high in the silent dark blue of the sky, by day or by night, can destroy a city so utterly, so savagely and suddenly, that it cannot even cry for help before it is dead. In Hiroshima the army staff didn't report to Tokyo for a very simple reason. The army commander at Hiroshima was dead. In the same instant his aide was dead, the third in line of command, and the entire army staff. No one was left to send a message to Tokyo; no facilities remained with which to send it.

This was an utterly different kind of raid; it cannot be compared with ordinary Superfort raids because it was the ultimate and absolute of saturation raids. All defenses were saturated instantaneously, simultaneously overwhelmed, and in the same split second annihilated. The fire department didn't fight the fires; a thousand sprang up in the same minute, in a thousand places. Anyhow the fire stations were destroyed, along with everything else in the city, and the firemen died with the other citizens.

There was no first-aid organization to care for the injured. The head of the Hiroshima medical staff was dead in the ruins of Hiroshima. His aide, and his aide's aide, and his assistant's assistant's assistant were each of them a charred corpse, strangely burned on only one side by the terrible, unbearable flash of light that had struck an almost palpable blow. The doctors were dead with the citizens; so were the nurses and the orderlies. An efficient emergency organization is based on the premise that catastrophe may strike, and improvisation must be expected; if the organization is any good at all, it will make out somehow, for ordinary intelligent citizens can always do some good as first-aid assistants. But in Hiroshima—in a city struck by an atomic bomb—there is a joker. There is no organization—none at all. The attack is too all-over, too general. The organization itself is gone, and there is no one to start an intelligent co-operative endeavor. In the almost undamaged suburbs of Hiroshima there were many who could have helped—if there had been organization. But it was near dusk when an organized rescue expedition finally fought its way in from outside.

A new effect also began to attack Japan's war economy. Hiroshima was a terrible wound in the body of the Japanese Empire. For just that first day it had not hurt; as with a soldier struck by a shell fragment, the wound was almost painless at first because of the sheer violence of the shock. Only gradually did pain begin to throb as the local shock lessened. Then tales of woe, of terror indescribable and inescapable, spread through Japan. Much as infection sets in in a soldier's wound and drains the body's strength, it consumed doctors, nurses, medical supplies and gave off morale poisons in the form of the burned, injured survivors. Men and women and children were dying of unearthly burns—radiation burns—in hospitals all over Japan, in Tokyo—Kobe—everywhere.

Dame Rumor was biting her fingernails; for once there was a tale of terror and destruction and devastation that could not be enlarged on. The first trains carrying out the injured filled the hospitals and dressing stations in the adjacent area quickly, so that subsequent trains had to take the injured farther. Toward the end the trains evacuating the wounded had to keep going for twenty-four hours before any medical attention could be given; supplies at nearer points had been exhausted. Rescue efforts at Nagasaki were far less effective, for the Japanese people had given up.

The extent of the destruction wrought by the Hiroshima and Nagasaki bombs could not be analyzed at once; that required a considerable amount of highly technical research into the strength of the materials employed in Japanese buildings. The Army has released some of the facts determined by the investigations. The methods used were originally developed decades ago for measuring pressures in heavy Army and Navy rifles. The ordnance engineer's very simple gauge consists of a small hollow steel cylinder, a little copper ball or copper rod, and a steel disc. The copper ball is placed inside the cylinder, and the steel disc rests on it as a piston. At the instant of firing the gun the pressures built up in the barrel try to drive the piston down into the steel cylinder, and the full pressure is exerted on the copper ball so that it is flattened out to a greater or lesser degree. After the test the copper ball is recovered and the flattening measured. With the strength of the copper ball known, the force required to flatten it can easily be calculated and the pressure of the explosion derived. If the copper ball is totally flattened, the pressure can't be determined more exactly than that it was "greater than" so many thousand pounds per square inch; if the ball isn't dented measurably, there is no answer. Any degree of deformation between those two limits can be accurately correlated with a certain pressure.

The half-destroyed buildings of Hiroshima and Nagasaki can be used in precisely the same way as measuring devices that reveal the exact intensity of the pressure wave at a given point. All that need be done is to measure the amount of deformation of the buildings—just as the amount of deformation of the copper ball is measured—and then take samples of the building materials and test their resistance to deformation. The two readily measured facts then tell directly the intensity of the pressure. The concrete-and-steel buildings of Hiroshima and Nagasaki served excellently as pressure meters. American buildings are not built nearly so solidly as the concrete-and-steel structures in Japan. The Japanese are not totally devoid of good sense, and they've had many generations of experience with their earthquake-ridden islands. In a region of severe earthquakes it is only good sense to do one of two things: build so flimsily that, when the structure collapses, it won't crush you, or build with such inordinate strength that even the violence of a major quake won't bring it down about your ears.

Many of Hiroshima's earthquakeproof concrete-and-steel structures—specially designed to withstand the most violent manifestations of one of Nature's more destructive moods—did withstand the atomic blast to some extent. Outwardly they didn't collapse, but many of the buildings were so twisted and distorted, so savagely shaken internally, that they are of no further use, save for their immense value as gauges of the terrible pressure that struck them. The figures available at the time of writing are preliminary, but probably quite accurate. They indicate clearly and conclusively that no steel-and-concrete building in the most modern city could protect its occupants against the violence of the bomb.

Naturally, the intensity of the pressure varies with distance from the point of explosion; it decreases very rapidly with increasing distance. Nevertheless, at a distance of approximately half a mile from a point directly under the explosion of the Nagasaki bomb—and therefore considerably more than half a mile on a direct line from the bomb, since it was exploded probably about 800 feet in the air—the pressure wave registered 11,950 pounds per square foot. Many office buildings have windows measuring 3 x 5 feet; on such a window area alone that blast wave would exert a pressure of only a little less than *90 tons*. Two such windows would experience a pressure about equal to the weight of a railroad locomotive or of twenty 10-ton trucks piled one on top of another. It is perfectly evident that no sane architect of a commercial building will design it to stand a strain even vaguely approaching any such terrible pressure. It could be done, no doubt—but the walls would have to be deeper through than the rooms inside.

At a distance of a mile the pressure had decreased to somewhat under a ton per square foot. Such powerfully built structures as the Empire State Building could resist such a load if it were applied directly downward; the steel skeleton is designed to resist the downward load of weight, and it has such a large factor of safety that even that immense strain would not crumple it. But the building is a tall, slim spire; if such a pressure wave struck it from the side it would be destroyed instantly. Buildings aren't expected to take any such strain horizontally. The Empire State Building, the Chrysler Building, and the like are designed to withstand the strongest gusts of the strongest hurricanes—and when an architect says "designed to withstand" something, he means that after calculating how much strength it would take to resist the attack, the building was made from two to five times as strong as that. Those great buildings would almost certainly resist a 200-mile-an-hour gust of hurricane winds—far stronger than any recorded hurricane in the United States. At 2½ miles the pressure of the blast wave of the Nagasaki-model atomic bomb was greater than the pressure of a 200-mile-an-hour wind. The blast wave couldn't tear down Japanese steel-and-concrete buildings at that distance. Since New York City is geologically stable, its buildings are less strongly constructed, and blast effects would be greater than in Japan.

The pressure wave, incidentally, is followed immediately by the low-pressure wave, a partial vacuum, that is characteristic of explosion waves. Usually when windows are broken by an explosion, the glass tends to fall *out* rather than *in*. The glass will be shattered by the explosion wave, but the low-pressure wave immediately afterward sucks out the air in the building violently, like a stupendous vacuum cleaner, so that the broken bits of glass still in the air are swept outward. This alternation of pressure and low pressure is disastrous to human beings. If the terrible crushing pressure of the compression wave does not cave in chest and ribs, the succeeding suction wave causes the air-filled cavities of the body to expand suddenly and fatally. The lungs explode with millions of hemorrhages, the stomach ruptures from the pressure of the air in it, and the intestines split in a dozen places. These effects were already well known; the citizens of London and all the other bombed cities of Europe and Asia were familiar with them. The atomic bomb did the same thing on a larger scale—not only because it reached out farther than an ordinary bomb, but because both the pressure wave and the succeeding suction wave lasted much longer.

Some Japanese buildings unquestionably are far flimsier than corresponding structures in American cities, but no building can resist such pressures as the bombs developed. As for the American citizen, he is built of precisely the same sort of materials and in the same way that the Japanese citizen is built. Japanese earthquakeproof buildings that were not too near the blast survived—but their survival was of no interest to their late occupants; the pressure wave and the succeeding suction wave had done for them.

No other nation engaging in atomic war would temper the effect of its bombs as we did in Japan. It could not afford to; the next war will give too much advantage to the nation that "gits thar fustest with the mostest." The atomic bombs of the future will be designed and used to achieve maximum destruction. After all, in discussing the effects of the atomic bombs on Japan we are discussing history—practically ancient history in the atomic field. The

Hiroshima bomb was the second atomic bomb the world had known; the Nagasaki model, the third, was obsolete even when it was dropped.

Today's physicists can see several ways to increase the effect of atomic bombs. The first and most obvious is to use more U-235 or Pu-239 in each bomb. Instead of combining two subcritical masses to make one supercritical mass, the scientists might bring together three, four, or a dozen subcritical masses. Or instead of the shapes already used the two masses might consist of a series of flat plates, each just below the critical mass and unfavorable in shape so as to be nonreactive by itself. With one group of plates meshed into another, the unfavorable shapes could be combined into a favorable cubic mass of far more than critical size. Another way to increase the power of the bomb is to apply it more efficiently—underground, where its terrific forces can work on solid rock.

The most interesting possibility, however, is to use atomic fuels that could not be used heretofore. The Cockcroft-Walton experiment involving lithium and hydrogen is capable of producing more than twice as much energy per pound of material as the detonation of plutonium or uranium. Furthermore, *ordinary* lithium and hydrogen will do. A chemical compound of the two elements, lithium hydride, is on the market at present for about $12 a pound in 100-pound lots, and the producers are hoping to get the price down to $5 a pound in the near future, since lithium is a very useful chemical that is finding more and more applications. The trouble with the Cockcroft-Walton experiment is that nothing happens unless the hydrogen strikes the lithium with a relative velocity representing 150,000 electron volts, and so few successful hits are made that less energy is released than is consumed. This drawback might be overcome.

As matter is heated, the atoms that make it up begin to move at higher and higher speeds. They not only move at high speeds, but *keep colliding again and again* at those high speeds. If a mixture of lithium and hydrogen were heated to a sufficient temperature, the thermal agitation would make the hydrogen and lithium atoms bombard each other repeatedly and continuously with the required 150,000-volt energy. If the hydrogen atom missed the lithium nucleus, it would have to keep on bouncing until it struck a lithium atom with which it reacted.

This kind of reaction is impossible at normal temperatures, because the molecules and atoms move so slowly. The normal velocity of an air molecule at room temperature equals about a fortieth of an electron volt; such an extremely low energy is too feeble to initiate even ordinary chemical reactions, let alone atomic reactions of the usual type. The immense importance of the U-235 neutron reaction is that it *does* take place with neutron energies of a mere fraction of an electron volt, such as are represented by normal room temperatures. If a molecule of hydrogen moving with 150,000-volt energy crashes into air moving at a fortieth of a volt, the hydrogen is almost instantly slowed. Cockcroft and Walton got around this difficulty by artificially accelerating their hydrogen atoms in an electric field and firing them down a tube that had no air molecules in it to impede the hydrogen. Even so, the lithium atoms had to be hit just right, or they would slow down instead of absorbing hydrogen nuclei.

If the lithium and hydrogen were heated to the necessary temperature, the atoms would gradually move faster and faster as the temperature rose and would reach correspondingly higher energy levels. As soon as a certain percentage of the atoms were moving with 75,000-volt energy, the reaction would take off of its own accord. For at 75,000 volts, when a hydrogen atom going one way met a lithium atom going the opposite way, the relative speed of impact would be the required 150,000 volts. When that began to happen, the enormous release of energy—17,000,000 volts—would raise the temperature of the mass rapidly and would cause still more reactions and still more energy release. The reaction would be self-sustaining—for the minute fraction of a microsecond necessary!

No ordinary method, as it happens, can heat the material to anything remotely approaching the 75,000-volt "ignition temperature" of the lithium-hydrogen reaction, for that temperature is in the neighborhood of 200,000,000° C. But the detonation of a U-235 bomb, which can be started at an ordinary temperature, instantaneously produces a temperature enormously higher than that;

so a U-235 bomb could heat lithium hydride to the ignition point. Temperature requirements stand in the way of several other powerful atomic reactions; the lithium-hydrogen reaction is simply one of the most potent and one of the best known. Other possibilities involve heavy hydrogen, but most are based on fairly common elements, all much cheaper than U-235 or plutonium.

TNT and similar high explosives were the primary destructive agents in the war ended in 1945. TNT is popular with the military forces because it is extremely difficult to make it explode. It can be burned safely. You can pound it or shoot bullets into it, and it won't explode. But if you detonate a bit of fulminate of mercury, or tetryl, near it, the TNT explodes. The small primer cap is called an "auxiliary detonator." Perhaps in the next war U-235 bombs such as annihilated Hiroshima will serve as standard primer caps for the real explosive.

The destructive radius of a bomb with an additional atomic fuel would be limited only by the determination of the attackers and the size of the target. The usual target will, of course, be the same as through all the ages of man's history—the cities of the enemy nation, its strongholds and production centers. The pattern of modern civilized life, huddled into cities, arose in a world of weak weapons; the mighty weapon of atomic energy makes it a paradox and an anomaly.

