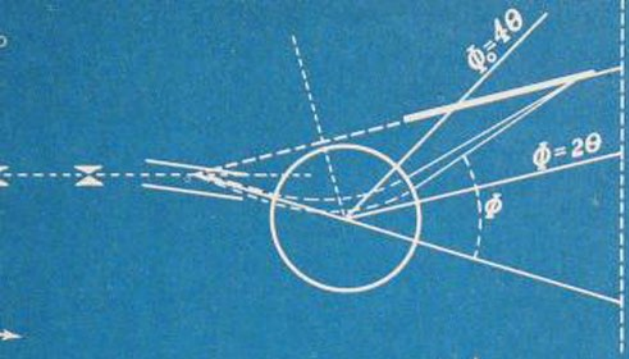
our friend the ATOM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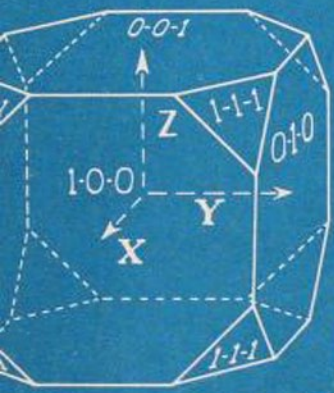
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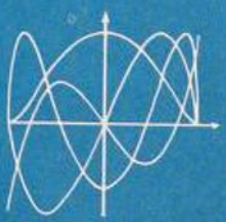

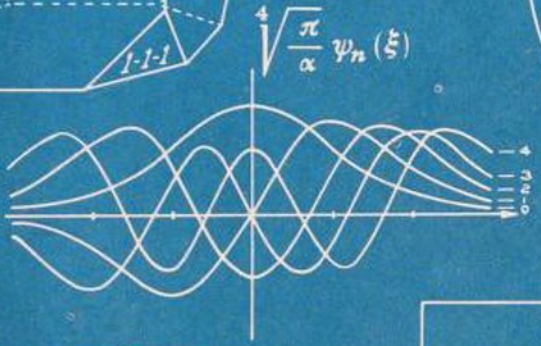
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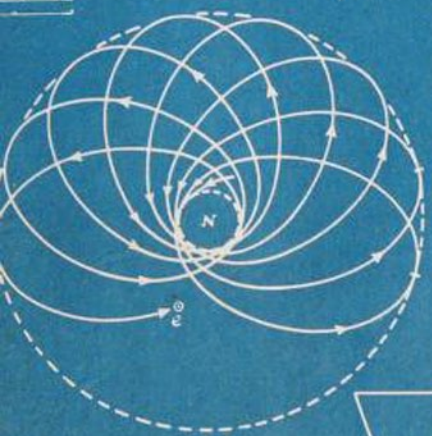
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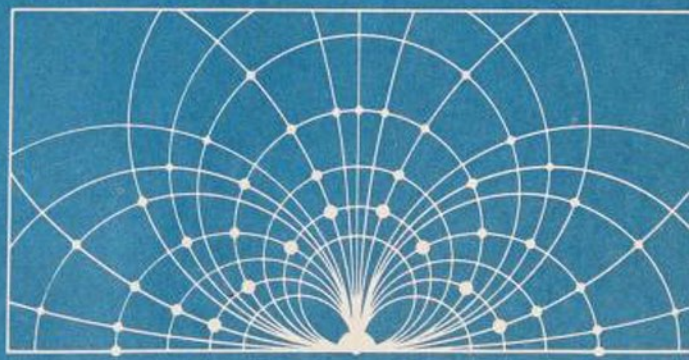

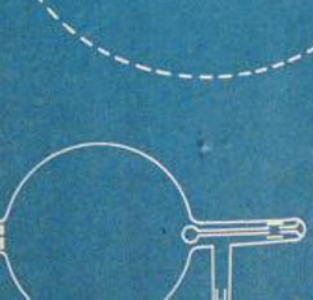

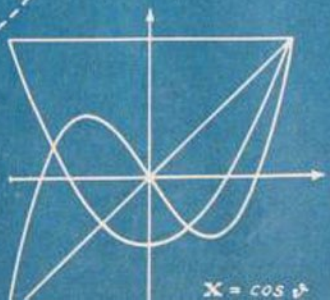
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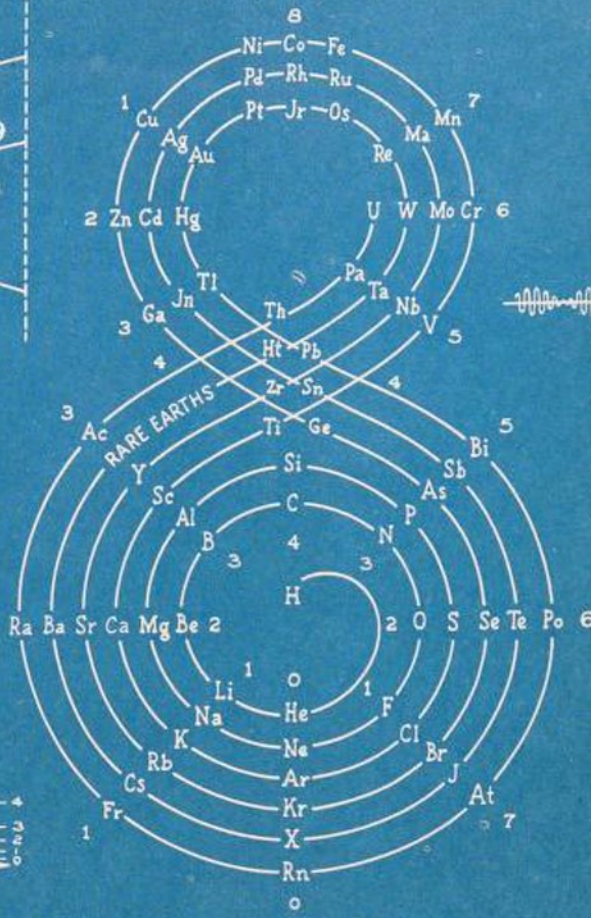
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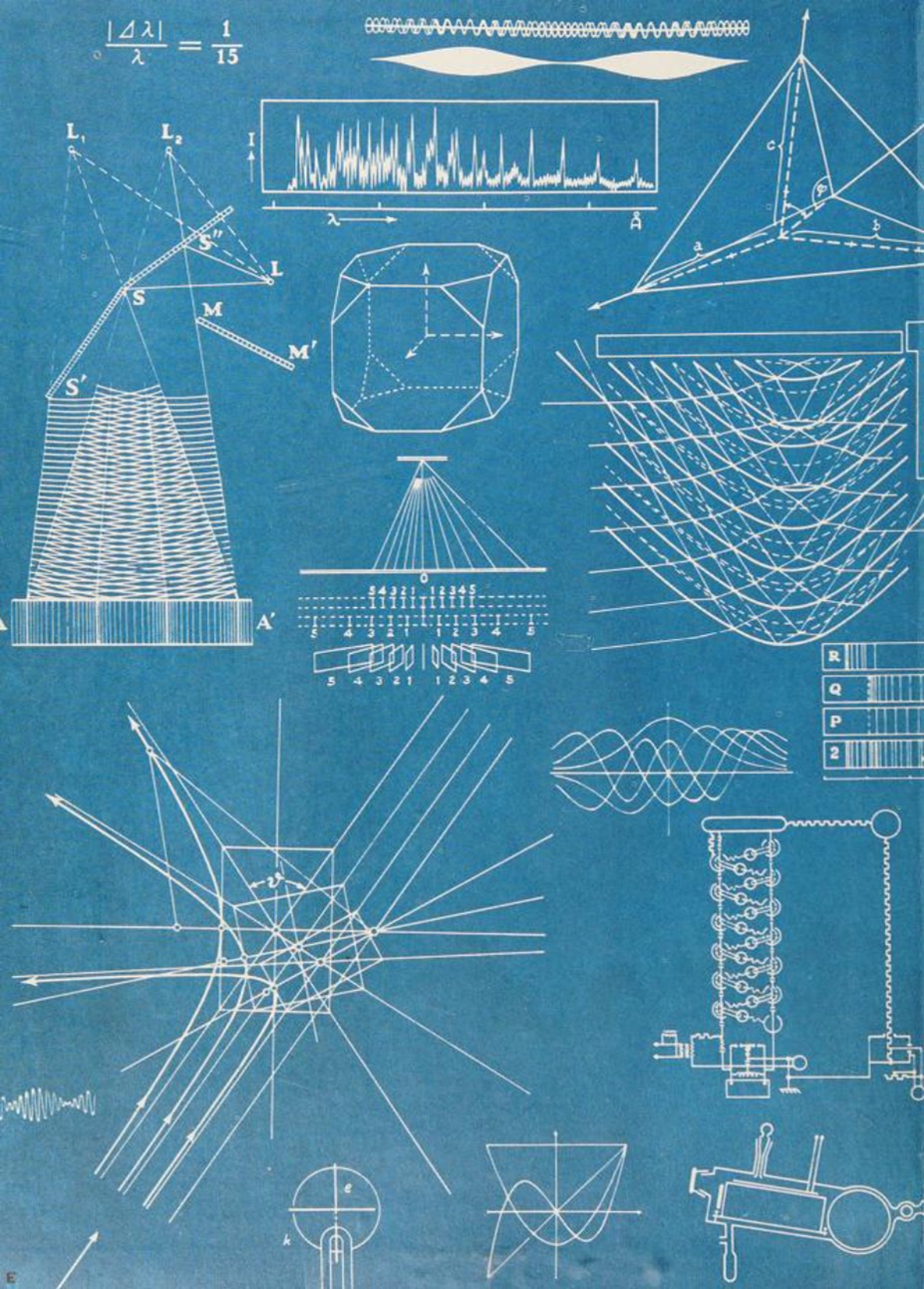
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our friend the ATOM

THE WALT DISNEY STORY OF

our friend the ATOM

by Heinz Haber

SIMON AND SCHUSTER • NEW YORK

The illustrations in this book are by the following
Walt Disney Productions staff artists:

Claude Coats
John Hench
Paul Hartley
Bill Layne
Bill Bosché
Anne Siberell
Frank Armitage
Don Peters
Dick Ung
Collin Campbell
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Jay Gould

Art Direction: Paul Hartley

FOREWORD

FICTION often has a strange way of becoming fact. Not long ago we produced a motion picture based on the immortal tale *20,000 Leagues under the Sea,* featuring the famous submarine "Nautilus." According to that story the craft was powered by a magic force.

Today the tale has come true. A modern namesake of the old fairy ship—the submarine "Nautilus" of the United States Navy—has become the world's first atom-powered ship. It is proof of the useful power of the atom that will drive the machines of our atomic age.

The atom is our future. It is a subject everyone wants to understand, and so we long had plans to tell the story of the atom. In fact, we considered it so important that we embarked on several *atomic projects*.

For one, we are planning to build a Hall of Science in the TOMORROWLAND section of DISNEYLAND where we will—among other things—put up an exhibit of atomic energy. Then, our *atomic projects* at the Walt Disney Studios were two-fold: we produced a motion picture and this book, so that we could tell you this important story in full detail. Both grew together. Many illustrations appear in both, and we gave them the same title: *Our Friend the Atom*.

With our *atomic projects* we found ourselves deep in the field of nuclear physics. Of course, we don't pretend to be scientists—we are story tellers. But we combine the tools of our trade with the knowledge of experts. We even created a new Science Department at the Studio to handle projects of this kind. The story of the atom was assigned to Dr. Heinz Haber, Chief Science Consultant of our Studio. He is the author of this book and he helped us in developing our motion picture.

The story of the atom is a fascinating tale of human quest for knowledge, a story of scientific adventure and success. Atomic science has borne many fruits, and the harnessing of the atom's power is only the spectacular end result. It came about through the work of many inspired men whose ideas formed a kind of chain reaction of thoughts. These men came from all civilized nations, and from all centuries as far back as 400 B.C.

Atomic science began as a positive, creative thought. It has created modern science with its many benefits for mankind. In this sense our book tries to make it clear to you that we can indeed look upon the atom as our friend.