17. *ATOMIC STRATEGY AND TACTICS*

ALL our former concepts of strategy and tactics must now be thrown out and an entirely new order of things instituted. In past ages the function of any military force was to protect its own bases, its own sources of man power, supplies, and assistance, while destroying the enemy sources of supply. The enemy army had to be defeated simply because it stood in the way of an attack on the enemy centers, not because the defeat of the enemy army was an object in itself.

Defeat of an enemy army may not be necessary in the future. If the atomic bombs can be made to destroy the enemy centers without interference—or effective interference—from the defending forces, there will be no real need to engage the enemy's military strength. Such a short cut to victory has hitherto been impossible; on the ground one army intercepted another, while in the air fighters intercepted bombers. Throughout the whole course of warfare there have been very few exceptions to the general rule. One of the exceptions was devised by the Nazis in 1944 and 1945. No means was found to intercept the attack of the V-2 rocket bombers. Only luck gave the atomic bomb to the Allies instead of to the Nazis. With the V-2 *and* the atomic bomb the Nazis would have had the ideal military weapon—a means of attacking and destroying the enemy centers of power that was not open to interception by the defending military forces.

People generally do not take in the difference between the V-2 rocket bomb and the V-1 buzz bomb. Actually the difference is immense; they are totally unrelated, as diverse as a Shooting Star jet-propelled fighter and a horsecar clanking down a cobbled street. V-1 was a miniature airplane, a clockwork-controlled, fast-flying model plane carrying a one-ton pay load. It had wings and a jet-type engine; it flew through the air and was supported by the air. It was simply a robot-piloted airplane. V-2, on the other hand, was a completely new weapon. It was a true rocket; it had no wings, but was propelled and lifted entirely by the exhaust gases of a furiously burning combination of liquid oxygen and alcohol. It was *not* an airplane. It operated best at an altitude of *60 to 70 miles.* The less air around it, the better it worked, for it did not need air to support it, and it carried its own oxygen in tanks. By the time the driving power was exhausted it was traveling at a mile a second—3,600 miles an hour—and continued by momentum, simply coasting. It landed at a speed of some half mile a second, or 1,800 miles an hour. It could not be shot down by antiaircraft guns, for it was traveling almost as fast as the shells from the guns. Since it moved about four times as fast as the fastest fighter plane and at least as fast as the shells from aircraft cannon, no plane could either approach it or hope to shoot it down.

V-1's, the robot planes, were shot down in quantities. But V-2's, the rocket bombs, *cannot be shot down.* The United States delivered its atomic bombs by B-29. As it happened, neither of the aircraft used was shot down, but many B-29's were lost over Japan, and certainly any single B-29 could have been destroyed if the enemy had been aware of its special mission. With rockets to deliver them atomic bombs would be far more inescapable.

British and American forces in England were able to watch the Nazis' V-2 rocket bombs, taking off from continental European areas, in the radar 'scopes of the giant microwave early-warning set on the British coast. They could see the trace of the V-2 rise, arch over, turn; they could watch it coming toward England. They could watch its descent and know when it was going to strike. They could tell approximately where it was going to strike. But they could not do anything whatever to interfere with its flight. Had Herr Goering gone on the air and told them that "This one is an atomic bomb, and it will strike the center of London!" they couldn't have done anything but watch its trace on the radar 'scope.

At the time the Nazis were destroyed, they had in development rocket bombs of two new types. One was a modified V-2 with gliding wings. After the rocket motor had driven it to an altitude of

60 or 70 miles, the machine would turn on a long slant; as it fell into the denser atmosphere, the wings would support it. By this device the range would have been extended from the 250 miles or so of V-2 to nearly 2,000 miles.

The second modification was a step-rocket. V-2 itself weighed 12 tons at take-off; the glider type might have weighed 13 tons. The step-rocket would have weighed 85 tons at take-off. Actually it consisted of two rockets. One was a gigantic affair that could carry a 13-ton pay load to an altitude of 70 miles at a speed of 2,000 miles an hour, just as the V-2 carried its one-ton pay load of explosives 60 to 70 miles up. But the 13-ton pay load of the 85-ton rocket would have been the modified glider V-2. At the moment the combination reached the 70-mile altitude, the big rocket would detach itself, hurl the V-2 on ahead, and descend by parachute for recovery and re-use. The modified V-2 with glider wings would start its independent part of the trip 70 miles up, with all its fuel and power reserve intact. It would have had no trouble whatever in reaching Chicago, Detroit, New York, Washington, or any of the important Northern or Eastern production centers of the United States. That was a weapon worked out during the last war, with purely chemical fuels. It was developed in haste by a nation in desperate straits.

The combination step-rocket proposed by the Nazis could have attained a speed of about 3 miles a second with their fuels and equipment. A third step could have been added, allowing the speed of the rocket to reach 5 miles a second. With improved and possibly atomic-based fuels, the simpler two-step-rocket also could have been driven to 5 miles a second. That figure of 5 miles a second is crucial. A body moving just outside Earth's atmosphere at that speed *will never fall to earth.* Instead it will become a tiny moonlet, going in an eternal orbit around the planet through endless millions of years, unless it is disturbed by some new action. If its rocket motor should be restarted and push it toward the Earth a bit, it would, of course, strike the planet.

Once the rocket has attained a speed of 5 miles a second, its range is infinite. It can strike any point on the planet from any point on the planet. At 3 miles a second it can strike New York from Germany. Adding 2 miles of speed does not just increase the range 60 per cent; a critical point has suddenly been passed, and the range has become infinite. Thus within easy reach of present-day engineering is a rocket bomb loaded with atomic explosive, which can take off from any point on Earth and attack and annihilate any point on Earth.

What defense can there be against such weapons? Underground cities would be worse than useless; they would simply be that much closer to the point where the atomic bomb can work with maximum effectiveness. A rocket bomb traveling 4 miles a second when it hit could be designed to penetrate 500 to 1,000 feet of solid rock before detonating. If the city were buried 5 miles down, the atomic bomb would probably not be able to reach it—but after an atomic bomb went off somewhat overhead, the city would be a monstrous tomb for millions, sealed from the upper world by 5 miles of broken, twisted rock. It might well be many days before the last of the entombed city's air was exhausted; lights operated by power from atomic piles might still burn for ages thereafter, but no eyes would see them.

Active defenses today are equally worthless, because of one extremely vital difference between the atomic bomb and previous weapons. *One such bomb destroys a city.* In relation to atomic weapons there is only one statistic that counts: "Did *one* get through?" Shortly after the atomic bomb was first used and Japan had surrendered, the Navy allowed publication of the fact that it had a radar-controlled gun that would shoot down a plane 10 miles away. This weapon gave the Navy's antiaircraft fire its deadly effectiveness and defeated the Kamikaze attacks. It was sometimes described as an "answer to the atomic bomb." It was an adequate answer to the Kamikaze planes, since only 2 per cent of them got through, but it would not be an adequate answer to the atomic bomb.

Through all past military history weapons have been statistical in their effects. For the future the situation is basically different. If one atomic bomb can get through by any means whatever, the job of annihilation will be done. Weapons of the past have been to a city as a bee sting is to a man; enough of them will kill the man. The atomic bomb is like the swipe of a lion's claws; just one will do the job. The beekeeper may or may not wear a mask; a few stings are annoying, but not annihilating. The lion hunter must see to it that not even one lion gets close enough to reach him.

The robot-controlled rocket bombs of the Nazis were never knocked down. No known weapon can hit them. Robot rocket bombs in the future—the immediate six-months-hence future—could be television-eyed, radio-controlled, and atomic-loaded. Their speed of approach could be so high that nothing but the 186,000-mile-per-second velocity of radar beams could catch them—and radar beams couldn't hurt them.

Counterrockets might possibly be designed, but the counterrocket is a far more difficult problem, because it must reach the incoming bomb in an inordinately short time. At 5 miles a second it does not take long for an attacking rocket to arrive; to destroy it the counterrocket would have to start from rest, accelerate to an enormous speed, guide itself accurately to its target, and detonate close enough to damage or destroy it. When an object is moving 5 miles or so a second, it takes an enormous amount of force to make it turn sharply. The attacking bomb doesn't have to turn sharply, but the defensive counterrocket must if it is to make contact.

In the realm of physical science no defense against atomic bombs is even suggested at the present time. But who knows, someday men may actually attain defensive weapons such as science-fiction writers have dreamed up. What defenses against atomic bombs have been conceived by the imagination of professional scientists who have turned science-fiction writers?

The primary suggestion has usually been a "wall of force." The only thing in the Universe that can stand up to the full, terrible blast of an atomic detonation is the barrier of binding energy that protects the nucleus. Unfortunately we see no chance of duplicating this effect.

The second basic suggestion of science fiction is a ray gun—a ray that automatically spots the attacking bomb and is coupled directly with a ray that destroys the bomb. Radar actually does the first part of the job; we have no ray for the second.

The third basic proposal is simply to scatter the population so widely that no atomic bomb can do a crucial amount of damage. That possibility is open to us today, of course. Such a total back-to-the-land movement would mean the complete disruption of our cultural pattern, and in all probability nothing short of the annihilation of our cities by atomic warfare will drive us to it.

The Crosby Foundation announced late in 1945 that they had developed a device to set off atomic bombs at a distance without precise knowledge of where they were. This should make it impossible to deliver a bomb either by airplane or by rocket. The atomic scientists have indicated doubts that the device will function, but assuming that it really can set off a U-235 or Pu-239 bomb, it may well outlaw itself. It would be as perilous to the user as to his enemy; it cannot distinguish between my bombs and yours.

After long fumbling we have reached the nucleus.

Smuggling atomic bombs into enemy territory is going to be easy to accomplish and impossible to prevent. Uranium is a good material for hardening steel, and there is nothing to stop a nation from shipping machine tools made of chrome-uranium tool steel to another commercial nation. That the uranium used in hardening the tool steel was U-235 would be hard to detect, even if the existence of uranium in the steel were suspected. It would be a simple chemical operation to recover pure U-235 planted in a mass of iron alloy, and secret agents could do it on the spot. These are not all the possibilities. Luminous paint consists of zinc sulphide and an alpha emitter such as radium. A minute quantity of the highly active radium will give the necessary luminosity; the same activity could be provided by nearly 2,000 times as much

U-235. Luminous watch and clock dials are, of course, a legitimate article of international commerce.

Tin is one of several metals that this country has to import in quantity, usually in the form of fairly massive pigs. Tin, like lead, is quite a good absorber of radioactive radiation. A considerable amount of U-235 or plutonium could be concealed in the center of a pig of tin, if a small quantity of cadmium were used to absorb neutrons, and the metal could still pass a fairly careful check for radioactivity.

If the lithium-hydrogen reaction can be initiated with the aid of a U-235 or Pu-239 primer, only a couple of pounds of the critical material would need to be smuggled in. Lithium hydride is on the open market. Several other reactions might be used. Some of them involve such common elements as silicon—available in any handful of sand or in broken window glass—and calcium, which is present in limestone, bones, and hard water.

Testifying before a Senate committee on atomic energy, Dr. Oppenheimer was asked if there were any scientific instrument that could detect an atomic bomb hidden in a packing crate. Evidently the senators had in mind the Geiger counter, which is sometimes used to locate lost, strayed, or stolen radium. Oppenheimer's reply disillusioned them: "Yes," he said, "there is an instrument with which the bomb could be located. It's called a screwdriver, and you open every case until you find the concealed bomb."

The military situation of a world with atomic weapons was accurately summed up in a science-fiction story by Anson McDonald*: "It's like this: Once the secret is out—and it will be out if we ever use the stuff—the world will be comparable to a room full of men, each armed with a loaded .45. They can't get out of the room, and each one is dependent on the good will of every other one to stay alive. All offense and no defense. See what I mean?" Incidentally, the specific atomic weapon McDonald had in mind in that story was radioactvie dusts rather than bombs. These dusts are a constant and immediate threat.

A great difference exists between a man shot with a .45 and a nation that has been attacked by atomic bombs and lost every

* "Solution Unsatisfactory," by Anson McDonald. *Astounding Science Fiction,* May, 1941.

major city. General Groves has estimated that 40,000,000 Americans might be killed in the course of a few hours by an atomic war; that would still leave some 100,000,000 Americans in the most violently vengeful mood imaginable. All of America's own atomic bombs or even a substantial percentage of them would hardly be caught in such an attack. Such warfare against the United States or any atomic-armed nation would be exceedingly dangerous. Counterattack against the aggressor would hardly be less murderous.

Human psychology is such that it is completely impossible to scare people collectively or for any length of time. The bombings of the cities of Europe proved that over and over again; the survivors in a much-bombed city were not sufficiently scared to make any marked effort to leave the city, though they fully expected a return of the bombers the next night. Every human being has a subconscious and unalterable conviction that death is something that happens to other people, but never to him. He hasn't died yet! Threats of terrible retaliation have not stopped aggression and will not stop it. There is a type of human psychology that positively enjoys the tension of threatened disaster; we must reckon with the adventurer who dares catastrophe for the thrill of a possible win.

The pattern of future atomic war must involve the use of either previously planted atomic bombs or rocket atomic bombs or both. In any case the aggressor nation will be under several stringent compulsions:

1. The source of the bombs must be absolutely secret. If the source is discovered, retaliatory annihilation will follow automatically.

2. The aggressor must not, dare not, invade. The landing of an invading army will automatically brand the aggressor as such and bring annihilation on his homeland.

3. The aggressor must not start any overt moves in any other direction that might suggest his having launched atomic attack to prevent interference with them.

Sabotage bombs planted previously will not reveal their origin, and the source of rocket bombs can be completely concealed in a number of ways. Since rockets can circle the Earth indefinitely, rocket bombs might be manufactured, sent aloft, and "stored" in convenient orbits months or years before they were to be used. Or they could be launched from secret bases—perhaps Antarctica, a Pacific island, or special launching ships in mid-Pacific. The icecap of Greenland would serve splendidly. Radar tracing of atomic bombs coming in from the North Pole, for instance, would yield only the unhelpful information that the point of origin was somewhere south of the North Pole!

Why attack at all if the nation attacked is to be totally destroyed and all its industrial plant rendered valueless, with invasion and capture impossible? One reason, of course, is simple revenge. Another possible reason is desire for dominance in some area where two major powers conflict over the control of several lesser powers. It would be to the advantage of either major power to annihilate the other. No overt moves toward the booty would be necessary; it would automatically and naturally fall into the hands of the aggressor. A combination of motives is also possible. As an instance, consider the present situation of Argentina. The Fascist government there has offered a haven to many Nazi refugees, scientists among them. Argentina itself aspires to dominate South America, in conflict with the aspirations of Brazil and with the sheer mass power of the industrial production of the United States. Argentina wants to industrialize herself. Brazil may be left behind. Except for the enormously greater industrial weight of the United States, Argentina feels, she might dominate South America. By working on the resentments of the Nazi refugees against us, she might be able to make an atomic attack. No further overt moves would be necessary to give the Argentine Fascists their full chance.

We cannot afford to forget the possibilities, as yet unexploited, of radioactive death dusts from the atomic pile. Every living thing in a city sprinkled with them would die. The dogs and the cats, the rats and cockroaches in the walls, and the birds in the trees would die. The trees and the grass would wither. The frightened people huddled in their bombproof shelters under 6 feet of concrete would die—killed by the penetrating gamma rays from the synthetic radioactives sprinkled on the ground above. Their bodies wouldn't decay; there would be no bacteria alive. *Everything* on the ground, in the air, or under the ground would die. Even the inside of a bank vault would not be safe from the rays from the synthetic radioactives.

This radioactive weapon is not like the atomic bomb. The bomb destroys everything; a city struck by an atomic bomb is mashed flat, as if by the heel of a giant. The synthetic radioactive weapon is more delicate. In a city struck by it fine lace curtains could remain fluttering in the breeze of an open window. The fragile wings of the butterflies on the ground would be intact. At night the city would be a fairyland glowing with a faint blue nimbus—for atoms of air would have been ionized by the gamma rays pouring out of the exploding atoms. There would probably be few corpses in the city, for most of the people would have fled after the planes had dusted their city as planes now dust cotton fields to rid them of boll weevils. But they wouldn't really escape; they would be walking dead—doomed women carrying their doomed babies out of the city.

A further weapon, nonatomic, has been developed during this war that might be brought to bear on the dispersed population of a nation shattered by atomic bombs. Biological warfare, involving the spread of various highly contagious diseases, could be effective against a nation already troubled with disrupted transportation, lack of power, lack of fuel to maintain small-town water-pumping stations, and the like. Hundreds of thousands of displaced city survivors would be wandering about the country, and disease might be spread rapidly.

The world finds itself in a condition of "all offense and no defense." This situation has never existed before.

As this book is being written, the final official reports of the Bikini tests have not yet appeared. But certain points are clearly established. First, the air-burst bomb—Test Able—destroyed relatively little of the fleet, but did considerable topside damage to such things as radar antennae, fire-control equipment, and abovedecks material. The water shock wave from this bomb was relatively weak; even so, it *sank more ships than had ever been sunk by a single bomb before.* That single ineffectively applied bomb constituted a major naval disaster. Radioactivity was a relatively minor nuisance; yet the Navy found that 90 per cent of the gamma radiation generated went sailing right through 18 inches of steel armor plate.

In Test Baker the bomb was set off about 60 feet below the surface of the water. This was practically a surface blast, for in the unimaginable violence of atomic fission everything within approximately 100 feet simply ceases to exist as matter in any form we know. Though the tower at Alamagordo was substantially over 100 feet high, no twisted steelwork was found after the explosion, nor any puddle of molten steel, nor even condensed droplets of steel that had boiled away. The metal had been converted to stripped or half-stripped nuclei and simply ceased to have recognizable mechanical or chemical properties of steel. Physicists wouldn't even be able to recognize the spectrum of iron in those tortured atoms. At Bikini the 60 feet or so of water over the atomic bomb instantaneously ceased to be water or even steam. The annihilation of the overlying water made an easy path of escape for the explosion's violence. The Navy's pre-Baker guess as to how the water column would look said that the column would have a pine-tree shape, with a spindle of water at the center rising perhaps 15,000 feet. These estimates were based on tests at "Little Bikini" in San Diego harbor with TNT test charges; since TNT doesn't have properties even remotely approximating the properties of an atomic bomb, it is not too astonishing that the predictions weren't borne out. A gas molecule escaping from exploding TNT may have a velocity of 2 to 5 miles a second; a fission-product stripped nucleus escaping from an atomic bomb will be traveling from 50,000 to perhaps 100,000 miles a second. The effects produced on surrounding matter in the two cases are as dissimilar as the effects produced by a ball thrown by a baby and the shell of a 20-millimeter cannon. At a reasonable distance from the site of the explosion, 200 feet or so, the effects of the two types of bombs differ primarily in magnitude and in radioactive effects. The atomic bomb's irresistible thrust extends a relatively short distance; beyond that range the mechanical effects are caused by more or less normal matter escaping from the primary effects.

If you saw the movies of the Test Baker explosion, you may have noticed that, as the stupendous column of water shot up, a perfectly circular white ring expanded outward across the lagoon, ahead of the far more spectacular, far bulkier wall of foaming water. That white ring was the shock wave, a shock wave made visible by its sheer and terrible intensity. It was that inoffensive-looking, inconspicuous white ring that sank the mighty, triple-hulled *Saratoga,* not the spectacular wall of foam. The old *Arkansas* was nearer to the explosion; there is evidence that the 25,000-ton battlewagon was tossed perhaps 100 feet into the air by the fury of the water column, but that was relatively unimportant, since the shock wave, traveling 4,800 feet a second, had already reached her and crushed her bottom. Test Baker sank far more tonnage of shipping than Test Able. That effect too was perfectly predictable, for when the atomic bomb had a chance to work in a medium that offered a reasonably stiff resistance to its irresistible thrust, far more energy was turned into mechanical thrust and far less became heat. Heat isn't effective against warships; it takes a great deal more energy to fuse a steel beam than to twist it into a pretzel, so that mechanical rather than thermal energy is needed against warships.

At Test Baker, too, the Navy got convincing proof that an atomic bomb is not simply a bigger, louder, and better bomb. Admiral Blandy, after waiting several weeks for the fantastically deadly radioactivity of the ships to die out, said, "This is a poison weapon." The underwater test differed from the air-burst test in a second important way; the water trapped and held most of the radioactive fission products, and the atoms of the minerals dissolved in the water trapped the neutrons escaping from the explosion and rendered them radioactive. The gamma radiation from the explosion itself was far weaker, because the dense medium of the water stopped most of the radiation. Water isn't a good gamma-ray absorber, but there's such a terrific quantity of it in a lagoon! In trapping the gamma rays and neutrons so that they didn't attack the test crew of pigs, sheep, goats, and mice, the water itself became enormously radioactive. The President's Evaluation Commission reported that the equivalent of hundreds of tons of radium was generated in the waters of the lagoon. This, plus some neutrons that were not trapped by minerals in the water, descended on the target ships of the test fleet when the 10,000,000-ton column of water collapsed back into the lagoon. The ships became radioactive. That's a term that's hard to appreciate. Heretofore "radioactive" has referred to minute pin points of radium or something barely detectable by sensitive instruments. It means something else at an atomic bomb explosion. In a quite proper sense, the explosion itself is simple radioactivity. In the target ships there was lambent death on the decks and in the decks, in the very metal of the ships—not sudden, spectacular death, but certain death.

Efforts were made to wash away the radioactivity. Much of it was in the metal, not merely on it, and couldn't be washed off. For some rather inexplicable reason, the Navy tried using Foamite on the destroyer *Hughes;* this is an excellent fire-extinguishing mixture, but nothing whatever can extinguish the nuclear fires of radioactivity. Since Foamite is designed to form a suds that sticks and clings, it would merely serve to trap and hold otherwise soluble radioactive material on the surface of the decks.

When solid matter has been made radioactive by an atomic explosion, time is the only cure. If radioactive iron were melted in a furnace, it would be neither more nor less radioactive; if it were chilled in liquid helium, the radioactivity would be the same. If an atomic bomb went off in New York Harbor, the city would be drenched with radioactivity, and the "survivors" would be carrying death with them when they fled. Rescuers would be barred by the death soaked into the soil, the streets, and such buildings as remained.

That tower of water that was hurled up by Test Baker was roughly half a mile in diameter at the base and nearly 2 miles high. If you have a map of your own town, lay out a half-mile circle on it; see what streets and familiar houses and buildings there are in that area. Remember that very few mountains in the United States are 9,000 feet high. The column of water, more than seven times as high as the Empire State Building, would have covered nearly all the area between the Empire State Building and the Chrysler Building in Manhattan. The radioactivity of the water was the real danger it carried. The Navy reported that all the test animals on several of the ships died. Among them were several pigs in the medical ward of one of the ships; the room was sealed, but ordinary steel armor plate won't stop gamma rays.

There are several points of interest in the Navy's reactions to these tests. The primary point, of course, is the evident belief of naval construction engineers that they can design vessels to withstand the atomic bomb. They are talking of turtleback ships, with no abovedecks equipment subject to damage such as was caused by the Test Able bomb, retractable radar antennae, and so on. In the course of some two or three billion years living creatures have tried armor as against speed and camouflage, but practically all important surviving species have given it up. The turtle still carries his armored and also well-camouflaged shell, but anyone interested in turtle meat can easily get some. Anyone interested in cracking the armor of any ship—or any target whatsoever—need only hit it with an atomic bomb or make a reasonably near miss. Even if a ship capable of surviving within 500 feet of the bomb could be constructed, it would be useless; the crew would be a bloody pulp buttered over the decks after the ship dropped back from 5,000 feet in the sky.

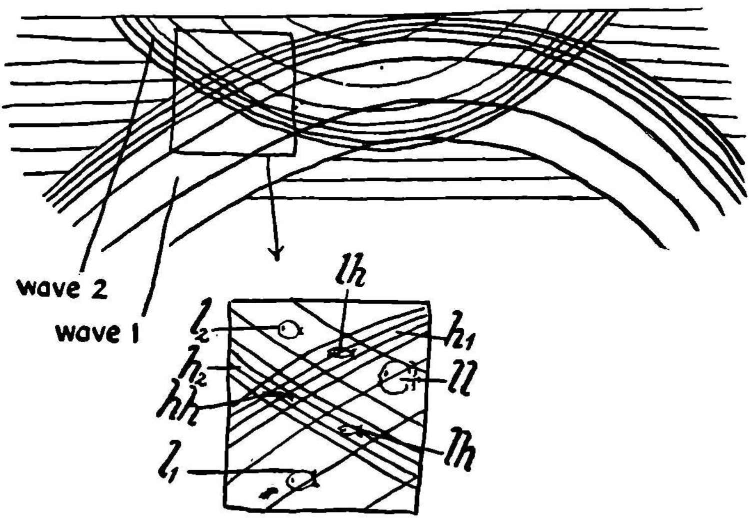
No structure can withstand an atomic bomb. In reporting the Test Baker results some two hours after the trial, Admiral Blandy indirectly acknowledged that; he stated that three ships had then gone down, the *Arkansas,* a concrete yard oiler barge, and an LST. There was no mention of the 200-foot LSM-60 from which the atomic bomb had been suspended; that was automatically canceled—annihilated. The mighty 42,000-ton *Saratoga* would have been canceled just as certainly if the bomb had been suspended from her.* If no ship, however armored, can withstand a direct hit, then all ships are in effect in a class with the destroyer. The destroyer depends for its success in battle on its basic resemblance to a rabbit. Rabbits can run; they can stop and turn in a length, and they breed fast. Unlike the rabbit, the destroyer packs a deadly punch, capable of sinking battleships, in its torpedoes. The great armored ship loses its reason for existence if armor can't

* If the *Saratoga* had been the bomb ship, she would have been converted into 42,000 tons of shrapnel raining down on the test fleet from some 10,000 feet in the air and would have been as great a menace as the bomb itself. If one of her main turbine rotors had fallen on the deck of a battleship, it would have gone on till it hit the rocky floor of the lagoon.

stop the probable weapon. One other type of ship besides the destroyer seems fully capable of operation in atomic warfare—the submarine. According to the Navy, Bikini indicated that "the only defense is distance"; camouflage is one excellent way of inducing the enemy to keep his atomic bombs at a distance, and the submarine has a reasonable chance at camouflage. It isn't perfect, by any means; during the late war magnetic detection methods were developed that permit a plane flying high over the sea to detect any magnetic irregularity in the water beneath. The degaussing system that worked well enough against magnetic mines won't delude the magnetometer; it's too sensitive and too adaptable. Other exceedingly efficient systems for locating subs were worked out, too, by the end of the war. The present cost of an atomic bomb appears to be in the neighborhood of $1,250,000. This expensive weapon will not be used against a cheap ship such as a destroyer or a submarine, but it's worth ten atomic bombs to get one $125,000,000 enemy battleship. The size of naval ships in the future may be determined more by the relative cost of ship and bomb than by any other single factor.