PROLOGUE

DEEP in the tiny atom lies hidden a tremendous force. This force has entered the scene of our modern world as a most frightening power of destruction, more fearful and devastating than man ever thought possible.

We all know of the story of the military atom, and we all wish that it weren't true. For many obvious reasons it would be better if it weren't real, but just a rousing tale. It does have all the earmarks of a drama: a frightful terror which everyone knows exists, a sinister threat, mystery and secrecy. It's a perfect tale of horror!

But, fortunately, the story is not yet finished. So far, the atom is a superb villain. Its power of destruction is foremost in our minds. But the same power can be put to use for creation, for the welfare of all mankind.

What will eventually be done with the atom? It is up to us to give the story a happy ending. If we use atomic energy wisely, we can make a hero out of a villain.

This, then, is the story of the atom. It is a story with a straightforward plot and a simple moral—almost like a fable. In many ways the story of the atom suggests the famous tale from the *Arabian Nights:* "The Fisherman and the Genie." Perhaps this tale even hints at what lies in our atomic future. . . .

The Fisherman and the Genie

THERE ONCE *lived an aged Fisherman, who dwelt in poverty with his wife and three children. Each day he cast his net into the sea four times, and rested content with what it brought forth.*

One day, after three vain casts, the old Fisherman drew in his net for the fourth time. He found it heavier than usual. Examining his catch, he found among the shells and seaweeds a small brazen vessel. On its leaden stopper was the ancient seal of King Solomon.

"A better catch than fish!" he exclaimed. "This jar I can sell. And who knows what thing of value it might contain?"

With his knife he pried out the stopper. Then, as he peered into the jar, smoke began to pour from it. He fell back in astonishment as the smoke rose in a great dark column and spread like an enormous mushroom between earth and sky. And his astonishment turned into terror as the smoke formed into a mighty Genie, with eyes blazing like torches and fiery smoke whirling about him like the simoom of the desert.

"Alas!" cried the old Fisherman, falling to his knees. "Spare me, O Genie. I am but a poor man, who has not offended thee!"

The Genie glared down on the trembling old man.

"Know," he thundered, "that because thou hast freed me, thou must die. For I am one of those condemned spirits who long ago disobeyed the word of King Solomon. In this brazen vessel he sealed me, and he commanded that it be cast into the sea, there to lie forever—or until some mortal should, by unlikely chance, bring up the vessel from the depths and set me free."

The old Fisherman listened in silent fear as the Genie's eyes flamed.

"For centuries," the great voice of the Genie continued, "I lay imprisoned deep in the sea, vowing to grant to my liberator any wish—even to make him master of all the wealth in the world, should he desire it. But no liberator came. At last, in my bitterness, I vowed that my liberator, who had delayed so long, should have no wish granted him—except how he should die. Thou, old man, art my liberator, and according to my solemn vow thou must die!"

"O," wailed the Fisherman, "why was I born to set thee free? Why did I cast this net and bring forth from the deeps this accursed vessel? Why must thou reward me with death?"

The fiery smoke swirled more swiftly about the Genie, and he gestured with impatience.

"Fisherman," he roared, "delay not, but choose how thou wilt die!"

The old Fisherman was terrified indeed. Yet in this moment of danger he was able to bestir his wits.

"O Genie," he begged, "if I must die, so be it. But first grant me this one wish. Thy great form did seem to come forth out of this little vessel, and yet I cannot believe it. Prove to me that one who is so mighty can indeed fit into such a little vessel."

The Genie towered above the little fisherman. His eyes blazed brighter.

"Old man," he thundered, "thou shalt see, before thy death, that nothing lies beyond my powers."

Swiftly the Genie dissolved into smoke, and the smoke funneled back into the little vessel.

Instantly the Fisherman leaped forward and thrust the leaden stopper, bearing the seal of King Solomon, into the jar.

"Now," he shouted to the imprisoned Genie, "choose how thou, in thy turn, wilt die! A prisoner thou art again, and back into the depths will I fling thee. All fishermen, and their children, and their children's children, shall be warned of the wicked Genie and forbidden ever to cast their nets here. And at the bottom of the sea shalt thou lie forevermore!"

The Genie's agitated voice sounded faintly through the brazen vessel. "Stop, stop! Only set me free once more, and thou shalt live!"

The Fisherman raised the vessel to cast it into the waves. "O Genie," he said, "only when I cast thee back into the sea shall I be safe."

The voice in the little vessel grew frantic. "Fisherman, hear me! Live thou shalt, and richly! Restore my freedom and I vow, by Allah, to grant thee three wishes, to make thee rich and happy all thy days. Good Fisherman, hear my solemn vow!"

The old man had little heart for revenge, and he bethought himself of what a friendly Genie might do for his ragged, hungry family. The Genie continued to entreat him for mercy. And at last the Fisherman pried out the stopper.

Once more the smoke poured forth, and again the giant form of the Genie loomed against the sky. With a great kick, the Genie sent the brazen vessel spinning far out over the waves.

The old Fisherman trembled, fearing the worst. But the Genie turned toward him, and bowed his towering form, and spoke gently.

"Fear not," he said. "You heard my vow. O Fisherman, my master, name thy three wishes. . . ."

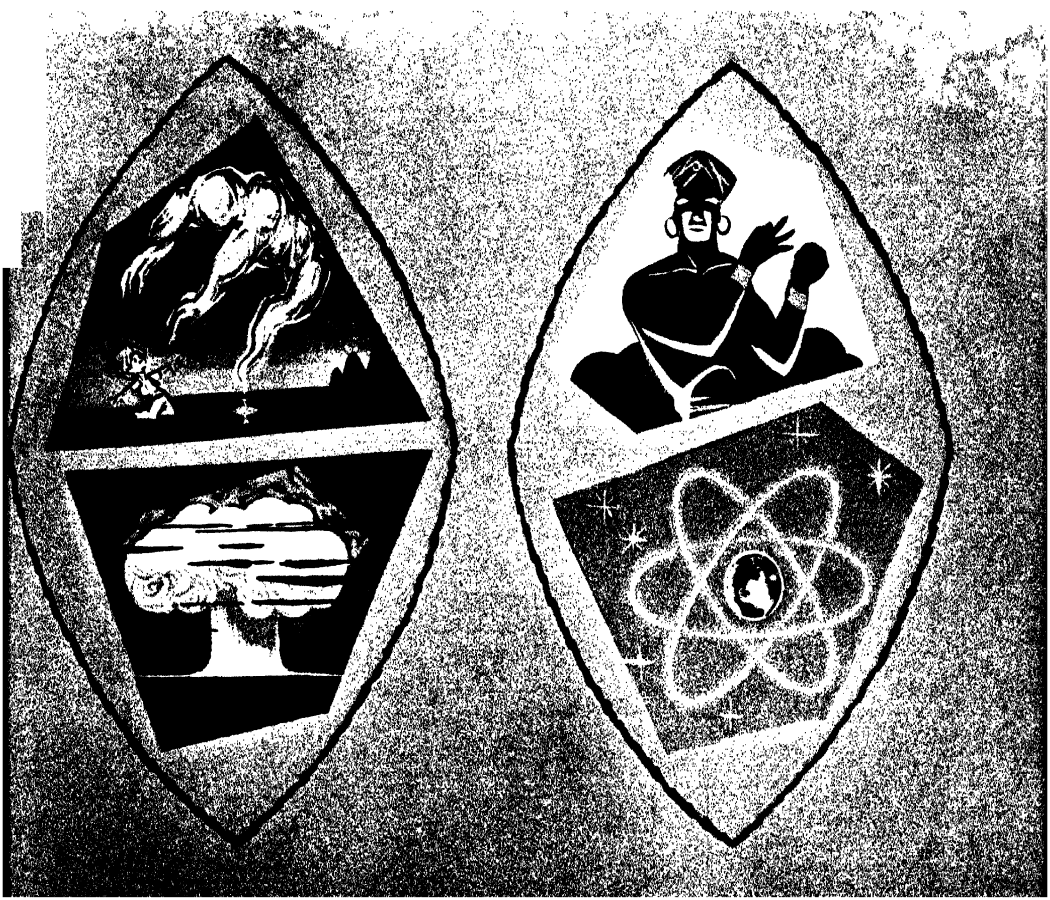
THIS FABLE tells of the age-old wish of man to be the master of a mighty servant that does his bidding. But to us it has a still deeper meaning: the story of the atom is like that tale; we ourselves are like that fisherman. For centuries we have been casting our nets into the sea of the great unknown in search of knowledge. Finally a catch was made: man found a tiny vessel, the atom, in which lies imprisoned a mighty force—atomic energy.

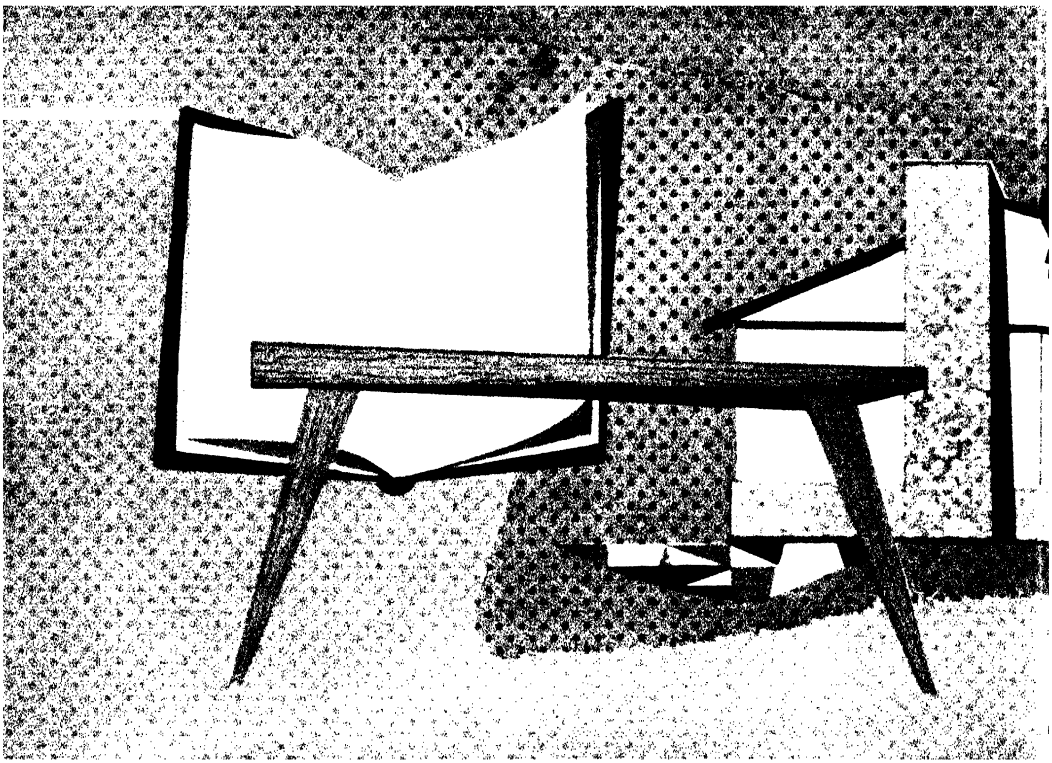
Like the fisherman, man marveled at his strange find and examined it closely for its value. He pried it open—split it in two. And as he did so a terrible force was released that threatened to kill with the most cruel forms of death: death from searing heat, from the forces of a fearful blast, or from subtly dangerous radiations.

And as it was to the fisherman, it is to us a great, an almost unbelievable marvel that such a tremendous force could dwell in such a tiny vessel.

Here we are, we fishermen, marveling and afraid, staring at the terrifying results of our curiosity. The fable, though, has a happy ending; perhaps our story can, too. Like the Fisherman we must bestir our wits. We have the scientific knowhow to turn the Genie's might into peaceful and useful channels. He must at our beckoning grant three wishes for the good of man. The fulfillment of these wishes can and will reshape our future lives.

So this is our story: how the atomic vessel was discovered, how man learned of its many marvelous secrets, how the atomic Genie was liberated, and what we must do to make him our friend and servant.

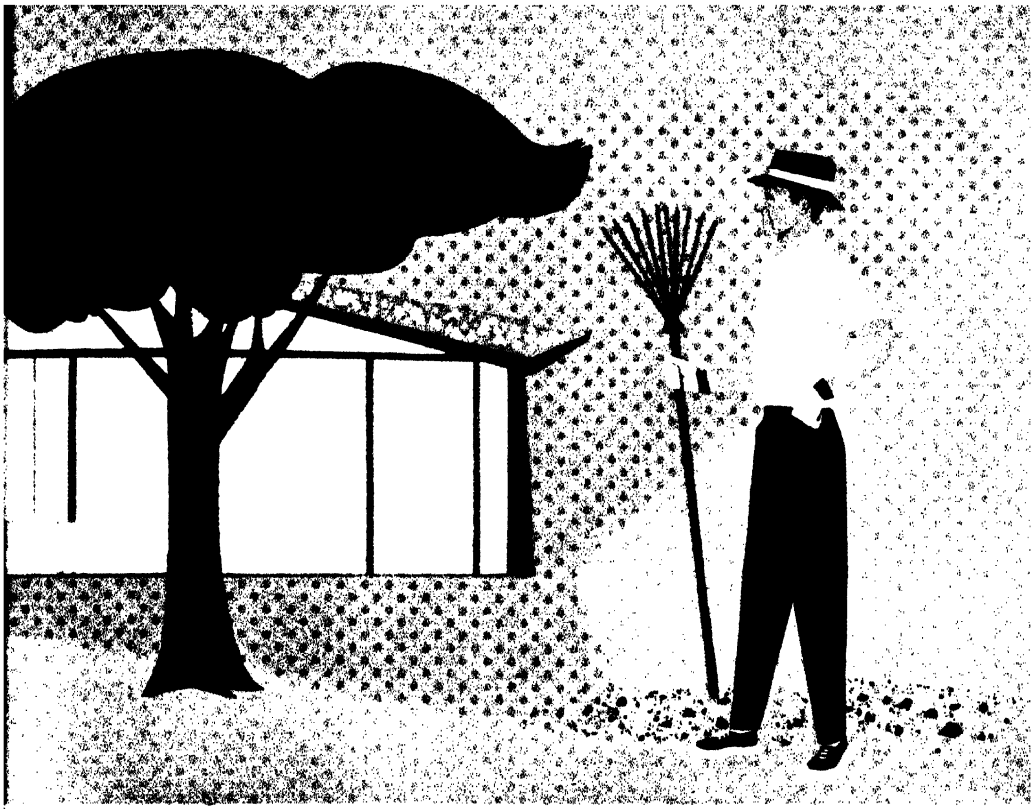




ATOMS EVERYWHERE

ONE DAY in August 1945 the world suddenly became conscious of the atom. This was the beginning of what is now known as the "atomic age." Before that day, the atom had led a rather obscure and quiet life in the textbooks of physics and chemistry, and nobody except scientists cared much about it. Many people didn't even know of the atom's existence—until that day in 1945 when a frightful flash burned the word "atom" into the mind of modern man.

Like the vessel the Fisherman of our fable had found, the atom had lain in the sea of the unknown for a long time. In fact, the atom had been in existence long before man himself, and even before the birth of the earth on which he lives. For eons the atom had been the chief actor on the



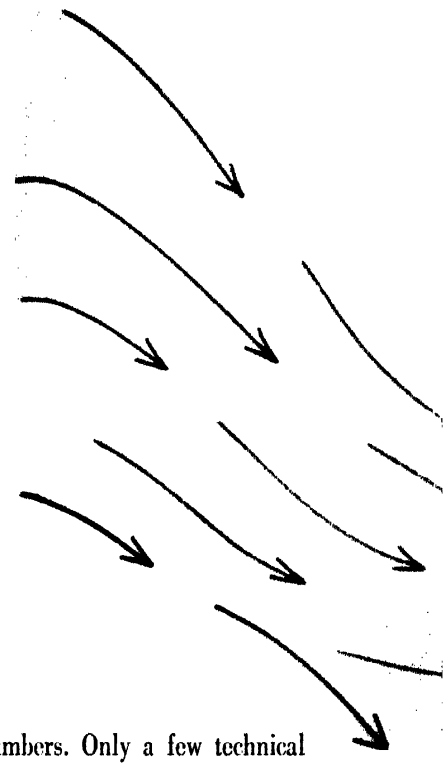
Everything around us is composed of atoms

stage on which the drama of the universe is in continuous performance.

Everything around us is entirely composed of atoms: the paper of the book you are reading, the table in front of you, your house, the trees—yourself, and the very air you breathe. Everything is composed of those absolutely invisible, extremely small particles.

Because atoms are so very small, their number must be extremely large. Consider how many atoms there are in a breath of air. Under normal conditions a human being inhales and exhales about one pint of air with every breath. This means that about 16 times in every minute you are inhaling and exhaling no less than 25,000,000,000,000,000,000,000 atoms!

The number of atoms in a breath of air is 25 with 21 zeros. This number is so big that it doesn't have a simple name. We use a composite name: twenty-five thousand billion billion.

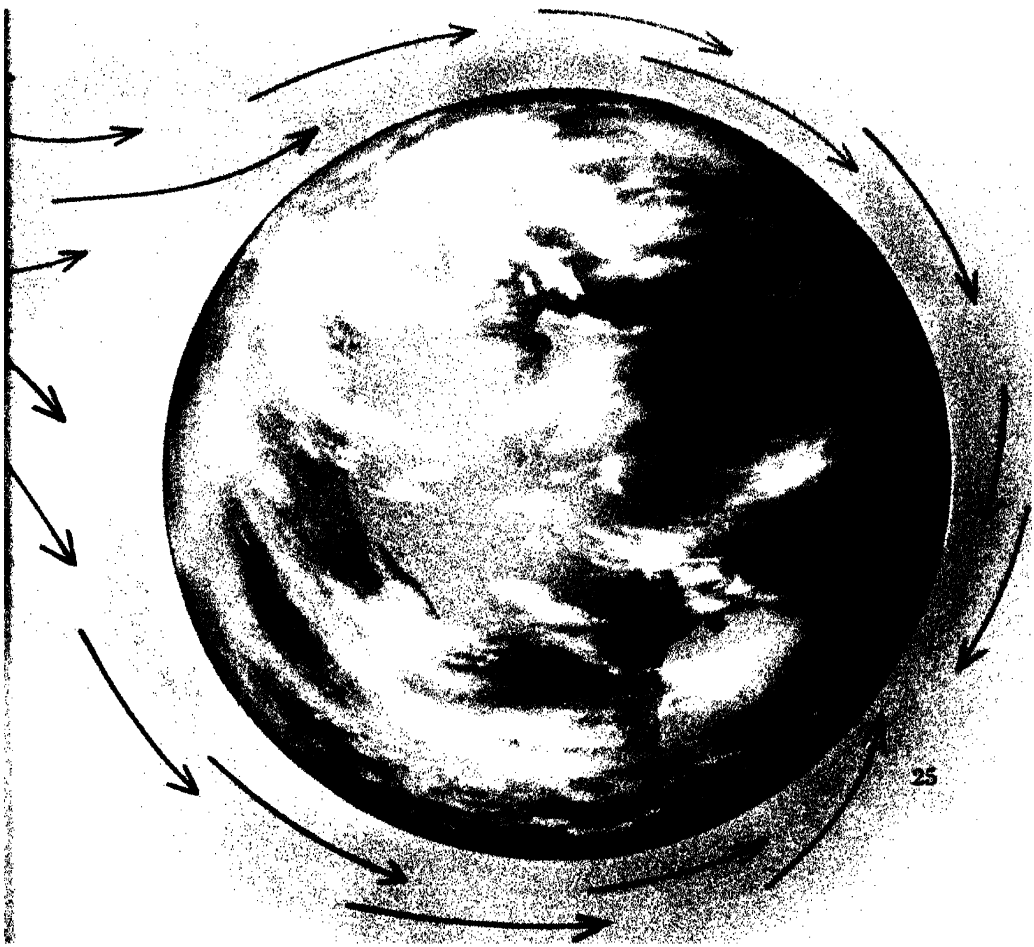


There is no way of grasping such big numbers. Only a few technical people are used to dealing with them. A number of this size must be broken down if we want to bring it closer to our understanding. Let's try this with an example—an example based on a wild idea.

Leonardo da Vinci, the famous artist and scientist of the Italian Renaissance, was 67 years old when he died in 1519. During these 67 years of his life he was breathing about 16 times in every minute, at the rate of about 25,000,000,000,000,000,000,000 atoms a breath. In his lifetime he must have pumped a tremendous grand total of atoms through his lungs. Now then, is there a chance that every once in a while you, in the twentieth century, inhale an atom that once passed through the lungs of Leonardo da Vinci?

The answer is this: In every single breath of yours there are no less than 2 billion atoms that were once breathed by this great man!

This is a fabulous, almost frightening result, but it is substantially true. The entire air of the earth has undergone thorough mixing since Leonardo's time. Storms, updrafts, hurricanes, trade winds have carried Leonardo's atoms all over the earth in all directions. Of course, Leonardo didn't breathe a whole new set of atoms with every new breath; in closed rooms, for example, he often re-breathed atoms that had been in his lungs once or even many times before. To be on the safe side, therefore, let's say that in each breath of Leonardo's only one out of 20 atoms was one that never before had been in his lungs. Even so, with every breath you take today, you inhale 100 million atoms that were once breathed by Leonardo da Vinci!



This example is possible only because atoms are permanent and indestructible. The few exceptions are so rare that we can disregard them here absolutely. So the atoms once breathed by Leonardo still exist. They are all around us in great numbers. And, of course, these atoms existed a long time before Leonardo's century. Being once in the lungs of this great man was just one insignificant event in the long life of one of these atoms—one single event in its life of billions of years.

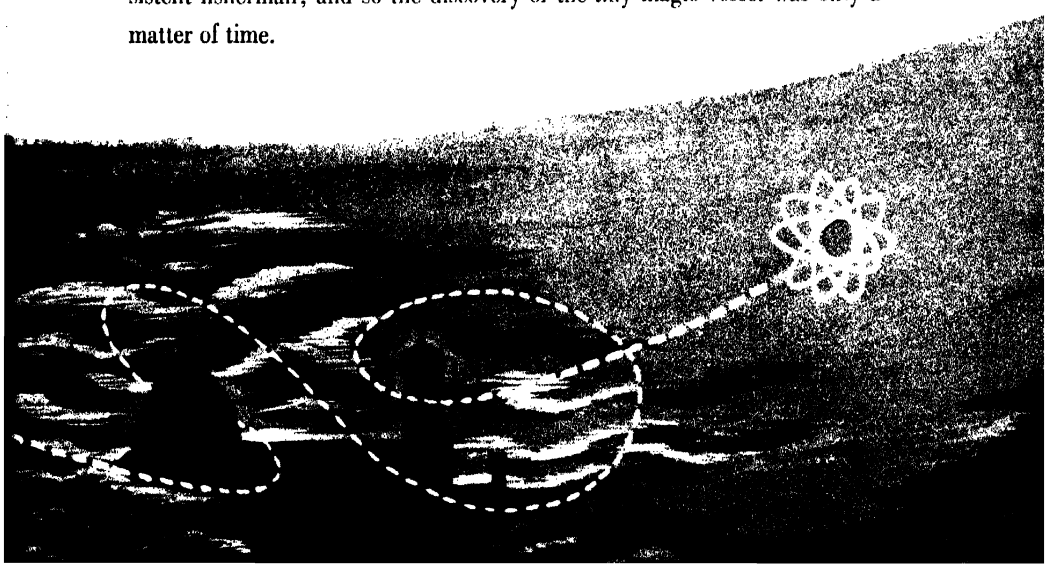
Like other atoms, this atom was probably created between 4 and 5 billion years ago. Many scientists believe that all atoms of which the planets, stars, and galaxies are built were created in a giant explosion that took place this long ago. Our atom was probably among them. For countless millions of years it drifted through the vast spaces of the universe. In the course of time, galaxies, stars, and planets formed. Our atom became part of a giant whirlpool of dust and gas that later was to develop into our solar systems. In this whirlpool full of smaller whirlpools our atom eddied around and around—thousands of millions of times. It still keeps whirling around, even today. For our atom got caught in a stream of matter that became part of the earth,