Test Charlie, the deep-water test of the atomic bomb, at this writing is "indefinitely postponed." That appears to mean it's been canceled. Atomic scientists had stated that only a deep-water test would really show the power of the atomic explosion against naval vessels, but there are several sound reasons for canceling the test. One is that it would cost about $35,000,000 or a bit more than a dollar for each family in the United States. The other reasons are less obvious. One may be that the Navy is already convinced that no type of ship design can possibly resist the atomic bomb. Besides, Test Charlie involves some highly unpredictable phenomena. What happens when we set off a bomb in the air is well known; the effects of the shock wave in Test Baker were sharply limited by the rocky walls of the lagoon; but no one has the slightest idea what might happen if an atomic bomb were set off at a depth of half a mile in sea water. It does seem fairly certain that it would not cause a spectacular flare of light and throw up a huge column of water; the inertia of half a mile of water is immense. All the stupendous heat energy of the bomb, all its nuclear radiation of gamma rays, all its energy, would be trapped deep in the water and converted almost entirely into mechanical impact—a fearfully intense shock wave.

Shock waves, when they work in three dimensions, are very tricky things indeed, especially in water. Water is normally regarded as incompressible, though sound waves in water do involve slight compressions, and the shock wave of a TNT explosion under water very definitely compresses it slightly. But no one has



Interaction of shock waves.

the slightest idea of the mechanical properties of water when it is compressed to the density of gold—and if Test Charlie is tried, some such density will be attained. A lot of water will be inescapably trapped between the irresistible expansion of the bomb, a force no matter can withstand, and the immovable mass of half a mile of solid water above. The atomic bomb is going to expand, and the half mile of water can't possibly move out of the way fast enough; no one can guess just how it will behave.

The wave from the bomb will travel in all directions, up, down, horizontally, and at all angles between. The downward wave will be reflected up from the sea bottom. The upward waves will be reflected down from the air surface. Two loud noises can—and do.

under the right conditions—make complete silence; similarly, two shock waves can completely cancel each other. Explosion waves consist of two parts: a primary high-pressure shock wave immediately followed by an intense low-pressure wave. The structure of shock sound waves and the manner in which two such waves can react to cancel each other in certain spots and doubly reinforce each other in other places is shown in the diagram on page 258.

Because of the cancellation effect, it is perfectly possible that a ship a mile away from the detonation will be completely unhurt or only mildly rocked by surface waves. Yet because at some points the shock wave will be doubly reinforced, it is possible that a ship 50 miles from the scene may be crushed into a twisted ball of metal.* During the war the Navy developed a method of finding lifeboats at sea that was called *sofar,* a contraction of *so*und *f*ixing *a*nd *r*anging. The occupants of the lifeboat had only to drop overboard a special depth bomb with which the lifeboats were equipped. The depth bomb carried a special detonator to set off the 5-pound charge of TNT when the device had sunk to a depth of about half a mile. Properties of sound waves in water are such that at that depth a wave will travel outward for immense distances with almost no loss. The signal of a lifeboat bomb dropped off Dakar was picked up by special shore-based listening stations in the Bahamas, several thousand miles away. If the sound wave from 5 pounds of TNT can be picked up at a distance of 2,400 miles, what will the shock wave of an atomic bomb be like at a distance of 2,500 miles?

These unpredictables make Test Charlie highly unhealthy. No one knows the danger zone; no one can say, "Observation ships will be safe here." Test Charlie now stands "indefinitely post-

* These cancellation-addition effects have been observed many times in air shock waves from ordinary explosions. Two men walking down a street in London together during the bad days were hit by the blast wave from a bomb. The man *nearer* the bomb explosion was merely scratched by a few bits of rubble. His companion beside him was killed instantly by blast compression. The uninjured man was lucky enough to be standing in the zone of cancellation; his companion was in the zone of doubled intensity. This general type of apparently freak action is common—but completely unpredictable!

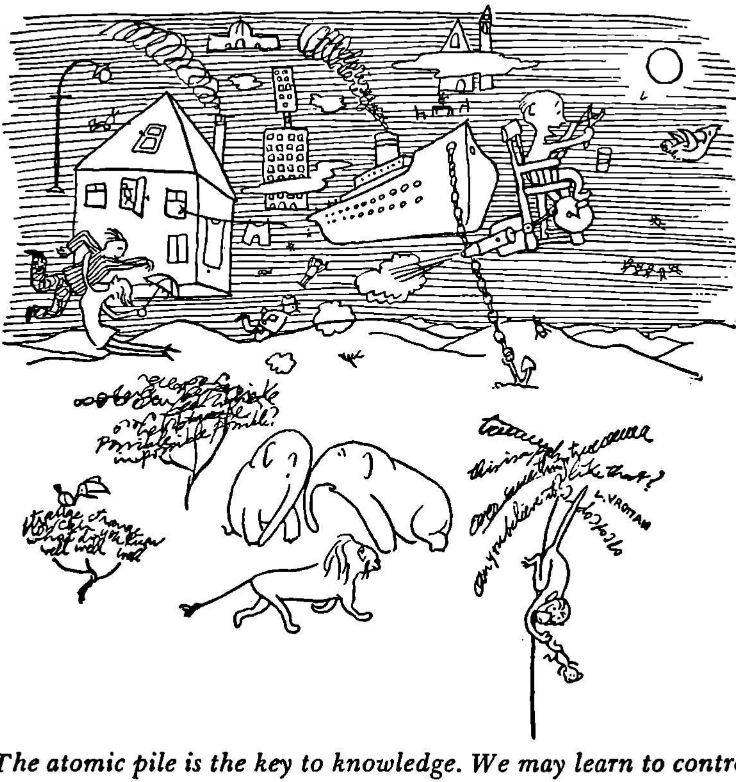
poned." But we'll find out how atomic bombs act in deep water, whether they create tidal waves, initiate earthquakes, or what not, just as soon as someone tries an atomic war. The effects of deep-buried or deep-sunk atomic bombs are something we can't predict yet; we'd be wiser not to find out.

18. NEW POWER FOR PEACE

ATOMIC-POWERED devices have already made their appearance in your everyday life, and some are at work in industry today. During the next ten years, in all probability, the glowing hopes for atomic gadgets are going to be completely broken. The only atomic power devices that are apt to come in in the immediate future will be on just about the scale of those we have now and have had for nearly half a century. The luminous dial on your watch or clock is an atomic-power device; disrupting radium atoms supply the energy that generates the light.

You'll have no atomic-powered automobile or private plane. Electric power will be much cheaper—but because of improved design of coal-burning boilers, better transformers, more efficient distribution systems, not because of atomic power. No nation will supply its needs for copper, tungsten, or other important industrial elements by transmutation. Your house will continue to be heated by coal, oil, or gas, not atomic energy. The most potent atomic gadget you'll see during the next ten years or so is likely to be an "atomic battery" that may run flashing traffic blinkers, but won't generate enough power to light a flashlight.

For the general public the much-advertised atomic age is about to open with a dull thud of disappointment and a growing conviction that it has been badly oversold. So far atomic energy can be applied in large, effective quantities only for destructive purposes. It will not be performing useful everyday tasks at any near date, precisely because it is too immensely powerful, and we know too little about it. Nevertheless, it may indirectly be going to save your life. For the present, this whole business of atomics *has* been enormously oversold in every respect except two. It is everything anyone anywhere has suggested in the way of superweapons, and then considerably more. The other value of the atomic pile has hardly been pointed out. It is the key to knowledge of a whole new sector of the Universe.



The atomic pile is the key to knowledge. We may learn to control gravity.

The great trouble with the present type of atomic-energy engine is that it releases raw heat and also raw, horribly deadly radiation. The heat can be applied to generating steam and thus made available, but the raw radiation must be stopped somehow if any living thing is to come anywhere near the device. Whether the engine is to be used for powering a vehicle or as a fixed power and heat installation, this basic and inescapable requirement must be met.

The atomic pile itself may weigh as little as 100 pounds and be capable of generating 100,000,000 horsepower, but the shielding that will make it possible to live within half a mile of it will weigh 100 tons. If the shielding is solid lead, the 100 tons will not bulk large, since lead is dense. If the shielding is concrete, much thicker layers will be needed; but concrete is not as heavy as lead; so the total weight of the shielding will still be about 100 tons. No matter how you wriggle, you must still have that 100 tons of dead weight.

Use in commercial planes is blocked for some years to come; to carry a 100-ton engine, a plane would have to weigh 700 or 800 tons, or roughly ten times as much as the largest plane now flying. There is one exception to that general statement; military planes using atomic engines are quite possible—small military planes, perhaps no larger than a modern fighter. Atomic energy is released by the pile in the form of pure heat; a jet-propelled plane converts heat directly into motion, and so an atomic pile would work very efficiently and easily in a jet-propulsion engine. A very small, light pile can deliver an immense amount of power. It's shielding that rules it out for commercial but not for military purposes.

Both the Army and the Navy are working on drone planes, which would take off, fly, and land under remote radio control. No living thing need come within a half mile of such a ship. With a raw, unshielded atomic jet engine a plane of unlimited range, incomparable speed, and incredible maneuverability would be possible. Such a plane will almost certainly be built; *it constitutes the third great atomic weapon.* The first is the bomb; the second is radioactive dust; the third is the death *spray*—not to be confused with a death ray. No living thing can come within half a mile of an unshielded operating atomic engine, and nothing will live if the operating atomic jet engine of a drone plane is brought within half a mile of it. In flight the plane would be surrounded by a glowing blue nimbus of radiation—harmless to machines, deadly to men. It could knock out an entire enemy bomber formation by simply flying close to it. It could wipe an armored column out of existence by a single low pass. It could strafe a city in a most devilish way; if it flew low overhead, the city would become a death trap, while if it were shot down, there wouldn't be any city left.

Such a plane could not be used for commercial purposes. It would kill instantly any living passengers, and commercial freighting service too would be impossible; radiation would render even ingots of pig iron too radioactive for use by the time they were landed. The unhealthy nature of this death-spray plane gives in sharp relief the proper picture of the atomic pile without that inescapable 100-ton load of shielding. At each further mention of the atomic pile remember tons of shielding are needed—and under what circumstances the shielding might be omitted; in an interplanetary rocket ship only the side of the pile toward the passenger compartment of the rocket would have to be shielded.

Anyone with enough money could presumably have a 36-wheeled, 175-ton two-passenger runabout equipped with atomic power, but his choice of routes for touring would be limited; few bridges could take such a load. Since the pile would generate only heat, some form of steam engine or the like would be required to turn the heat into motion. No present knowledge of atomic energy is capable of giving you a practicable atomic-engined automobile—or an atomic-heated home, either.

Present knowledge of atomic energy reactions is not going to turn any "have-not" nations into "haves." It would be fine indeed if someone developed a method of transmuting some cheap, widely available element like iron into copper or figured out how to make several silicon atoms into one tungsten atom. Silicon constitutes nearly a quarter of the Earth's crust; if we could set up some kind of atomic pile to turn it into copper, silver, gold, tungsten—whatever metal we wanted—it would solve all Earth's economic ills. Or would it?

At the Hanford piles uranium is burned to transmute some of the uranium to plutonium. In the process so much heat is generated as a by-product that the icy waters of the great Columbia River are measurably warmed. The production of the finished element—plutonium—cannot amount to more than a few kilograms a day, but a few kilograms of plutonium is enough; it takes only about one kilogram to devastate a city. In industry copper, tungsten, and similar metals are needed by the ton or the hundreds of tons. Despite the silver bloc, silver is an industrial metal of primary importance; we want not just a few pounds of it a day, but a few hundred tons a day.

Converting uranium into plutonium releases heat equivalent to about 1,000 tons of coal for each pound of plutonium produced. It involves a 200-Mev fission reaction. Most atomic reactions are nowhere near as violent as the uranium-fission reaction and involve only about 1 Mev; so we'll assume that copper-making transmutation produces heat equivalent to only 5 tons of coal per pound of copper produced. For a plant to be useful we need at least 100 tons of copper a day from it. This means that we'll have to run a reaction equivalent to $100 \times 2{,}000 \times 5$ tons of coal per day, producing heat equivalent to 1,000,000 tons of coal per day.

All that heat will have to be thrown away. The plant can't possibly be located near a city; the health danger from radioactive by-products would be too great. "Heating all outdoors" is now so easy it's a menace. That much heat will raise some 500,000,000,000 *tons* of water from the freezing to the boiling point each day if a water-cooling system is used. Several cubic miles of cooling water would have to be pumped through the system daily. In ordinary engineering developments, once excess heat has been transferred to a river or a lake, the engineer can forget it—it's taken care of. The Columbia River takes care of the Hanford piles; it absorbs the heat, and that's an end to the problem. But if we start working on transmutations yielding a daily 100 tons of whatever metal we're after, the problem is vastly different, for we can no longer regard the river or lake water as the final destination of the heat. Such a plant would produce boiling-hot water, a Mississippi River of it. This river would throw most of its heat into the air in the form of great clouds of water vapor. The heated air would start rising, and the result would be a permanent local hurricane of unimaginable violence.

The heat could not be used to advantage to warm up the cold regions of the Earth, either. The heating would be much too sharply localized; it would simply cause an enormously violent local disturbance of air currents that might result in long-range changes if it were kept up, though if the change were favorable in one sector, it would be disastrous somewhere else. For instance, Greenland might be warmed to habitability if wind currents shifted enough, but incidentally the Gulf Stream would change its course, and northern Europe would become glaciated.