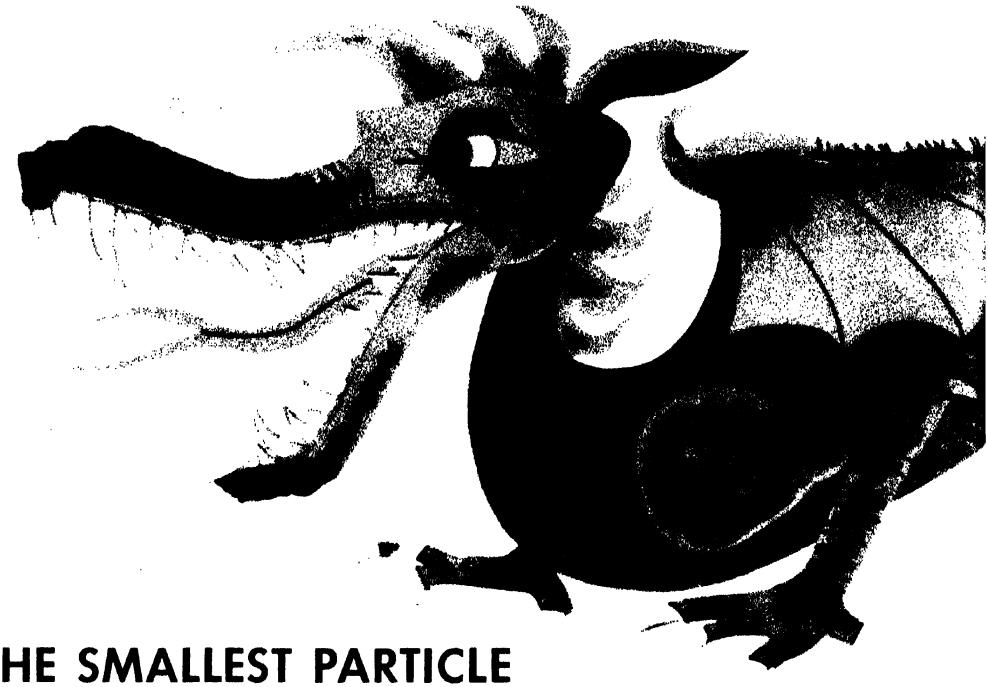
and, as everyone knows, the earth spins around its own axis, and at the same time it swings around the sun. Our atom, being part of this planet, still keeps whirling along at a dizzying pace.

Originally, our atom was caught inside the earth's crust. It rested there for millions of years before it reached the surface. Finally it was spewn forth from the depths in a prehistoric eruption of a volcano. Since that time it has spent most of its time in the air. Every so often it has lodged in the body of some kind of life form, only to be released back into the air after a period of captivity. More than 450 years ago it happened to drift around the city of Florence, Italy, and Leonardo da Vinci inhaled it. After a short while the atom was again expelled, and once more it began to tumble around all over the planet. Right now it happens to be close to you, and you are about to inhale it with your next breath.

What a history! But there is one more thing to be said about that atom—something even more marvelous than the countless numbers and almost unbelievably small size of the atoms that make up the universe. Our atom, like every other one, holds a secret—the secret of a tremendous force hidden in its tiny body. This energy is the Genie of our fable.

The release of the atomic Genie has been one of the most momentous achievements in the history of Western man. The achievement itself has had a long history. Before scientists learned of the energy of the atom, they had to find out about its parts and its architecture. And before this, the atom had to be discovered. No easy task, considering its smallness! But man is a persistent fisherman; and so the discovery of the tiny magic vessel was only a matter of time.



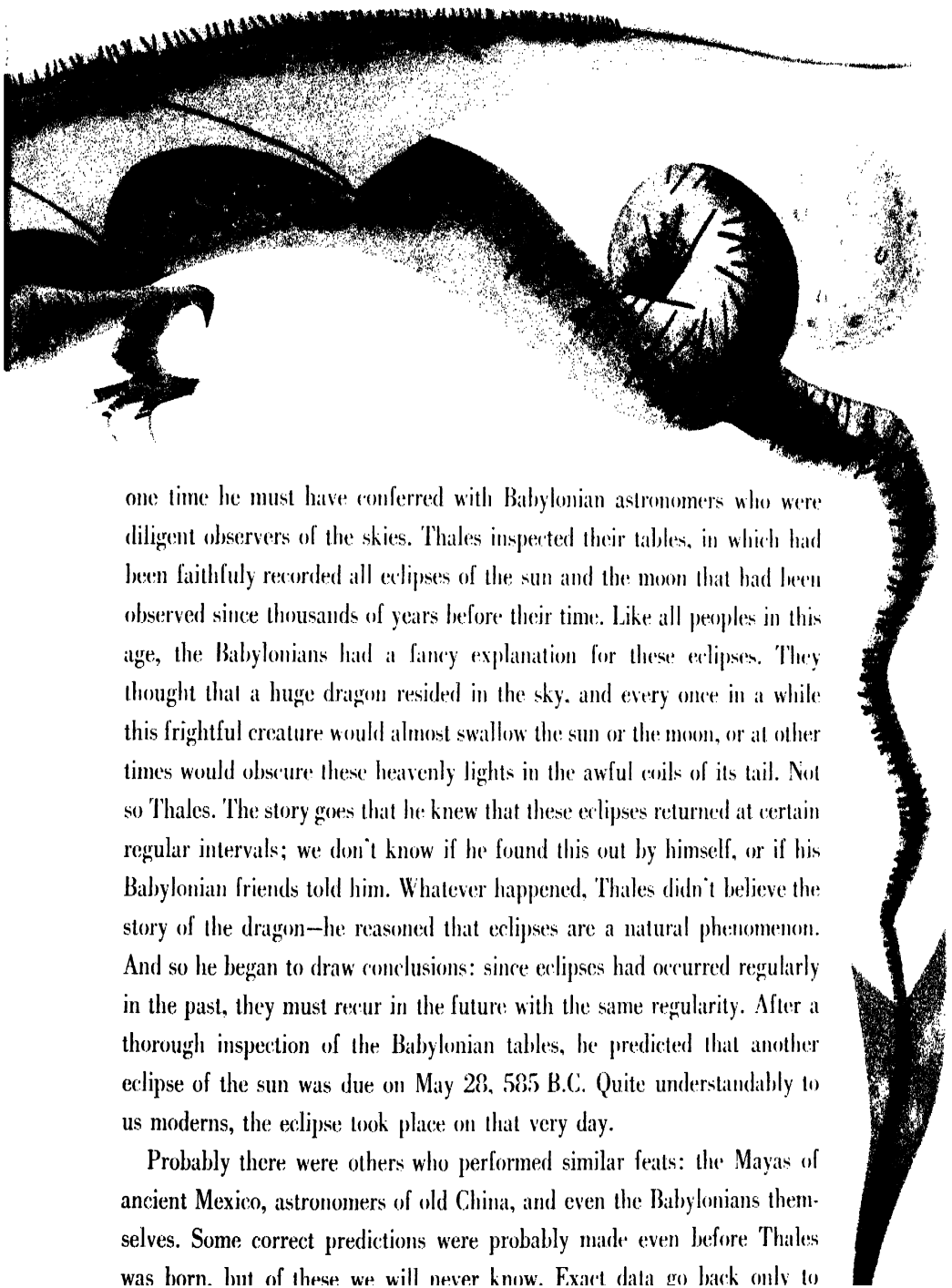


THE SMALLEST PARTICLE

KNOWLEDGE of the atom is something that belongs to our own time. It is a new and modern thing; the atom meant little or nothing to people who lived only a generation ago. But actually the idea of the atom is quite old—amazingly old. The first man we know of who thought of the atom lived more than 2,300 years ago. He belonged to a group of philosophers who, centuries before the birth of Christ, began to reason about the world around them. They were the famous philosopher-scientists of ancient Greece.

Before these men were born, it was thought that everything in the world was the work of gods, genies, and demons of all kinds. Most were obviously quite unfriendly, and man looked upon them with awe and superstition. The Greek thinkers, however, began to reason systematically. They refused to be frightened by superstition. They used logic and tried to understand and explain Nature and her laws. In fact, these philosophers were the very first who reasoned that there is such a thing as a law of Nature that a reasoning mind can detect and understand.

This enlightened period in the history of man began with the great Thales of Miletus, a city in Asia Minor. Thales was one of the first of the Greek philosopher-scientists. During his lifetime he traveled a good deal, and at



one time he must have conferred with Babylonian astronomers who were diligent observers of the skies. Thales inspected their tables, in which had been faithfuly recorded all eclipses of the sun and the moon that had been observed since thousands of years before their time. Like all peoples in this age, the Babylonians had a fancy explanation for these eclipses. They thought that a huge dragon resided in the sky, and every once in a while this frightful creature would almost swallow the sun or the moon, or at other times would obscure these heavenly lights in the awful coils of its tail. Not so Thales. The story goes that he knew that these eclipses returned at certain regular intervals; we don't know if he found this out by himself, or if his Babylonian friends told him. Whatever happened, Thales didn't believe the story of the dragon—he reasoned that eclipses are a natural phenomenon. And so he began to draw conclusions: since eclipses had occurred regularly in the past, they must recur in the future with the same regularity. After a thorough inspection of the Babylonian tables, he predicted that another eclipse of the sun was due on May 28, 585 B.C. Quite understandably to us moderns, the eclipse took place on that very day.

Probably there were others who performed similar feats: the Mayas of ancient Mexico, astronomers of old China, and even the Babylonians themselves. Some correct predictions were probably made even before Thales was born, but of these we will never know. Exact data go back only to

the first time when the light of the sun was blotted out temporarily by the moon.

Around 465 B.C., about 80 years after the death of Thales, the philosopher Democritus was born in Abdera, a little town in Thrace, a province of ancient Greece. To the best of our knowledge, Democritus was the first to think of the atom. Some historians believe that still another philosopher, Leucippus, had the idea of the atom as early as 500 B.C.; but Democritus of Abdera went far beyond expressing just an idea. He developed a full atomic theory which later turned out to be a fabulously clear foresight of many detailed facts discovered by modern science. Democritus has justly been called the father of the atom.

We don't know how Democritus explained his atomic theory to his disciples. In those days, discourse and argument were a great art, and each philosopher had a number of devoted students. The ancient Greeks loved to walk while they indulged in their arguments. So Democritus sometimes might have led his students to the coast of the Mediterranean for a demonstration of his ideas. He might have picked up a clod and said:

> "Look here, if I crumble this clod in my hands, I get smaller clods. Now I rub one of these smaller clods between my fingers, and what I get is fine dust. Let's inspect this dust on my fingers more closely. It consists of small particles that we can barely see. Next, I rub this dust still more, with the result that my fingers become powdery. This powder must also consist of small particles —too small for the human eye to see.
>
> "Now, I contend that these tiny powder particles can be rubbed down to still smaller ones, and these, in turn, can be reduced further to yet smaller particles. If I go on in this fashion, I shall finally come to an end. Then I shall have reduced matter to its smallest particles, which cannot be broken down any further. These smallest, indivisible particles I call 'atoms.' "

It was Democritus who gave us the word "atom"; that is, he used the Greek word *atomos*, which means something that cannot be cut.


ΔΗΜΟΚΡΙΤΟΣ

"See," Democritus might have continued, "how this beach appears to be a solid carpet. But on closer inspection we see that it is composed of millions of grains of sand. If we think of grains of sand as atoms and pack them together, they can be molded into any desired form.

"It is in this way that Nature uses her atoms to build all things . . . the earth—the water—air and fire."

Democritus saw the universe as a vast void in which the atoms reside. The atoms themselves are thought to be created eternally; they are indestructible and of indivisible hardness. They are absolutely full and incompressible. The atoms themselves remain forever unchanged; but through their incessant motion and ever-changing arrangements among themselves they weave the colorful tapestry of the physical world.

Then Democritus might have explained the nature of solid metals, the liquid water, the gaseous air. Such was his remarkable insight into the true nature of things.

There are many different kinds of atoms, Democritus told his students: little smooth spheres, sharp-edged cubes, and irregular ones with rough surfaces. If a mass of rough atoms are packed together closely, they will stick to each other, and it becomes almost impossible to tear them apart. This would explain the toughness of metals, and why most of them can be cut only with great difficulty.

Other atoms are smooth and heavy, like highly polished balls of steel. If they are heaped upon each other in great numbers, they begin to slide freely over one another because there is hardly any friction between them. This mass of atoms would then be fluid, like—water! This would

explain the heaviness of water and, at the same time, it would account for its easy fluidity.

Again, other kinds of atoms are both light and smooth. They float about freely, moving constantly in all directions. A large mass of such atoms would give us the fleeting air and the wavering flames of fire.

When he envisioned his atoms, there was one thought foremost in the mind of Democritus. The atoms themselves stood for permanence and eternal stability. They represented a universal, unchanging law of nature. But there was also everlasting change in the world of atoms. They were ever active, rearranging themselves in new designs and patterns, only to break up again in search of new arrangements. This everlasting change included man himself. Democritus taught that a human being undergoes constant change: when he breathes he inhales new atoms which become fixed in his body, replacing others that are expelled with the air he exhales. In this way man himself becomes part of the everlasting change that makes the world.

All these thoughts and explanations are truly prophetic. With a few small qualifications the theories of Democritus can serve as an excellent introduction to a book on modern atomic physics or chemistry.

Despite their brilliant clarity, the ideas of Democritus became lost, or almost so. His writings vanished, and only a few fragments of his teachings were relayed through the centuries. But there was another reason why the atomic theory of Democritus was forgotten, and stayed forgotten for a long, long time. This reason was Aristotle.

The philosopher Aristotle was born in the year 384 B.C., when Democritus was still alive. Aristotle did not believe in the

existence of the atom. He used, instead, arguments of the following sort:

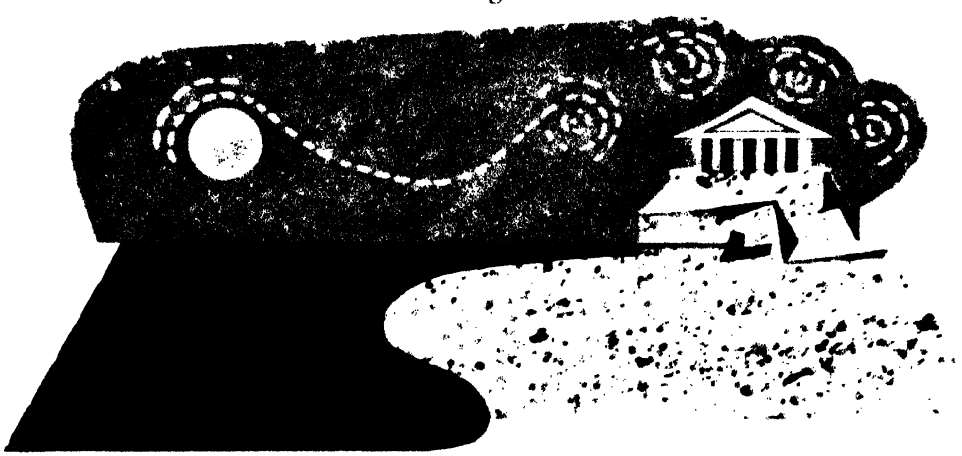
"If air and fire consisted of small, solid particles—how could they rise? They would fall to earth like a shower of pebbles!"

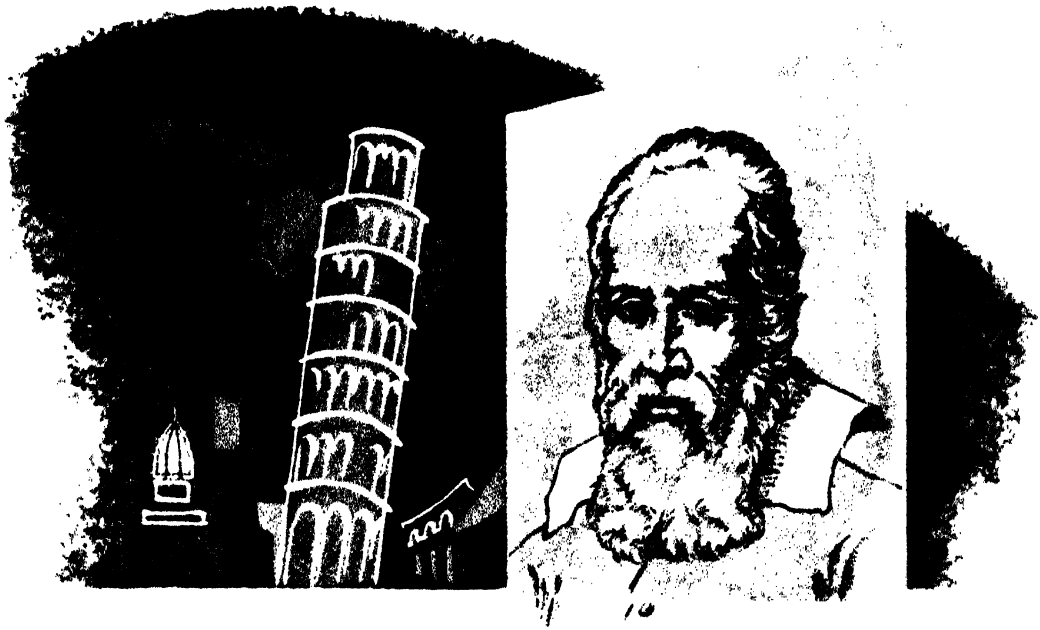
To explain the nature of the universe, Aristotle used simple elements. Unlike the atoms, the basic elements of Aristotle were visible to the eye and noticeable to the touch. To him there were four qualities: hot, cold, moist, and dry. Earth, for example, was cold and dry, water was cold and moist, air was hot and moist, and fire was hot and dry. If something was moist, it was so not because it contained atoms of a liquid as Democritus had taught; to Aristotle something was moist simply because it contained "moisture."

These explanations were disarmingly simple and compelling. Hot, cold, moist, and dry—earth, water, air, and fire: these were homely, everyday terms that did not require any abstract thinking like Democritus' atoms. Aristotle explained things by themselves—their true nature could be seen with one's own eyes and they could be felt with one's own hands.

Such was the basis of the philosophy of Aristotle. Of course, the whole system of his thoughts was complicated enough, but the premises of his philosophy were simple and appealing. His ideas governed the mind of man for almost 2,000 years.

Democritus and his atoms were forgotten.





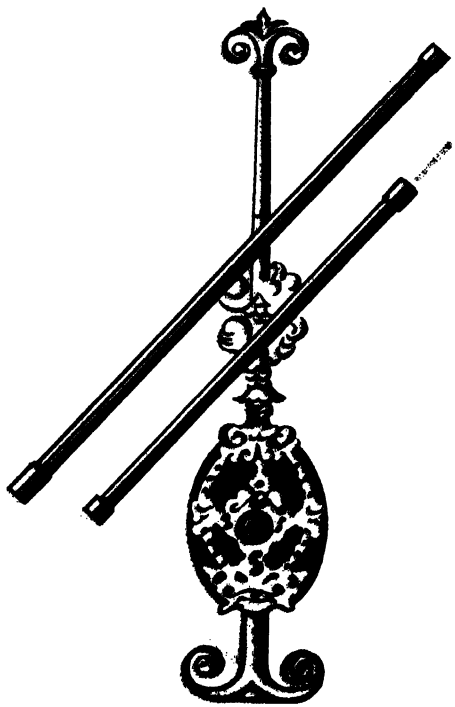
NEW VISTAS

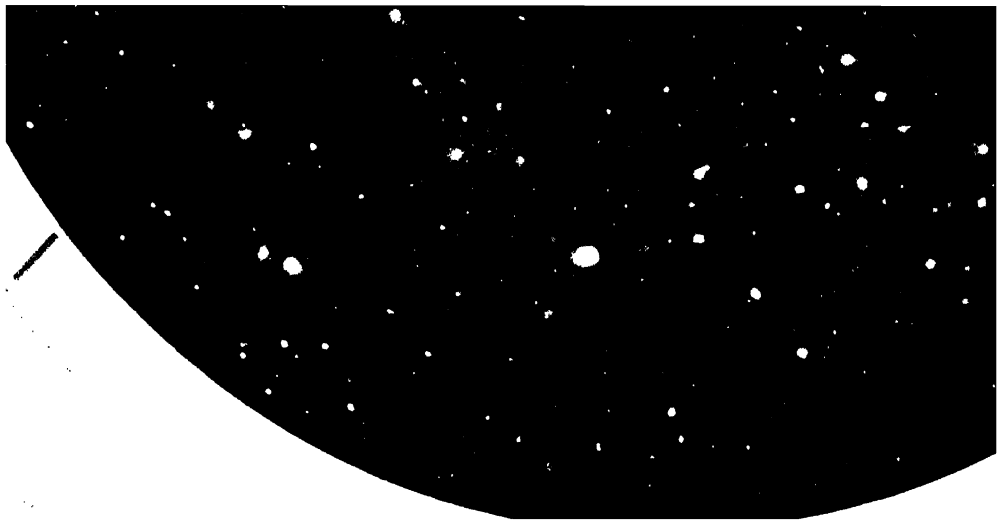
THE YEAR was 1589. A young man, barely 25 years old, was appointed professor of mathematics at the University of Pisa, Italy. He was paid a yearly salary of 60 scudi—a little more than 50 dollars. He didn't last through his three-year appointment. He left before his time was up, but not because he felt underpaid. He decided to leave before his colleagues ran him out of town. His name was Galileo Galilei.

The reason why Galileo aroused the ire of the whole faculty was simple: he didn't live up to the rules. Immediately after his appointment he began to tell his students that Aristotle and his teachings were amiss. If we explain wetness by saying that it is wet, he argued, then we shall never discover the true nature of things. He refused to accept the theories of Aristotle at face value, as his colleagues had done for centuries. The philosophy of Aristotle already was more than 1,900 years old, and for this reason alone it had to be respected. But Galileo decided to make his own investigation of things, and what he saw with his own two eyes inspired him to fight for his ideas. It was to be a long fight, and it lasted through the 78 years of his rich life.

Galileo was convinced that a scientist must go beyond mere thinking. He must also act, and so Galileo did. A famous law of nature formulated by Aristotle, for example, stated that heavy things fall faster than light ones. This appeared more than plausible to everyone. And it was considered perfectly easy to demonstrate the truth of this "law": just drop an iron ball and a bird's feather, and see for yourself!

Galileo thought this classical example was too obvious. So, according to his account, he took an iron "bomb" weighing 100 pounds, and an iron cannon ball weighing only half a pound. According to Aristotle the bomb ought to fall 200 times faster than the cannon ball. Galileo wanted to prove that this simply wasn't so. He hauled the two objects to the topmost story of the Leaning Tower of Pisa and dropped them from this overhanging vantage point. He released the two objects at exactly the same time. Both the bomb and the cannon ball tore into the ground, the bomb leading the ball by less than the breadth of a finger. They had been falling at practically the same speed. The little difference Galileo attributed to the action of air resistance—which, incidentally, also explains why the feather falls slowly. In a complete vacuum a feather drops like a rock.





This experiment exemplifies the kind of tests to which Galileo put prevailing ideas. Galileo started a mode of thinking which is still in use today. Since Galileo we have decided open questions in science by observation and experimentation.

Even though he was eminently successful with his first experiments, Galileo could not convince his colleagues that Aristotle must have been wrong. But his experiments were the beginning of the end of the domination of man's thinking by untested ideas. Man now went actively after new discoveries, and Aristotle, though still respected as a philosopher, became discredited as a physical scientist.

In writing about science it is difficult to get away from Galileo. Even though this great man probably never used the word "atom" in all his life, we must stay with him for a while in our story of the atom. With his further work he did much to open the eyes and minds of the scientists that came after him. Unknowingly, he prepared the ground for a revival of Democritus' ideas.