A home-heating device burning atomic fuel could make use of plain dirt for gamma-ray shielding. A couple of hundred feet of dirt would be as effective as 3 feet of ray-absorbing steel or a foot of lead—and much cheaper. Still, digging a hole 200 feet deep would cost something. The uranium needed would take a bigger bite out of your funds—more than 10 tons at $20 a pound. "Ash removal" would run into money, too. The atomic combustion of uranium does produce a sort of ashes—the fission-product atoms, which constitute neutron-absorbing impurities and will halt the chain reaction if they accumulate sufficiently. Periodically the uranium slugs would have to be taken out of the pile and processed chemically, and the purified uranium would have to be separated, put into aluminum cans, and returned to the pile. Complicated automatic machinery would be required, and that means that your hole, already 200 feet deep, must be several times larger than the average house.

Though small private installations of uranium plants are fantastic, industrial use of the uranium pile would not be open to the same objections. No one can afford to buy crude petroleum, set up his own cracking still, and produce his own supply of gasoline and lubricating oil for his automobile, cooking gas for the house, and fuel oil for heating; but the products of commercial-scale enterprises in this field are within reach of all of us. Building a uranium pile for industrial use would unquestionably cost something on the order of $1,000,000 to $10,000,000 for a complete installation, including automatic ash-removal equipment; against that cost, however, it must be realized that for a modern 100,000-kilowatt electric power plant just the boilers, stoking machinery, and ash machinery represent an investment of upward of $1,250,000, with the cost of the plant building, generators, turbines, switchboards, and so forth additional.

Mobile installations are also possible commercially. The standard small local-line passenger locomotive usually weighs in the neighborhood of 250 tons. Weight is useful in a locomotive, because it gives the engine tractive grip on the rails, and this enables it to pull a heavy train. Atomic piles instead of boilers would therefore be quite practicable for locomotives. Ash removal would be simple and relatively cheap, because one large central processing plant could handle the uranium slugs for all the locomotives on the railroad's lines.

Much the same can be said about ships. The Navy is undoubtedly much interested, because atomic power will make possible ships with unlimited cruising range. A single pound of uranium contains the heat energy of 1,000 tons of coal; so it would be no trick to fuel a battleship for a 100,000-mile cruise. Even more interesting to a navy is the fact that a submarine capable of indefinite submerged cruises can be built. Present-day submarines are limited by three factors:

1. Like any other ship, a submarine must be fueled. Submarines already have about the greatest cruising range of any type of warship, but extending their range is still a pressing problem.

2. A submarine, when submerged, cannot get oxygen enough to allow the use of coal, oil, or other normal fuels. The result is that two different kinds of propulsive engines—one for surface cruising, one for submerged cruising—must be carried. The submerged-cruising engine is usually an electric motor fed from storage batteries that are exhausted in a relatively short time.

3. Men need oxygen. When the small supply of fresh air in the submarine's hull is used up, the sub must come to the surface, or the men will die.

An atomic-powered submarine would overcome all three of these limitations. The uranium pile would supply indefinite cruise radius. Further, since the pile does not require air, the engines run by it would work perfectly above or below surface, and the fullest power could be obtained either surfaced or submerged. A submarine capable of 35 knots when submerged would be possible, and such a sub could run down and sink any ship in any navy. Not even a destroyer could escape it on the high seas—for surface ships are slowed down by having to fight the waves; submarines don't have to. With unlimited electric power available below the surface, the men could have an inexhaustible supply of perfectly fresh sweet air. The Earth's atmosphere is kept sweet and well oxygenated by the action of green-leaved plants, which consume our exhaled carbon dioxide and give off the oxygen we need. In a few cubic yards of space a number of high-intensity plants that grow very fast would absorb all the carbon dioxide produced by 50 to 100 men. The supply of fresh air could be maintained forever, as it is on Earth—with powerful fluorescent lights to supply the necessary substitute sunlight for the growing plants.

Passenger liners will be interested, too; oil is expensive, and uranium fuel is extremely cheap, once the equipment is installed. A 100-ton atomic pile is far too heavy for an automobile, but it's a featherweight by comparison to the immense and ponderous boilers of a big passenger liner. The saving of weight there would be real, worth dollars and cents to a shipping concern. Even more important, no huge bunkers full of fuel oil would be needed; only a little uranium would be consumed in a fast transatlantic trip.

One pound of highly purified natural uranium costs about $20, but *every atom of it is atomic fuel.* Not only the U-235, but the U-238, too, can be consumed in an atomic pile. This point has not been stressed sufficiently, though it is implicit in the Smyth report. Many writers seem to have concluded that only the U-235 in natural uranium could be used as atomic fuel. That is true of atomic bombs, but in atomic piles all uranium is atomic fuel. Consider the fission of an atom of U-235 in a uranium pile. This fissioning atom produces fission-product nuclei and on the average yields slightly more than two new neutrons. One of these two new neutrons must be absorbed by another U-235 atom to sustain the chain reaction. One of them *must not be absorbed by U-235*—it *must* not. If it is absorbed by another U-235 atom, the rate of reaction will be doubled; if that happens through another cycle, it will be quadrupled. Precisely that sort of phenomenon struck Hiroshima. The second new neutron must be made to escape or must be absorbed in some atom that will not fission, or the pile will vanish in a stupendous detonation within a fraction of a microsecond. The second neutron can readily be absorbed, of course, in cadmium control rods, boron, or any one of several impurities. But obviously the handiest and easiest way to absorb the dangerous extra neutron is to soak it up in an atom of ordinary U-238.

An atom of U-238 that absorbs a neutron becomes successively U-239, neptunium 239, and finally plutonium 239. And Pu-239 is precisely equivalent to U-235 so far as fissioning goes. In the long-run picture, then, we start with an atom of U-235 that fissions and produces two neutrons. One of these is used to maintain the chain reaction. The other is used to maintain the supply of fissionable material by transmuting U-238 into fissionable Pu-239!

This sequence is of great economic importance, because it makes possible the atomic reaction of all the uranium in the natural uranium ore. Since the purified natural uranium costs only about $20 a pound and is equal in fuel value to 1,000 tons of high-grade coal, uranium is obviously a very cheap fuel indeed. The sequence is important also because an atomic pile made up with uranium containing a high percentage of U-235 or Pu-239—say 25 per cent Pu-239—can be much smaller and more compact than a pile using only natural uranium. If the added Pu-239 had to be replaced continuously, the enriched pile would be very expensive to operate, but because the U-238 present in natural uranium added to replace fuel consumed would itself become Pu-239 and thus replace the consumed Pu-239 continuously, the enriched pile is practical.

The same type of sequence reaction, dependent on the fact that it is necessary to absorb the second fission-produced neutron in some nonfission reaction, makes certain other atomic fuels than uranium isotopes practicable at present. Thorium and protoactinium, as well as uranium isotopes, can be fissioned by neutrons, but both thorium and protoactinium require fast-neutron impact to cause fission. These two elements, in other words, act very much like U-238 and unlike U-235; hence they cannot be used in an atomic bomb, but they can be used in an atomic pile. Thorium itself cannot be used as an atomic fuel, but thorium added to an atomic pile operating on uranium "kindling" could take over the load by transmuting itself into fissionable material. Neither thorium nor protoactinium is anywhere nearly so plentiful as uranium, and neither will ever serve as a primary source of atomic energy to the extent that the more plentiful uranium will, but each can provide an extra bit of fuel.

Some known rich deposits of thorium can be mined more cheaply than some known low-grade uranium ore deposits. While uranium is present in the Earth's crust in enormous quantities, most of the deposits are very dilute ores. That does not by any means prove they are unworkable; current mining practice recovers gold profitably from ores that contain the incredibly minute concentration of 0.3 part of gold per million of ore. Geologists have found that uranium is present in the Earth's crust at an average concentration of 6 parts per million. On the average a handful of rock, gravel, or sand anywhere on Earth contains 20 times as high a concentration of uranium as is needed in the case of gold ore to make it commercially usable. Earth's available uranium fuel reserves are stupendous—and so is the problem of controlling uranium production.

At present the most intelligible, most carefully worked-out program for the industrial and economic application of atomic power under conditions that will control the production of atomic weapons is the State Department's Lilienthal report. The report does not aim at outlining a complete world-wide political control of atomic war; its primary purpose is to get the industrial and economic possibilities of atomic energy out into the open. Briefly, it establishes as a dividing line the simple concept that no one really wants to restrain the peaceful applications of atomic knowledge or atomic power. If the application is purely peaceful, it properly belongs in the public's hands; if it is dangerous, it can legitimately be regarded as a matter of military nature, to be held under political secrecy.

The report's proposals rely on the existence of a so-called "denaturing" process that will render plutonium nonexplosive. The exact nature of this denaturing process has not been revealed, but some guesses can be made. Natural uranium actually is "denatured," so far as atomic-bomb use goes. It is nonexplosive because of the presence of U-238; only when U-235 is separated, by a very large, very elaborate separation plant, can an explosive atomic reaction be induced with uranium.

To "denature" plutonium we would have to add to it some material that could not be separated from it save by an extremely elaborate plant, but that would render the plutonium incapable of explosive reaction. The obvious answer would be a plutonium isotope that was not fissionable. The only thing that cannot be separated from plutonium is, of course, plutonium. The plutonium we have come to think of when the term is mentioned is the isotope

Pu-239, but plutonium, like all other elements, has several isotopes. Apparently the nuclear physicists have discovered a feasible method of producing some nonfissionable plutonium isotope in quantity. The only question, then, is how this new plutonium isotope would behave in an atomic pile. Does it, like U-238, transmute to a fissionable isotope? If so, a pile using denatured plutonium would, in the course of operation over a period of time, rid itself of the denaturing agent.

The "denaturing" process cannot in any case be thought of as one that renders the nucleus of Pu-239 itself nonexplosive. When man reaches a stage of atomic knowledge sufficient to pull such a neat trick, there will be no need for uranium, plutonium, or other heavy-atom fuels, for it would require a manipulation of the nucleus of such finesse that it would do credit to a science a thousand years ahead of our present knowledge. The problem of denaturing plutonium is somewhat comparable to the problem of making gunpowder nonexplosive. No one yet has figured out any way to render a properly proportioned mixture of niter, sulphur, and charcoal incombustible—but it's very easy to add enough sand so that it will merely fizzle instead of exploding or to wet it down with water so that it can't be set off. Each method involves a dilution of the dangerous material, not a change in its nature. If the denaturing method applied to plutonium works satisfactorily, it is highly significant, because it assures that plutonium so treated can be used for nonexplosive purposes* and will free atomic power for commercial applications.

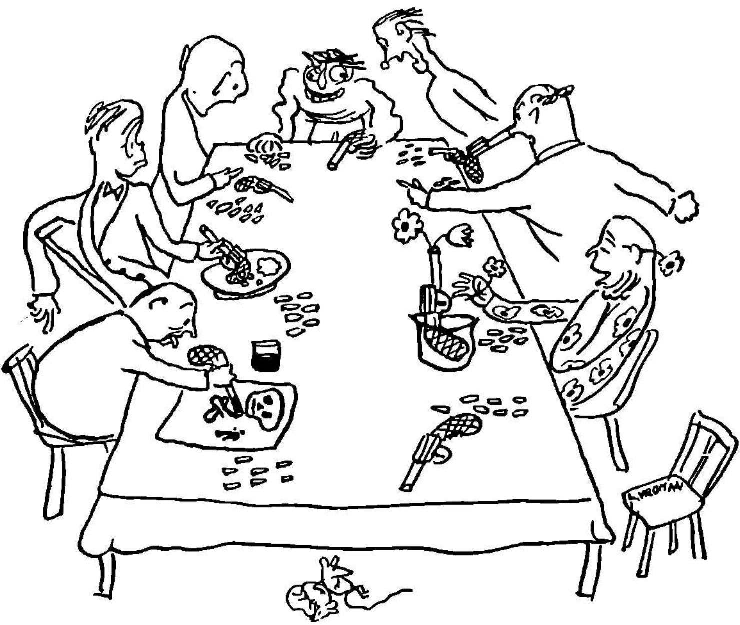
The Lilienthal report proposes, in essence, that an international authority be created that will have control over all uranium and thorium deposits. This world authority would mine, purify, and denature the uranium and plutonium. Only the denatured product would be released to individual nations, which would, in turn, sell it to industrial or research users. The plan is workable, because it takes in the important consideration of human nature by its sug-

* Unfortunately it does *not* assure that the plutonium cannot be used for *military* purposes. The atomic pile, while nonexplosive, is the source of the second deadly atomic weapon—the radioactive death dusts. Denatured plutonium, if it is of any use at all, must be usable in an atomic pile and hence could be used to produce radioactive dusts on a large scale.

gestion that the authority be set up in stages. At first only enough of the United States' atomic knowledge would be released to the authority to permit it to plan its work. Gradually, as other nations developed their own atomic processes, the United States would turn over to the authority more and more information. The United States would not be required to give up any secrets that had not already been mastered elsewhere, but it would be able to feed information and equipment to the authority at such a rate that the latter would at all times be equipped at least as well as any individual nation except the United States. This would tend to put a powerful damper on the urge to start an atomic arms race, yet would mean that no individual nation would find itself in a worse position than it would if the authority had not been created. Eventually the United States would have transferred all of its present monopoly of information to the authority.

The greatest protective service performed by the authority would lie in this simple fact: If it has control of all atomic fuel sources, any nation planning an atomic war will have to seize the atomic fuel plants of the authority in its own national territory first. This it will naturally be able to do at any time it chooses. But any nation that did take over uranium sources in this manner would be automatically signaling to the rest of the world: "Look out! I'm getting set to make atomic weapons for an atomic war!" It would be an open and obvious invitation for all the rest of the world to blast the war-minded nation immediately, before it could complete its preparations. Reverting to the analogy that Anson McDonald suggested in his science-fiction story, every man in the room has a .45, there is no way out, and each depends on the good will of the others to live. If the authority is set up, each man has his .45 on the table, with the cartridges in a pile beside it. Any man who starts putting the cartridges in his .45 is most seriously suspect; the others will have a chance to put some of their cartridges into him first. But the men remain perfectly free to use their .45's as nutcrackers, tack hammers, or paperweights or for any other peaceful purpose they can think of.