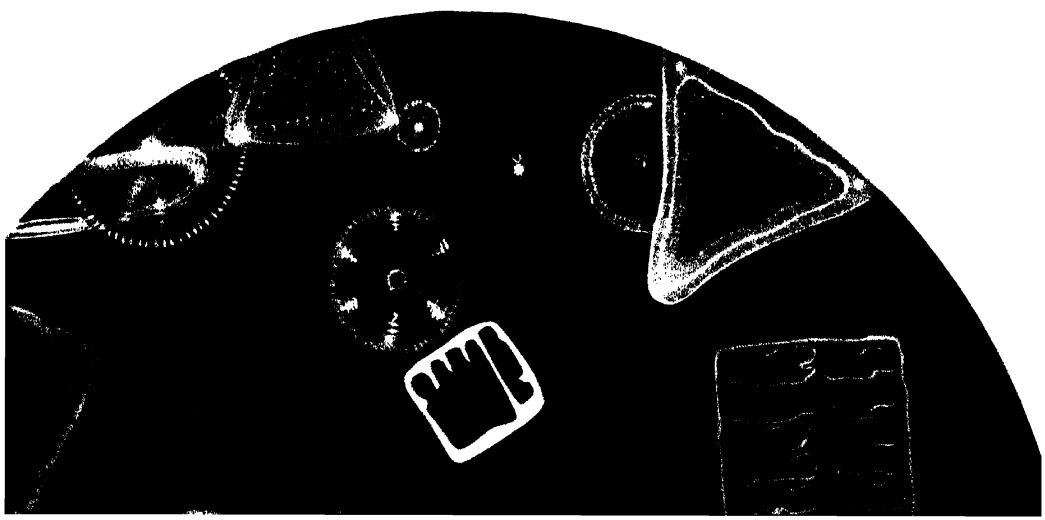
In about 1609 Galileo made a simple telescope and directed it at the sky. The telescope had been recently invented by a Dutch spectacle maker, Hans Lippershey, but when Galileo first held one in his hands he did not indulge in the pastime of making a distant church steeple appear much closer. To him, the telescope was not a toy but a scientific instrument. He used it for making those things come closer that man himself could not approach.

Within an incredibly short time, during 1609 and 1610, he made a whole series of truly sensational astronomical discoveries. His fame spread through all of Europe after he announced that there were mountains on the moon and that the sun sometimes showed spots. He discovered the four largest moons of Jupiter and observed with delight how these small satellites swung around the mighty planet just as, he was convinced, the earth and the other planets swing around the sun. He saw in this spectacle a small model of the solar system. He detected the rings of Saturn, although the poor power of his telescope would not reveal the whole beauty of this unique phenomenon in our solar system. He discovered that the planet Venus, our lovely morning and evening star, showed phases like the moon.

Often he must have pointed his small telescope at the Milky Way where its soft star clouds are brightest. There, through his telescope, the silvery shine of the Milky Way resolved itself into the twinkling of thousands and thousands of stars that no man's eye had ever seen. Never before had so much of our galaxy—a cloud of billions of stars in measureless space—been viewed by the human eye.

In 1610 Galileo published a famous book in which he told of his exciting discoveries. He aptly titled it THE STAR MESSENGER, and it did contain a age:

> "There is a vast universe all around us, filled with countless moons, planets, and stars—an outer space in which earth and man are lost as small, insignificant parts."



1670

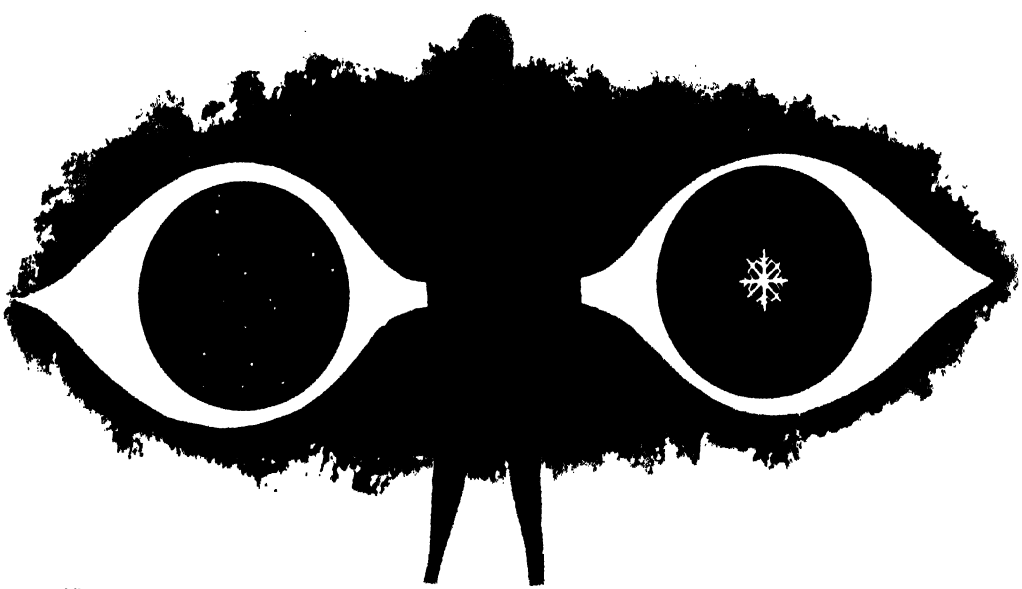
At about the same time another important instrument was invented—the microscope. It, too, was probably invented in Holland, but nobody can tell with certainty who its inventor was. Many scientists of that time built microscopes after the principle had become known. Actually invented before the telescope, the microscope remained a toy for almost a century, until the Dutchman Antony Leeuwenhoek used it for research. In many ways, Leeuwenhoek matched the feat of Galileo with the telescope. Leeuwenhoek, too, made a whole series of new discoveries when he began to use the microscope in 1670. But the microscope could not duplicate the sensation which the telescope had caused. Leeuwenhoek, for one thing, was not nearly so famous as Galileo, and also somehow people are more easily impressed by things big than by things too small for the eye to see.

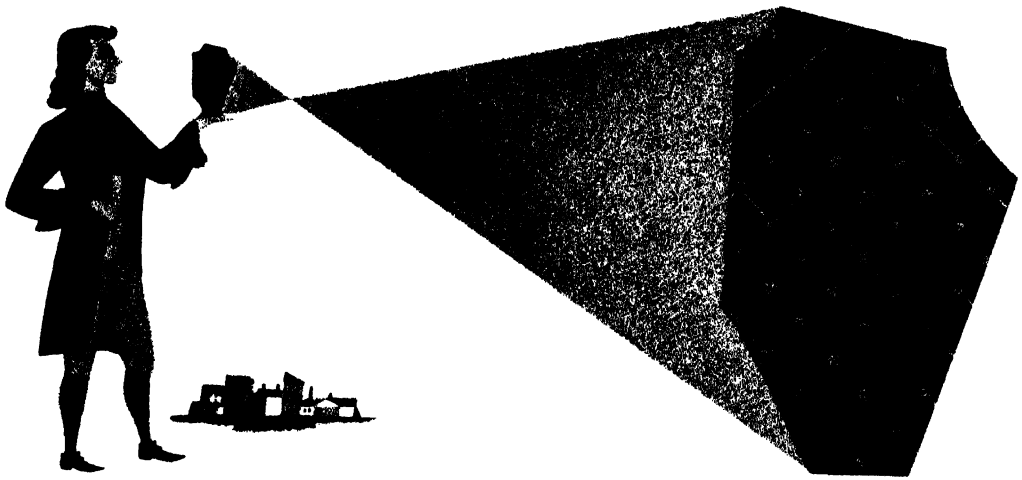
Yet Leeuwenhoek's discoveries were truly spectacular. Before his eyes unfolded an entirely new world, full of strange patterns and designs. He found them in the crystalline structures of metals, in wood, in snowflakes. He discovered order and beauty in the colorful wings of butterflies and bees, and in the filigree of miniature sea shells.

Galileo had taught scientists to go after new discoveries with an open mind. In this spirit Leeuwenhoek searched further. And he became the first man to see really tiny forms of life—little, one-celled animals that nobody dreamed existed. He found a new miniature universe, full of strange things dead and alive.

Man had for a long time only his own two eyes to use when he went out in search of new things. Then suddenly, in the seventeenth century, he built himself two magic eyes that enlarged the weak powers of his sight many hundred times. With these magic eyes he discovered the vastness of outer space and he saw the unbelievable smallness of inner space, equally full of things never seen before. And man found himself in the middle.

As late as 1580, a professor or student of the University of Oxford used to be fined five shillings every time he made a statement or used an argument contrary to the teachings of Aristotle. Before man could discover outer and inner space, Galileo and other scientists had to break down the prestige of Aristotle. Of course, the microscope could not show the atoms of Democritus. But it made man aware of hitherto invisible things, and soon he began to reason that small things must be composed of something still smaller. . . .





THE SECRET OF MATTER

GALILEO, the founder of our modern science, taught us how to make Nature yield her secrets. He asked shrewd questions in the form of experiments, and Nature herself gave the answers. This new way of research also included theory, the method of finding a result by sheer reasoning. Since Galileo, science has used theory and experiments as a powerful pair of tools to solve tough problems. Theory and experiment are like the two arms of a nutcracker: a nut cannot be cracked easily with just one lever.

The story of the atom shows this clearly. It was a long and tortuous road that was to lead to the discovery of the atom. The fisherman had to cast his net many, many times. . . .

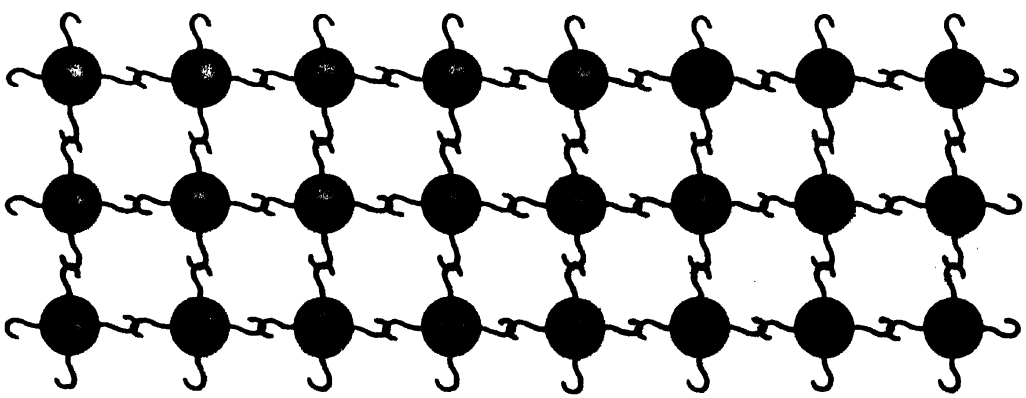
In the beginning there were no experiments that would detect atoms. A scientist could not take a piece of metal or wood and cut it into smaller and smaller pieces until he had separate atoms. The atom is so hopelessly small that it lies forever beyond the crude touch of human hands and beyond the dim sight of human eyes, even if aided by the most powerful microscope. So, when the atom emerged for the second time during the history of science, it did not appear as the result of an experimental study; as happened the first time, somebody just thought of it. It entered the scene of modern science as a pure theory.