Economic problems that stand in the way of peaceable applications of atomic power are real and tough. Despite the cheapness of this new fuel there is very little chance that your local power company will install atomic-powered plants in the immediate future. It doesn't dare to; the public reaction to a refusal to lower rates would be violent and would be immensely harmful to the company. Why not lower the rates, then? Because no matter how cheaply the utility company can generate power—even if it could do it for one ten-thousandth of a cent per kilowatt-hour—it cannot cut down the biggest items of its expense, which are involved



Under the Lilienthal plan each nation would have its gun on the table.

not in generating power, but in distributing it. Power lines are very costly contraptions, and they require constant maintenance by skilled, highly paid engineers and technicians. Also, because you insist on turning on your lights and your toaster, coffeepot, and waffle iron at the same time as your neighbors, the lines have to be made several sizes bigger and more expensive than is really needed during most of the day.

Besides, great technological problems would have to be solved before atomic power could be used by the utility companies. Modern steam turbines consume superheated steam at so high a temperature that the steam pipes can be photographed on special film by their own radiation. Enormously high pressures are used, and the special steels in the turbine blades are triumphs of metallurgical science. They have to be to stand the heat and pressures. The uranium slugs in an atomic pile are at present canned in aluminum—which would flow like water at the temperatures modern steam plants use! Under those conditions of temperature and pressure aluminum would explode on contact with water. The whole technique of the uranium pile would have to be altered. The thing could be done, no doubt, but neither easily nor quickly.

One job that seems fitted for the atomic pile is that of supplying hot water or low-pressure steam for heating factories and so on. The job may not be glamorous, but it is not to be sneezed at, either. Of all the fuel consumption for all uses in the United States, far and away the biggest use, bigger than all others combined, is for heating buildings. The giant Willow Run factory obviously uses an enormous amount of electricity for its machines, lights, and control systems, but it's rather easy to overlook the huge amount of heat energy required to keep that immense barn warm in the depths of a Michigan winter. Keeping the coal-burning buildings of New York warm for one day takes about as much energy as is contained in *20 to 30 atomic bombs!** Supplying the heat needs of the nation is actually a giant task. And for that job, in the special places where large demands for heat are concentrated, the atomic pile seems to be almost perfectly suited, though it isn't practical for detached-home heating.

The greatest yield of the atomic pile will be beyond any estimation of value, though the immediate practical uses of atomic power are almost sure to be definitely disappointing. This product can't be felt, seen, tasted, weighed, or valued in dollars and cents. The pile is the greatest source of knowledge man has ever tapped—the key, as we have said, to a whole new sector of the Universe. We can use it in the next few years only to study the simplest, nearest

* Another demonstration of the difference between energy released suddenly and energy released slowly. Remember that there is more energy in a pint of gasoline than in a pound of TNT, too.

things—we can use it only to study more effectively things we already know about. The immediate task of the atomic scientists must be the exploration of atoms. There are lots of mysteries there; beyond the atoms there are still further mysteries of which we have as yet no real inkling. We know gravity exists—but we do not know what it is, nor can we generate it. We know that the binding-energy force exists in atoms—but we do not know what it is, nor can we generate it. Each of those mighty forces must be the effect of some still deeper cause that is beyond our ken today. In this field of exploration of the unknown there will be two general classes of discoveries: those of immediate use and interest and those that supply clues to deeper mysteries beyond.

The more immediate type of investigations may save your life. The researches made possible by controlling the behavior of atoms can be of immense value even on the smallest scale. We can't make a ton of tungsten—but we can make half a gram of radioactive carbon, and that's more important to human beings. Carbon is the basic element of life chemistry, but the very mobility that makes it essential to life makes it impossible to keep track of by chemical methods.

An example of the sort of research that has become possible is the effort to determine how much carbon monoxide the human body can destroy. The exhaust fumes of aircraft engines contain carbon monoxide, which has a tendency to seep into the cockpit of a plane and to poison the pilot slowly. It was necessary to determine whether the human body can destroy carbon monoxide. That should be easy; just oxidize the carbon monoxide to carbon dioxide, and it's harmless. But can the chemistry of man's body do that? No chemical research would ever be able to tell. But by working with atomic physics chemistry found out. The nuclear physicists manufactured some synthetic carbon isotope of atomic weight 11 instead of the normal 12. This C-11 isotope is radioactive, with a half-life of about 20 minutes; chemically it's perfectly good carbon. The chemists took the sample, converted it to carbon monoxide, and let a volunteer breathe a little of it. Then the test subject's breath was passed through chemicals that would absorb carbon *di*oxide, but not carbon *mon*oxide. If the man's body had been able to oxidize any of the poisonous compound, it would appear as carbon dioxide and would be collected in the chemicals. The chemical filter was examined for radioactivity; there was none. The human body cannot oxidize carbon monoxide. Knowing that, our government made its requirements for aircraft design even more rigid. Protected from carbon-monoxide poisoning, our pilots remained more alert.

Biochemists will be able to advance their studies in hundreds of ways by using the products of atomic piles. Sulphur is a constituent element in one of the B vitamins; how is it used in the body? Let's make some radioactive sulphur and find out.

Hardening of the arteries is one of the common effects of old age. Is this accumulating deposit of calcium actually an accumulation—a deposit built up bit by bit over a period of years—or is it constantly laid down and taken up, laid down and taken up, in a cycle that continues removing it, but also replacing it? We may be able to tell by using radioactive calcium or some unnatural synthetic isotope of calcium. Can the deposit be made to dissolve away? We can tell much better if we know what happens to a particular lot of calcium the patient consumes.

Cancer consists of cells that have grown endlessly, planlessly—outlaw cells. Their chemistry must be different; there must be some chemical that the cancer cells will absorb more rapidly than normal cells. If we can find such a chemical, perhaps we can learn how to make it a poison that will seek out and kill cancer cells just because they *are* cancer cells. Synthetic atoms from the atomic piles will make such investigations far easier and far faster.

The massive streams of neutrons, the heavy concentrations of gamma rays, and the relatively huge quantities of synthetic radioactives provided by the atomic pile will permit a hundred kinds of biochemical and medical research. It is in some such way that the atomic energy we now have may save your life—though the actual medicine or treatment given the patient may have nothing directly to do with atomics. If it is found, by research methods making use of "tagged atoms," that a certain chemical compound is very rapidly absorbed by cancer cells, cancer specialists throughout the world will be able to use that chemical, but they won't need the atomic pile at that stage; the chemical will be just an ordinary product of a pharmaceutical laboratory.

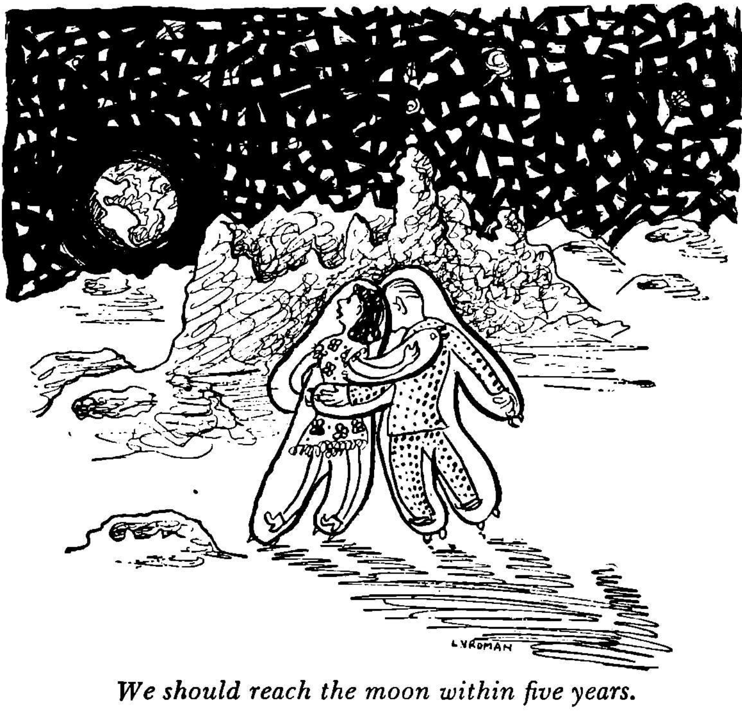
The field of more distant researches is the one in which the almost unguessable potentialities of nuclear physics will begin to show up a decade or two hence.

Our knowledge of atomic energy allows us now to release and utilize the energy of one particular type of atom—the superheavy element uranium and those above it. We can get at that energy by reshuffling the nucleons that constitute the uranium nucleus and forming two smaller nuclei from them. Those nucleons that we simply reshuffle in the atomic pile, or in the atomic bomb, are the real energy. When we learn to *consume* them—not simply shuffle them, but actually annihilate them completely—we will have tapped the energy of matter. At present we haven't any clues to how the trick of annihilation can be done. But there are clues that it is done in Nature. The cosmic rays that enter our atmosphere from outer space sometimes show energies not of millions, but of billions of electron volts. They are of the right order of magnitude to represent the annihilation of nucleons. There are nucleons in all matter, any matter; if we can release the energy of the nucleons themselves, we will consume with equal ease uranium, air, water, or sand.

We will learn, too; the uranium pile is the tool we have needed. We may learn as much about gravity as we now know about electricity and magnetism. If we can and do, it will mean the end of airplanes. An airplane supports itself in the air by leaning on the air for support; a balloon supports itself by floating on air; each is *controlled by* gravity. A machine that could instead *control* gravity would make it possible for a 50,000-ton battleship to defy gravity simply and directly.

The economic effects that would flow from such a discovery are almost incalculable. For one thing it would make every point on the Earth's surface precisely as accessible as any other point. Cities exist today because they represent concentrations of easy communication and transport; if we learn to free ourselves of gravity, the heart of the Gobi Desert will be as easy to reach as the Hawaiian Islands or New York. Each will be freely accessible from above.

All this may seem like far-distant dreams, faint hopes for the third and the fourth generation. Perhaps. It may work out that way. But probably it will not. Within fifteen years we may well be able to tap the energy of the nucleons themselves and get unlimited energy from any matter. We may learn enough about the nature of the binding-energy force within fifteen years to use it as a gamma-ray shield, for the binding-energy force of an atomic nucleus apparently can, and does, stop gamma-ray penetration. With a shield



We should reach the moon within five years.

of that nature, a weightless shield of pure energy, tiny atomic engines would become possible.

In the fifteen years after 1930 we progressed from complete ignorance of half the constituent particles of the nucleus—the neutron and positron—to atomic bombs. Another fifteen years will take us to the 1960's. Children born in the war will be passing from high school to college. Children born the year of the bomb will be going out on their first dates. Pre-Pearl Harbor children will be setting up homes and starting families. Men will be operating laboratories on the Moon, where the total lack of atmosphere makes astronomy infinitely simpler and all outdoors is the ultimate in hard vacuums. The electronics engineers will be having a wonderful time there because in their airtight suits, developed already for use at extremely high altitudes on Earth, they can actually be inside their experimental vacuum tubes. Chemists, studying the distillation of substances at really low pressures, will be making new synthetic biological products.

We should reach the Moon within five years. It could be done in 1948 if either the government or some major movie studio decided to do it! Experts on rocket-ship design say that a larger, improved version of V-2 capable of the Moon trip could be built for about $3,000,000—the cost of a standard A picture. Incidentally, the submarine that can cruise submerged for an indefinite distance can cruise just as well out in empty space if it is equipped with atomic-powered rockets. Man finds himself in just as inhospitable an environment under the water as in the vacuum of space; in neither sphere can he find breathable air, but must carry his own air wrapped in an airtight hull. Mars and Venus will prove accessible, too—and habitable for adaptable pioneers.

It will take many men and many years to tell the full story of atomic energy, and probably only the youngest of the readers of this book will live to see even a good indication of the shape of that age to come. No human mind can predict what will emerge from discoveries still to be made, any more than Volta could see in the future of his electric batteries such things as radar contact with the Moon, the great Hell Gate power station in New York, or the baffling mystery of a transformer. The first space ships should come in our time. Other things that are completely unimaginable to us now will follow them fairly soon. We can err in our forecasts only on the side of conservatism.

Nevertheless, we are unfortunate. We are a lost generation—the people who live through the interregnum between the closing of the age of chemistry and the opening of the atomic age.

19. THE HUMAN X IN ATOMIC POLITICS

PSYCHOLOGY and nuclear physics are at very nearly the same stage of development as sciences. Psychologists know what it takes to drive a man into a complete mental explosion, but they do not yet know how to help him release his mental energies under strong, steady control. Similarly, nuclear physicists know how to drive an atom into complete explosion, but they cannot release its energy as a steady, controlled flow of power. These two incomplete sciences—psychology and nuclear physics—are now abruptly confronted with the atomic bomb. If men knew more about themselves, about how to control their emotions and angers, the politics of the atomic bomb might be strictly logical. But our self-knowledge is as fragmentary as our knowledge of the atom. A magnificent example of the psychological confusion precipitated by the coming of the atomic bomb is the present conflict of ideas among the Army, the atomic scientists' organizations, and the Congress of the United States.