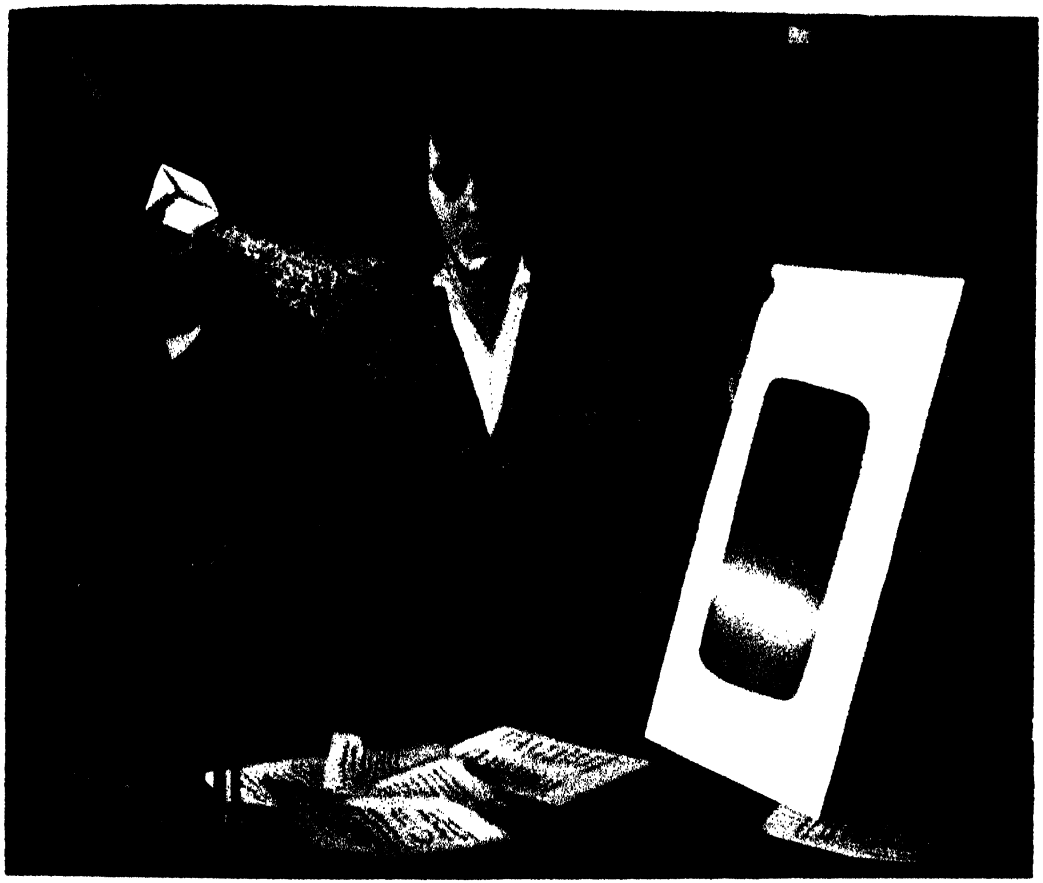
We owe the revival of the atomic theory to a man who, like Democritus himself, was more a philosopher than a scientist: Pierre Gassendi, of France.

He was born in 1592, and sixteen years later was already a teacher of rhetoric in his home town of Digne, France. At the age of only nineteen he was offered a position to teach philosophy in the village of Aix in southern France. Like Galileo, Gassendi disputed Aristotle, and in his early twenties he wrote a biting dissertation in which he exposed the fallacies of the ancient master's philosophy. His manuscript was so sarcastic that his friends advised him to moderate it, because Aristotle was still in high esteem with the most influential scholars of that time. Gassendi's works were finally published in 1658, three years after his death. They could no longer do harm to him then.

The atomic theory of Gassendi is not much different from that of Democritus. Probably Gassendi had knowledge of the ideas of the old thinker; but he added a few of his own. He thought that atoms of solid bodies must possess small hooks that would interlock to form strong networks like those of metal bedsprings. In this way, Gassendi thought, solid materials like metals and rocks are given their toughness and hardness. He gave much thought to this problem of how atoms could stick together. At one place in his writings he even claimed that there is a force acting between all atoms that makes them hold on to each other like so many small magnets.

With this concept of a "magnetic" attraction between atoms, Gassendi was verging on a theory of physics. This might be the reason why the great physicist Sir Isaac Newton, discoverer of the law of gravitation, was much interested in the books of Gassendi. Newton, too, believed in atoms. He even thought that light rays are composed of a fast stream of extremely small particles that flow away in all directions from a source of light such as a candle. To Newton all things—solid bodies, liquids, gases, and even intangible light—were composed of atoms. At one time he wrote the following:





Newton thought even light is made up of particles

> "It seems probable to me, that God in the Beginning form'd Matter in solid, massy, hard, impenetrable, moveable Particles, of such Sizes and Figures, and with such other Properties, and in such Proportion, as most conduced to the End for which He form'd them; and that these primitive Particles being Solids, are incomparably harder than any porous Bodies compounded of them; even so very hard as never to wear or break in Pieces, no ordinary Power being able to divide what God Himself made one in the first Creation."

Naturally, all this was theory. Newton expressed this clearly when he began his statement with the words: "It seems probable to me. . . ." The experimental proof of the atom's existence still lay a long time in the future.

Matter had now to be studied—matter, the visible and tangible stuff of which everything is made. For in matter lies the atom.

What kinds of matter are there? There are so many kinds that they are hard to classify. The ancient philosophers had their simple system: they spoke of the four elements—earth, water, air, and fire. All matter below their feet was earth: rock, sand, clay, and all metals that lay buried in the ore. The ocean, lakes, and rivers consisted of water, the atmosphere of air, and the sun was built of fire. There is hardly any worthwhile information in this crude system—just enough so that Democritus and Gassendi could speculate about atoms sticking together to form the solid earth, just enough to tell that atoms of liquids are slippery, and atoms of gases are free to fly about.

This system of the four elements was confusing in many ways. What if water froze and became solid ice? Was it still water or did it become earth when it froze hard? What if a piece of gold was thrown into a red-hot crucible, where it melted and started to flow like water? Did it become water when it became fluid? No, the ancient elements lead into a dead-end road. Before they were removed from the thinking of science, there could be scant progress. So, when Robert Boyle, of England, entered the scientific scene, he cast aside the old four elements.

Unlike Galileo and Gassendi, Boyle was a rich man. He was born in 1627, son of the Earl of Cork. At the age of eight, Robert was sent to Eton, and later to France, Switzerland, and Italy. After the death of his father he inherited a considerable fortune. To him science was, so to speak, a hobby. He must have found it quite absorbing, because he never found the time to marry.

In 1661 he published a book under the title *The Sceptical Chemist*. It was a good title, for the book advised his colleagues in chemistry to clear their minds of the mystery and black magic contained in the old writings. Most of the books Boyle attacked had been written by the old alchemists, who searched for the secret of making gold from lesser metals like lead or iron. Boyle was convinced that gold could not be "made"; it was something only Nature could create. It could not be found in the green flasks of a magician

Boyle thought all matter could be broken down into elements

unless it had been put there in the first place. To Boyle, gold was an "element," by which he meant that it was a basic substance that could not be composed of or made from other substances. He taught that some other kinds of matter—copper, silver, and the strange fluid mercury—were also elements.

Boyle was convinced that all the different kinds of matter which the ancients found so confusing, could be reduced to a much smaller number of such basic substances. There are many kinds of houses, all different in size, style, and appearance, but all can be reduced to bricks, pipes, beams, rafters; such are the elements of a house. But just as the composition of a house can be "analyzed" to consist of bricks, pipes, beams, and rafters, Boyle thought that more complicated kinds of matter like clay, salt, or glass could be understood as being composed of two or more elements. Their build-up could be found by "chemical analysis." All this sounds simple today, but when Boyle applied his idea of the element to the chemistry of his time, it was a great feat.

More than a century had to pass before Boyle's idea of the chemical element brought science one step closer to the atom. Again we must go to France; this time to Antoine Laurent Lavoisier.

This great chemist was an extremely active man. He was tall, handsome, and an acute thinker. It was he who brought order and rule into chemistry, which before him was little more than a disorganized play of cooking, boiling, and mixing according to all kinds of fancy recipes. Lavoisier began to weigh and to measure. Applying his scales shrewdly, he soon cleared up one of the great chemical mysteries of his time: he explained what happens when something burns.

A very superficial observation shows that things lose weight when they burn. When you shove a log into the fireplace, it is heavy. Then it begins to burn, slowly it falls apart, and after a while it shrinks to a small heap of

ashes. The ashes are so light and fluffy that you could blow them away.

Actually, things *gain* weight when they are burned! A burning piece of wood develops a lot of smoke, vapors, gases, soot, and ashes. If all these could be collected, their combined weight would be greater than that of the original log. This is a rather unexpected result. It takes a clear mind like that of Lavoisier to expect what most people would not expect. He took a piece of the chemical element sulfur, weighed it accurately, then burned it under carefully controlled conditions so that the resulting smoke and vapor could be weighed. When he did weigh them, they turned out to be heavier than the original sample of the sulfur.

On November 1, 1772, Lavoisier sent a sealed envelope to the secretary of the French Academy of Sciences. The envelope contained a note describing in a few sentences what he had observed. Lavoisier also promised that some time later he would publish a detailed account of his experiments. He sealed this note in an envelope so that later, if challenged, he could prove to everyone that he was the first to discover the chemical principles of combustion.

What happened to the sulfur was simply this: in burning, the element sulfur combined with the element oxygen in the air. This combination occurred in what is called a chemical reaction between the two elements. The smoke and vapors, of course, had to be heavier than the sulfur alone, because oxygen had been added to the sulfur while it burned.

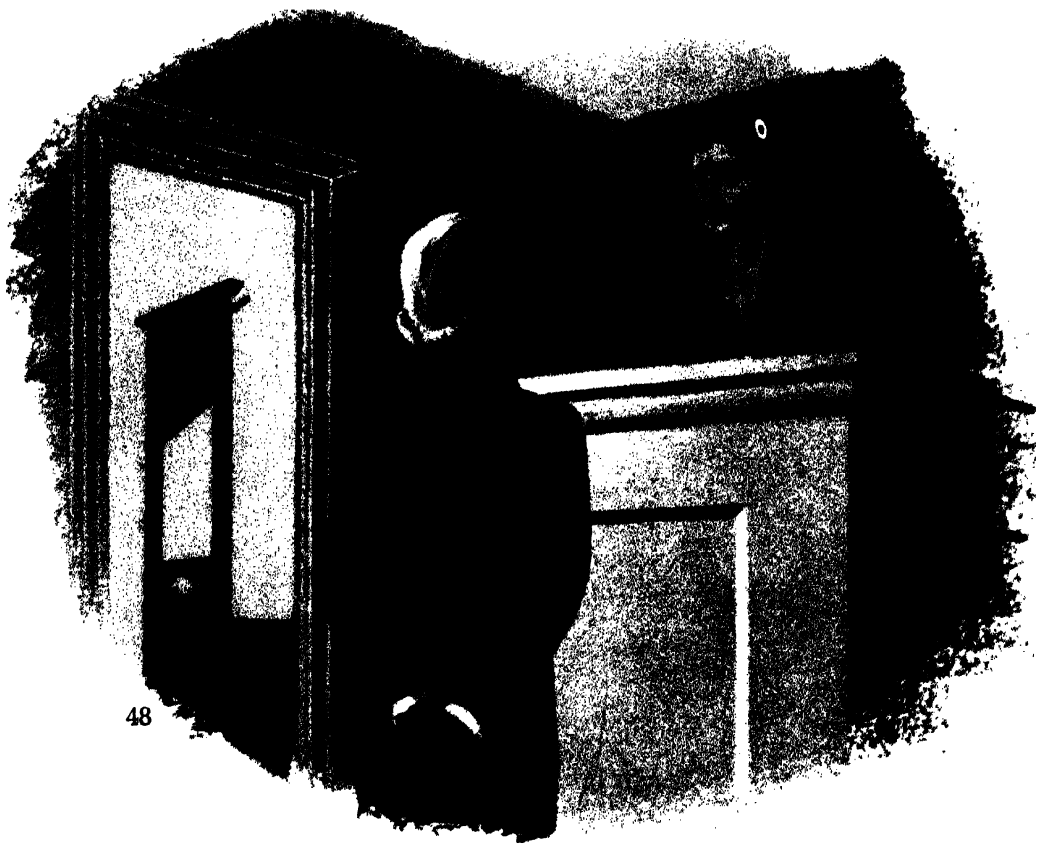
With his scales Lavoisier had looked into the nature of a chemical reaction more deeply, more knowingly than any chemist before him. He could prove with precise measurements that Nature builds matter by combining different elements as in a recipe. Lavoisier made the scale the chief tool of the chemist, and it has remained that to this day.