The Army feels that the United States possesses the greatest military secret in history and that it is absolutely essential to maintain possession of that secret. As a result it has clamped absurd censorship requirements on the atomic scientists; they are forbidden to discuss or describe effects that are self-evident to any competent nuclear physicist, whether he's ever been near an atomic bomb plant or not. An atomic scientist who stated, shortly after the Hiroshima bomb was dropped, that the detonation of U-235 would induce radioactivity in matter near by was instantly pounced on, though any college junior in nuclear physics could have stated the fact. It is as obvious to anyone with a little information as that a fire will leave ashes.

The Army officer is a military technician, a highly trained, competent specialist in the science of military defense. He is not able to understand or appreciate fully the special background knowledge of the nuclear physicist, any more than the nuclear physicist can fully appreciate the mental background of the military man. During the Manhattan Project work one of the high Army officers in charge protested to one of the top nuclear physicists: "The trouble with you scientists is that you have no idea how to obey or give orders." The nuclear physicist answered: "You forget that a research scientist, by the nature of his work, is exploring unknown territory, but he comes nearer to knowing something about it than anyone else in the world. He is the only one who can hope to see what needs to be done and can do it. He is accustomed to making up his own orders and carrying them out himself."

Of course, the Army cannot possibly enforce effective censorship in a field like nuclear physics. A top-rank nuclear physicist can spot hidden giveaways in a seemingly innocuous report. If the atomic scientists should determine to revolt against censorship, the very nature of their exceedingly specialized subject would make it impossible to censor their work effectively. Throughout the whole politics of atomic energy runs the same refrain: *Only good will and voluntary co-operation can make control possible.* In science a secret can be imparted without a forthright statement. All that is needed is to plant a leading question in another researcher's mind; he can figure out the answer himself. Nazi censorship could have prevented Hahn and Strassmann from reporting on their elaborate chemical investigations as fully as they did; even without Lise Meitner's guess, the conclusion that the uranium atom fissioned could still have slipped through to the outside world without the politicians' or militarists' knowing what was happening. Suppose the German researchers had simply published a paper on "Energy Equations of Neutron Bombardment in Uranium"; when another atomic scientist saw the figure 200 Mev, the whole elaborate story would have been clear to him. No mention of nuclear fission would have been needed; the figure 200 Mev would have been enough.

Secrecy was purely voluntary from the start of the atomic bomb project. A lot of talk has been made about the tremendous efforts to keep it dark and their marvelous success. Except for the voluntary co-operation of the technical press of the United States, Canada, and England these efforts would have been futile. Trade journals in the United States were well aware of the undertaking. No industrial chemical journal's editorial and reporting staff could fail to register the immense chemical jobs involved in the preparation of tons of extremely pure uranium, of extremely pure graphite, and of high-purity fluorine for the Oak Ridge plant. The men who work for these papers make a business of knowing where large-scale activity is going on in their field. Several large technical publishing firms are clearing houses for information from many trades. Unprecedented orders for concrete would mean something to any contracting journal. An electrical contracting journal would naturally know about huge and very unusual electrical contracting jobs. It's mechanically impossible to organize a project of such magnitude in total secrecy. The thumb of a censor can't suppress the story from above, either. In a nation devoted to the concept of a free press arbitrary dictation would challenge thousands of keen journalistic minds to slip revealing clues through to the reading public. Actually, the press did suppress clues, confuse and conceal facts, and help in every other possible way to keep the story dark—but it was done voluntarily.

By the same tokens censorship of nuclear physics is possible now only by voluntary coöperation. The atomic physicists know the terrible forces with which they are dealing, and they deeply fear the enormous violence of them. The door has been opened to the ultimate forces of the Universe, and nations simply cannot afford to bungle the job of controlling them. The scientists are dismayed to find that the average Congressman cannot take in the principles involved in nuclear fission. The physicists are deeply and genuinely disturbed, because not only the United States but the entire world must now rely on the Congressmen in Washington for protection against atomic war. Of course most professional scientists deeply distrust professional politicians anyhow, for a simple but exceedingly important reason.

The scientist is logical and likes to reduce problems to terms of natural law. His mind understands and relishes decisive, clean-cut facts. Frequently such a man is not strongly social. He is not indifferent to people so much as baffled by their erratic responses to impersonal thought. The kind of mind that enjoys the intricacies of a structure of pure logic tends to find human reactions disquieting.

The politician is interested primarily in people—how they react, what pleases them and what displeases them. People are not logical, and no two human beings react alike, as hydrogen atoms do. Understanding the reactions of human beings requires a kind of mind that cares little for rigorous logic, but is fascinated by the failings, the foibles, and the magnificent strengths of humanity. A man schooled by years of experience with people will have learned long since that logic is not to be trusted as a guide to social action. Feelings—hunches—emotions—these are the pointers.

Now that the atomic scientist has suddenly reshaped the conception of the world in which we live, he cannot understand the politician who more or less decides what we shall do about it. And the professional politician equally fails to understand the atomic scientist. Most congressmen have not even read the Smyth report, which was intended for professional technical men; it aimed no higher than the level of a Sigma Chi lecture, but the Sigma Chi is a professional scientific society. Probably the Sigma Chi as a whole could not get much out of a discussion of the intricacies of legislative politics. The congressman's whole experience has repeatedly shown him that logic sounds fine, but doesn't work. In politics it certainly doesn't; human beings are not logical. It isn't in the least logical for a man who has already been wounded to charge an enemy machine-gun nest; there is no logic in risking almost certain death. The congressman knows that though human beings are not logical, they can be magnificent; thousands of ordinary men would charge machine-gun nests in spite of wounds and logic.

The congressman is profoundly convinced that the most potent forces in the Universe are human. Just who's running the atomic piles—men or atoms? Certainly atomic energies are terrific, but it was men who harnessed them. It is human forces of determination, intelligence, and skill that have made the atomic energies do our bidding. Pure logic does not fit human affairs; it must be seasoned with understanding compromise, voluntary co-operation, and mutual agreement. And indeed, throughout the whole application of atomic energy to human politics, *good will and readiness to co-operate are essential to mankind's continued existence.*

The United States stands in a unique position at this moment of world history—in a situation that has never occurred before and may never occur again. We possess an absolutely irresistible military weapon with which we could conquer every nation on Earth and establish a single world government. We have the bases, the planes, and the bombs to do it. No nation on Earth could make more than a token attack in return. By conquering the world right now and establishing American police inspection guards in every city on the planet, we could make sure that no other people would learn how to make atomic bombs. By strict logic this is the way we should use our power. But the very thought is revolting to the American people. We do not want conquest. We want to let alone and be let alone, each man to live as he sees fit. Condemning millions of Americans to spying on and policing a hostile world is abhorrent. It wouldn't work anyway. Before another century has passed, probably before half a century has passed, science will find out how to use *any* matter as atomic fuel. Shortly thereafter someone will find out how to build the apparatus so simply, in secret, that police inspection can't catch him. Then God help America!

A world government is apparently the answer, though it cannot be instituted by force, but must be generated out of good will and voluntary co-operation. We do not have one yet, and the United Nations organization is not, at present, on the way to becoming such a government. The trouble is that every nation on Earth—and that definitely includes the United States—would have to relinquish the right to determine its own foreign policy and the right to retain more than a minor police force. The Federal Government of the World would have to be master over every nation—as absolute and unquestioned as the Federal Government of the United States is over our forty-eight States; New York state cannot refuse to co-operate with our Federal Government any more than Rhode Island can. The basic need for some drastic change in government is that the world is now equipped—or very shortly will be—for unlimited offense, but no defense.

At this accidental and fleeting moment the United States alone has atomic bombs. England has the "secret," which is only as valuable as knowing where a pistol can be purchased; the United States has the actual bombs. England would have to set up her own uranium piles and produce her own atomic bombs. Of course, no other nation will ever have to spend $2,000,000,000 learning to make atomic bombs; the basic research has been done. The great Oak Ridge plants have already become completely obsolete as progress has moved on along fresh lines. Though the engineering technique has not been revealed in detail, the basic theory is open to anybody. Just as the United States learned in two years how to produce synthetic rubber, other nations can learn in a few years how to produce atomic bombs.

Perhaps Sweden is closest to duplicating the American achievement. During the war years scientists were free to carry on research there, and Sweden is a major industrial nation quite competent to produce all the necessary engineering equipment.

Russia, of course, is doing its utmost to duplicate the Anglo-American work and will unquestionably succeed within a few years. Atomic scientists estimated a maximum of six years from mid-1945, but they felt that four was more probable. The Soviet government is extremely distrustful of Anglo-American intentions and greatly desirous of being able to protect itself against all comers. Probably no nation on Earth would have more to lose and less to gain from warfare than Russia. Already she has about as much land, population, and natural resources as she can handle. Given time to develop her great possessions, she can attain a very high standard of living. But for that Russia needs a period of peace more than anything else.

Switzerland, France, and the Netherlands are all quite capable of developing their own atomic bombs. Czechoslovakia and Belgium are particularly favored; they are both industrial nations, and each possesses major uranium deposits. The mines from which Becquerel obtained the uranium with which he discovered radioactivity lie in Czechoslovakia. The largest known uranium deposits are in the Belgian Congo.*

Denmark must certainly have most of the necessary theoretical

* Belgium was the only nation that supplied the United States with more value in reverse lend-lease than we supplied to it. The war ended with the United States $90,000,000 in debt to Belgium, though the Belgian homeland was a wrecked, starving country when it was finally liberated, requiring much and unable to supply anything.

data on hand now. Niels Bohr, who did a great deal of the theoretical mathematical work for the Manhattan Project, is a Dane.

Any first-class or any second-class nation absolutely must have an atomic pile. Atomic power may not have much economic importance for many years to come—but atomic data are of the utmost importance. It will bear repeating that the one product of the atomic pile with irreplaceable and inestimable value is knowledge. Denying atomic piles to a nation would not bring on immediate economic collapse, but it would mean disaster some fifteen or twenty years hence, for it amounts to denying the nation institutions of higher technical education. It amounts to banning physics, electronics, and biochemistry in the colleges and permitting only the arts and such science as can be gathered from the works of Archimedes, Aristotle, and other Greek philosophers. Technical-minded citizens would be forced to leave to seek citizenship where they could study. The nation would quickly lose its technical brains. Invention would come to a stop. The nation's economic status would be undermined, and within half a generation it would slip into obscurity. It would be a mere backwater dependent on nations of greater technical knowledge for its industrial supplies. To deny a nation the right to operate and study atomic piles is to deny it the right to an economic future and to condemn it to death by intellectual starvation.

Our own military men are at present so powerfully impressed with the possibilities of atomic energy for warfare that they are denying our own people the right to study and learn. Military rules and regulations have had a disastrous effect already. How hampering these regulations are can be judged from the fact that none of the major nuclear physicists originally in charge of the Manhattan Project—the men who started it and carried it through—has remained with it.

When a great scientist appears, a school of first-rate men gathers around him. Years ago Lord Rutherford became the center of such a school in England. Cockcroft and Walton were in that group; so was C. T. R. Wilson, who invented the cloud chamber. Einstein became the center of a group. Dr. Lawrence, the inventor of the cyclotron, attracted several top-notch nuclear physicists; one of them was Dr. Oppenheimer, who led the work in bomb development at Los Alamos, and another was Dr. Anderson, who discovered the positron. Science usually makes its greatest advances when such a group—a team, practically—of top-notch men work together with the right research tools.

All of the great teams that worked to invent the atomic bomb have broken up. Our nuclear physicists have returned to their own laboratories. Plainly our overzealous military men and politicians, in their anxiety to assure America the exclusive possession of atomic secrets that can't possibly remain secret very long, have forced these major scientists to give up research with the most powerful instruments. Meanwhile, other nations are giving their best researchers every facility possible. Hampering requirements of secrecy can cause trouble almost as serious as the economic disaster that would come from forbidding a nation to have atomic piles.

Psychological frictions occasion sincere and dangerous differences within a nation; with equal sincerity, but far more dangerous violence, differences of psychology can cause friction between nations. Russia, bugaboo though she is to many of our politicians, is not likely to precipitate war. Her only major needs are warm-water ports, which she will probably get peaceably, and—peace! An atomic war that would annihilate her cities is the last thing she could want. Russia is not the only conceivable troublemaker. Let's look around among the nations. Take Czechoslovakia, a small nation with limited resources and area. She has been conquered, tortured, and oppressed by various neighbors for generations. Currently she violently dislikes Germany. Czechoslovakia is only one of a number of nations that have a possible impulse—and reason—for vengefulness. Let's consider the situation of such a nation if it had a supply of atomic bombs.

If it has atomic bombs, no nation is "little" any more. Four hundred years ago, if a man five feet two did not have very good manners and a pleasant personality, some fellow six feet two killed him out of hand. Over several thousand years it has been convincingly demonstrated that a good big man can whale the tar out of a good little man any day in the week. Recently the same proposition has been given a grand test on a national scale, with the age-old answer. Germany decisively defeated a smaller nation, France, mopped up a collection of still smaller nations along the

English Channel, and then made the disastrous mistake of tackling Russia in the unfortunate delusion that Russia was a poor big nation. Japan, under a similar misconception, took on the United States. The result was as usual; the smaller nations were defeated.

As between individuals the picture was completely changed with the invention of the revolver. The "equalizer" of the old West made it possible for the slight Billy the Kid to become a major terror. A big man was now simply a bigger target; when all men were armed with revolvers, quickness of reaction counted more than size. In fact all men were suddenly reduced to the same size—the size of a revolver bullet. The atomic bomb has the same implications for nations. The principality of Monaco, if it were armed with atomic bombs, would be a far more deadly opponent than Soviet Russia without such armament. In the old West no one ever raised the question whether it was fair for a big brute of a man to shoot a little fellow—if the little man had his gun with him. The primary consideration in the atomic age will be similar. Any nation armed with atomic bombs can destroy the cities of any other nation. For a short period—probably not exceeding ten years—there will be some nations that have atomic weapons and some that do not. Thereafter all nations will be so armed.

General Groves has said that it would take twenty years for others to duplicate the work of the United States and England in making the atomic bomb. The atomic scientists say it could be done by 1949 or at least by 1952 by a nation starting about where we did. This judgment seems likely to be more accurate, though less comfortable. If Sweden—as seems quite possible—has bombs before Russia, what will be the effect on world politics?

The current United Nations organizational setup recognizes the realistic facts—of the past. It is based on the propositions that there are big nations and little nations and that big nations are bound to have powers that little nations do not. The Big Five, for example, can veto any United Nations operation against themselves, while smaller nations must take it and like it. This arrangement may not accord with an idealistic philosophy, but it does fit the facts of all past history. If the Duchy of Luxemburg doesn't like a ruling of the United Nations, there is nothing practical that Luxemburg can do about it, as things stand, in the face of the great nations of the world. On the other hand, if the United States disapproves of a United Nations ruling, the United Nations would be wise to step back and think the situation over more carefully. Only the most devastating sort of all-out war could impose a distasteful ruling on this country even if we did not have the atomic bomb in our defense armory. Russia, Britain, China, and France have been given the same preferential status we were. If Russia disapproved of a ruling, she, too, could make it excessively costly to impose a foreign will on her. The veto power simply recognizes these facts.

What is going to happen when Sweden shows up with atomic bombs? The pragmatic considerations that applied to the Big Five now apply to Sweden—or to any little nation that may develop atomic weapons ahead of the rest. Any attempt to impose a ruling on an atomic-armed nation will be impossibly costly. Suppose the ruling is simply a demand that Nation X cease an invasion of a neighboring nation's territory. Nation X may reply: "We need the room. What do you think you're going to do about it?" The logical answer would be: "Well—that's very unfair of you, but we can't sensibly do anything." If the United Nations did attack Nation X with atomic bombs, X would probably be thoroughly destroyed, but in the meantime the innocent neighbor nation would have been destroyed, too. Moreover, Nation X would certainly use as many city-annihilating atomic bombs as possible against the powers that sought to discipline it. Obviously there would be a great net loss all around.

Humanity is not logical. Just as an individual will charge a machine-gun nest, so a nation will charge to the attack against such a situation. Fear will not stop the aggressor; he wants what he wants, and he intends to take it, come hell or high water. Men have had that kind of unreasonable determination ever since cavemen developed the habit of taking bearskins away from the obviously dangerous bears that grew them. Nor will fear stop the men who are determined to have a just and decent world. Men have fought and died "for the principle of the thing" since long before the first Christian martyrs amused Rome.

So long as national sovereignty survives, the atomic-armed aggressor is going to be a constant menace. Revolvers raised the question of how to handle such egomaniacal juveniles as Billy the Kid. The atomic bomb, making it possible for nations, too, to behave like problem children, will enlarge the scale of delinquency from crime to catastrophe.

Two different levels of personal combat were recognized by different social systems in the past. The duel was respectable in many societies; the feud was also sanctioned. In some ways the duel is a fairly practical method of improving the human race; in the long run it eliminates from the racial strain individuals afflicted with bad manners, slow reactions, or stupidity. The feud is a basically different concept; it pits family against family and punishes innocent members for the mistakes or misdemeanors of any individual. War is essentially a vast expansion of the feud; for humanity as a whole it is a disaster, annihilating many innocents in order to do away with a guilty few. Atomic warfare is a further expansion of the idea, on such a scale that we must somehow rule it out completely or be ruled out ourselves. To attempt to enforce peace among the nations is simply impractical; with their atomic weapons they can laugh like a bad boy at a cranky teacher. Further, it is silly to hold a *nation* guilty. The nation doesn't declare war, or order bombings, or provoke war by moving its troops about threateningly; these things are done by individual officers of the national government. For world survival we must retreat from the present intolerable situation of national feuding to the tenable and enforceable level of the duel. Try the dangerous individual, punish the guilty individual, not the nation.

The United Nations as it now stands is incapable of preventing warfare because any national government that disagrees with a decision of the United Nations can refuse to bow to it and can bring the nation it governs into war against the world—and force the world into war. If the United Nations had existed in 1938 when Hitler was demanding the Sudetenland, it could have told him he couldn't have the Sudetenland, and he would then simply have taken Germany to war against the world. If a world government had put Hitler *as an individual criminal* on trial for attacking the peace of the world, the situation would have been profoundly different. The national honor of the German nation would not have been accused or at stake; the trial would have been that of an individual.

The only other method of attaining peace is to deny all nations the right to make war. We'll pass a law! But can we make it stick? Consider your own personal reaction to a suggestion that the United States be forced to yield up its atomic bombs, atomic bomb plants, armed forces, coastal defenses, and military establishments and turn over all military equipment of whatever nature to a world army controlled by a United Nations cabinet and executive. Such an arrangement would make the United Nations' rulings workable. What would its rulings be, once peace was assured? If the peoples of the world had democratic representation according to their numbers, this body would be controlled by two nations, China and India. With a little vote swapping in the United Nations congress, a world-wide prohibition against the eating of beef could be engineered; cattle are sacred to the multitudinous Hindus of India. Several hundred million Mohammedans might also do something about the eating of pork; the pig isn't sacred to them, but taboo, and like the W.C.T.U. they might feel it their duty to protect others from consuming something unclean.

No, we can't ask nations to give up their sovereignty—not yet, anyhow. They won't; they'll risk atomic war first and fight to make their determination stick. We'd get further faster by dropping the feud concept of international relations and returning to the individual-responsibility level.

Even the creation of a real world government would not by itself constitute a complete and permanent solution to the problems of the atomic age. Basic difficulties arise within nations whose people are essentially homogeneous as to racial background, education, and general traditions. In the United States many disputes are kept from flaring into physical warfare only by the police power of state and nation. The struggle for power that is now going on between labor management and business management—as distinct from labor and ownership, since to an increasing extent individual working men and women are acquiring the stock of the big corporations—gives a measure of the depth of internal cleavages. With the best of good will, quite violent disputes can break out.

Presumably democracy must now be the objective of all government, but what *is* democracy? Demo-cracy ought to mean the rule of the majority of the people, just as auto-cracy is the rule of an absolute monarch or a small privileged class. Democracy is heavily restricted in the United States by the Bill of Rights, which is undemocratic to the extent of assuring the individual of rights that the will of the majority cannot take from him. The rule of the majority is not unqualified in the United States. Other nations have quite different definitions of democracy and show the same human tendency as Americans to save the world for democracy as quickly as possible in the way *they* know is right. There is and always will be a great deal of truth in the classic definition of "mulish," "stubborn," and "firm": "He is mulish; you are stubborn—but I am firm."

Psychology has not yet advanced far enough to permit all men to live sane, balanced, and tolerant lives. That has not hitherto been essential to survival; in the not too distant future it may be. Men never have agreed with each other on how governments should be run, and there is no form of government whatsoever that is not desperate tyranny to some group of individuals. The thoroughgoing anarchist feels—and very genuinely—that any organized government is a cruel enslavement; a man who craves power over his fellows will regard anarchy, since it would deny him that satisfaction, as a tyrannical system! Obviously no government of any kind—or even a total absence of government—can give both of these human types their fulfilment. A really mature science of psychology, however, might be able to adjust their viewpoints to cheerful acceptance of things as they are; no government can hope to appease them both, or many other somewhat less extreme types, without the help of psychology.

The existence of malcontents and indeed uncontentables is of no great import to the world today. But it will be. The nihilistic anarchist would happily sacrifice his life in the course of annihilating the "tyrannical bureaucracy" in Washington. His spirit is willing, but the explosives he can lay hands on are weak, as yet. He can't get atomic bombs—which would do the job he feels so desperately needs doing in order to save the world as quickly as possible in the way *he* knows is right. But his intellectual or his psychoneurotic heir may be able to.

The history of human inventions shows a typical curve of progress and complexity. Inventions usually start out relatively simple and just efficient enough to function. Radio receivers are only one of many examples; the crystal set was extremely simple and barely workable. A period of development follows, during which the mechanism, whatever it is, becomes simultaneously more and more efficient and more and more complex mechanically. The theory of the device is also becoming more and more highly developed. This period is represented in radio receivers by the development of the neutrodyne receiver with three or four dials, each of which had to be individually adjusted. Then the curve of complexity reverses itself, and the apparatus grows steadily simpler and simpler in mechanical structure, while the theory advances to greater and greater heights. Radio receivers are just past the peak of that curve; the modern set with a single control that does all the tuning represents an enormous increase in simplicity.

Much the same applies to aircraft engines. The Wrights' engine was relatively simple and just efficient enough to get the plane off the ground. The fighter plane engine of 1944 represented the peak of the mechanical complexity curve—a marvelously ingenious, highly effective, and incredibly complicated way of doing something simple; that is, turning heat into motion. The jet motor of 1946 is starting down the reverse curve from complexity to a more efficient simplicity; the theory is far more complex, the knowledge of metallurgy and machine-tool design required for its production is far greater, but the mechanical structure of the thing is very nearly ultimate simplicity. There is only one moving part.

The atomic engine is at the very beginning of the curve of complexity. In the coming years it will grow far more complex than the system of uranium slugs and graphite block that we have now. Efficiency and controllability will mount; so will complexity. But the atom is the smallest unit of matter, and the essence of controlling it must be simple. When men know enough of the theory, atomic engines will be simple and easy to produce. Sooner or later—perhaps within a half century—such a degree of simplicity will have been reached that half a dozen men, working in a cave or a forgotten cellar, will be able to set up an atomic bomb.

If psychology hasn't learned how to detect and treat crackpot malcontents by that time, no large governmental unit can con-

In a cave or a forgotten cellar an atomic bomb can soon be set up.

tinue to exist on Earth. It will be equally vital to develop and apply methods of detecting unstable individuals with a tendency to commit suicide as a revenge. The "Good-bye, cruel world!" type that decides to take part of the world with him will be a menace to many others besides himself. We have just seen what devastation can be wrought by an unstable psychoneurotic who could command great destructive power. Hitler did sufficient damage. The existence of atomic power makes it inexpressibly urgent for psychology to develop techniques that can really help man obey the dictum, "Know thyself!"

Congress, in its belief that human forces are greater than atomic forces, is essentially right. But just as there are unstable radioactive atoms, so there are unstable men. We must learn how to discover and to correct those instabilities in men, and some means of making men more tolerant must be found. Professional politicians are pragmatic psychologists—they can tell with remarkable accuracy how the mass of people will react. The atomic scientists are doing all they can to show those practical psychologists the real meaning of the atomic power that has been put in their hands. Both congressmen and scientists are handicapped, for neither knows enough of the science he represents. Psychology and nuclear physics are both too new.

Further handicaps beset physicists and practical psychologists alike. The general public remains conservative to the *n*th degree. People do not want to change their ways. Yet the whole pattern of civilization we have grown up in was blasted into nonsense at Hiroshima. For all the years of recorded history big nations have had privileges that were denied to small nations. For most of recorded history big men held privileges they denied to little men. Kings owned their subjects; feudal lords owned their peasants as slaves. The development of firearms, which made the little man as deadly an opponent as the rich man who could afford armor and a horse, broke the back of the old feudal system. Technology progressed slowly in those days; the concept of an inventor—a man who made a business of thinking up new and better ways of doing things—hadn't been invented itself. It took a long time to change a world of feudalism into a world of personal liberties wherein every man had a right to self-respect and the respect of his neighbors. Technology advances enormously faster these days. In the period of a single generation's memories we have come from a wingless era of horse-drawn transportation to one of rocket ships, radar beams, and jet-propelled planes.

Within a period that a child born in 1935 will be able to remember, we may very probably see a total reorganization of the pattern of civilization. In one way or another the concept of nationalism must be broken down and dissolved away. Either a world state or city states such as the ancient Greeks knew may emerge. In recent centuries the small state became impractical and could exist only as a tolerated pet of some great state, for no small state could defend itself against powerful enemies. In just the same way the little man used to exist as the serf of a feudal lord who defended him against other feudal lords, because the little man could not defend himself. When the little man found a weapon—the gun—that permitted him to defend himself against the armored knight, individual liberties came. Perhaps atomic weapons will lead to an era of self-respecting, mutually respected small states. Perhaps they will lead to a world state. In either case the rate of progress of technology—and it is the forces of technology that are bringing the change—advance so rapidly that the next fifty years should set the pattern, the new pattern of a new civilization.

The instinctive reaction of any man is to dislike the idea of profound shifts. The "American way of life" is going to be changed, and because men inherently dislike and distrust the unknown, the reaction is: "No! I like it this way. Change can only make it worse!" What we want does not matter. The forces of technology, politics, human aspiration, economics, everything that affects the pattern of civilization, are at work. Change will come. Our people have just completed a mighty effort, fighting to preserve that "American way of life." In the course of the effort atomic weapons were developed, and they simply speed the time when the pattern of life must be profoundly changed. The men who fought in the Spanish-American War fought for an American way of life—and look what's happened to it! The introduction of the automobile, the motion picture, and the radio have given the nineteenth-century pattern a twist toward a new direction. Does anyone seriously mourn the days when there were no X-rays to aid surgeons, dentists, and cancer therapists, no sulfa drugs or penicillin? The next half-century will see the pattern changed even more violently, for the technological forces are greater now, backed by the power of the atom.

There are two great tasks for the next half-century:

We must learn more about atomic forces.

But we'd be wise if, first, we learned more about man—the one greater force that can twist atomic energies to its will.