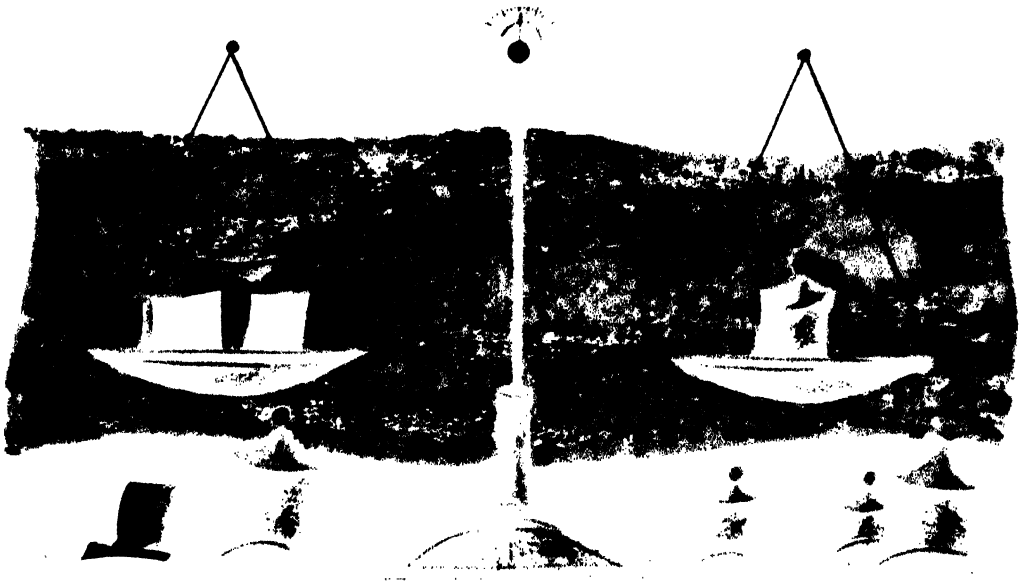
Lavoisier recognized that the chemical element is of great importance to the understanding of the nature of matter. He spent much effort on the elements themselves. He compiled the first list of elements—a total of 28. A hundred years before his time there were assumed to be only 4; today we know over a hundred.

The great Lavoisier met with a tragic death. In May 1794, during the French Revolution, he was arrested on the trumped-up charge that he had mixed water into the tobacco of the soldiers. The Revolutionary Tribunal sentenced him to die on the guillotine. During his trial he pointed to the many services he had rendered his country during his active life as a scientist. The judge cut him short: "The Republic doesn't need scientists!" He was executed within 24 hours.

Later the famous French mathematician Lagrange bitterly remarked, "It took them but a moment to sever that head, though a hundred years, perhaps, will be required to produce another like it!"

After Lavoisier, scientists knew that everything around us consists somehow of chemical elements. These combine and mix in certain ways to produce the colorful variety of all kinds of matter—solid, liquid, and gaseous. Democritus and Gassendi had spoken of atoms in the same terms. Obviously, chemical elements and atoms somehow must be related.





PATTERNS

THE JUDGES of the French Revolutionary Tribunal could kill Lavoisier, but they could not kill his work. He was the first to use a scale in his laboratory, and the chemists who came after him continued to weigh and measure.

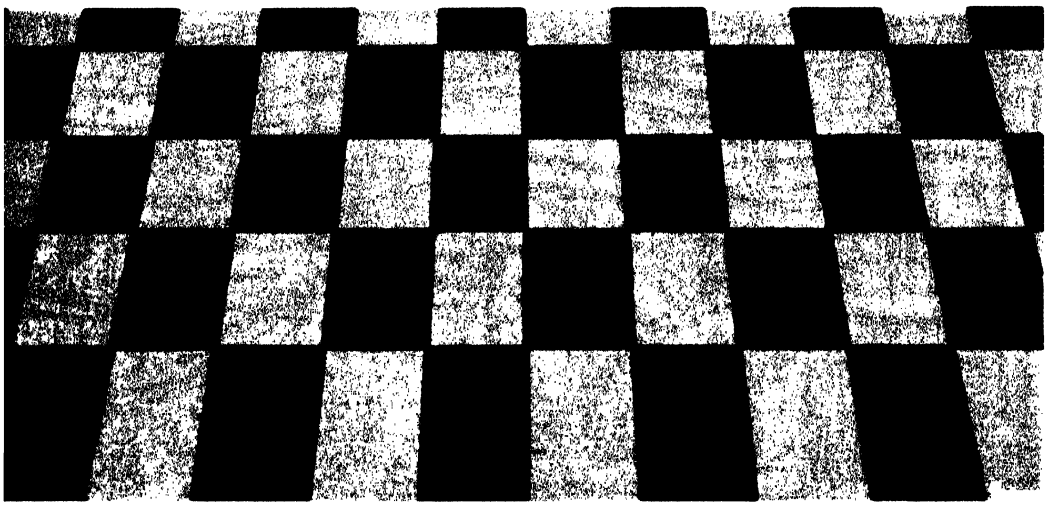
It wasn't long before the chemical scale revealed a great and important secret about matter and about how Nature mixes her elements. Actually, it turned out that "mixing" wasn't quite the right word.

There is such a thing as a true mixture. We can mix sugar and sand so thoroughly that it would be practically impossible to separate them again. They can be mixed in any amounts and in any proportions.

But there are other kinds of "mixtures" that work only in certain ways. Suppose you want a checkerboard pattern of tiles on a floor—alternating black and red squares. For this pattern the "mixture" of the black and red tiles is to be 1 to 1. Suppose all the tiles are to weigh 120 pounds; then, when the tile man comes, he should bring 60 pounds of black tiles and 60 pounds of red ones. If he brings 50 pounds of black tiles and 70 pounds of red ones, he will wind up with 20 pounds of red tiles too many for the job. The checkerboard pattern demands an exact mixture.

There are many other kinds of mixtures. Consider a floor to be made of tiles in a pattern like the one on the opposite page. Each blue tile is surrounded by eight yellow tiles. This pattern takes three times as many yellow tiles as blue ones. To lay such a floor, a tile man will bring 30 pounds of blue tiles and 90 pounds of yellow tiles. Here the tiles will mix only in a 3-to-1 ratio, just as the checkerboard allowed only 1 red tile to 1 black one.

Now we see that the word "mixture" isn't quite right if it comes to regular



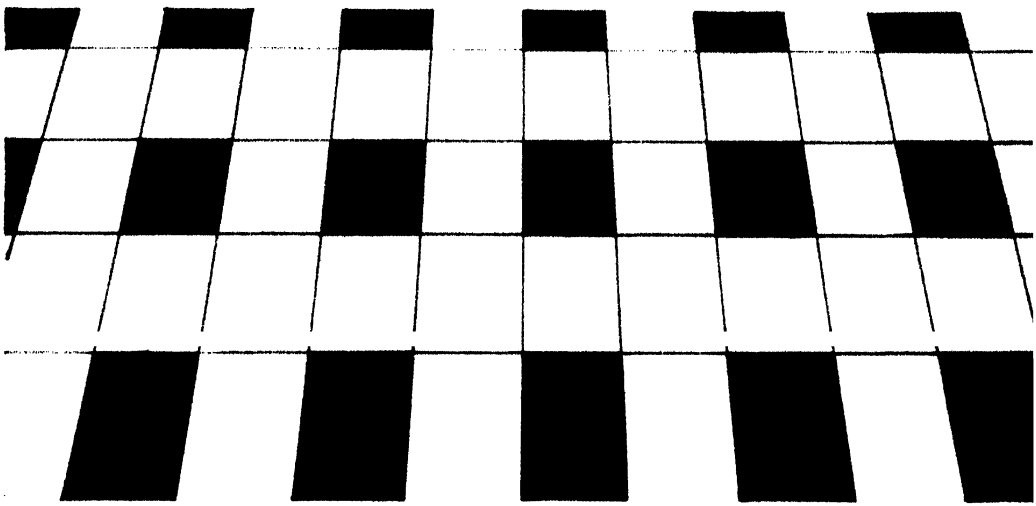
patterns as in tile floors. A mixture of sugar and sand is a true mixture. In laying a floor, however, we find that tiles fall naturally into a pattern; they join in a regular fashion. If it comes to patterns that are regular, we would do better to speak of "compounds" rather than mixtures.

Now, around 1800 there were many chemists conducting countless chemical experiments in their laboratories. They weighed and measured.

These scientists found that some elements did indeed mix in any desired amounts. They simply fell together like so many handfuls of sugar and sand. But most elements behaved differently. When they were put together, they didn't simply mix—they combined in a chemical reaction such as Lavoisier had shown for combustion. And most elements did combine only in certain, fixed amounts. It was discovered, for example, that 46 ounces of sodium

always combined with 71 ounces of chlorine to produce 117 ounces of table salt. Similarly, 1 ounce of hydrogen would only combine with 8 ounces of oxygen to produce exactly 9 ounces of water. If 2 ounces of hydrogen were mixed with 8 ounces of oxygen, 1 ounce of hydrogen was left over.

For a number of years these chemists were busy with their scales, their minds set on finding out how many ounces of one element would combine with how many ounces of another element. They published long tables of



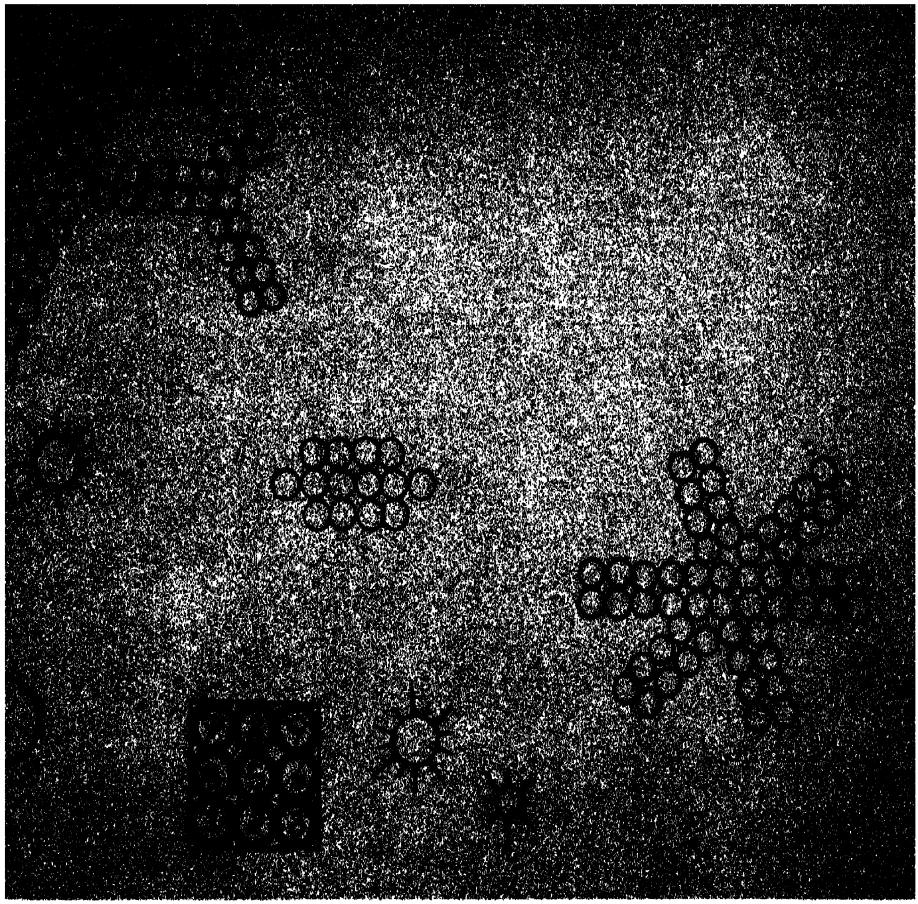
these combination weights. Their work was very important, but somehow they did not fully realize what was emerging—not until, in 1808, the great English physicist and chemist John Dalton showed them.

John Dalton was born a poor country boy. He came from a Quaker family, and from his early youth he had to look out for himself. As a young boy he worked on the farm, but he soon found that he could earn his livelihood with his clever little head much better than with his hands. At the age of only twelve he started to teach school in the village, and only three years later he became an assistant teacher at a boarding school. At nineteen he was made principal of that school, and in the course of the following years he studied Latin, Greek, French, mathematics, and natural sciences. The rest of his life was spent teaching in English universities.

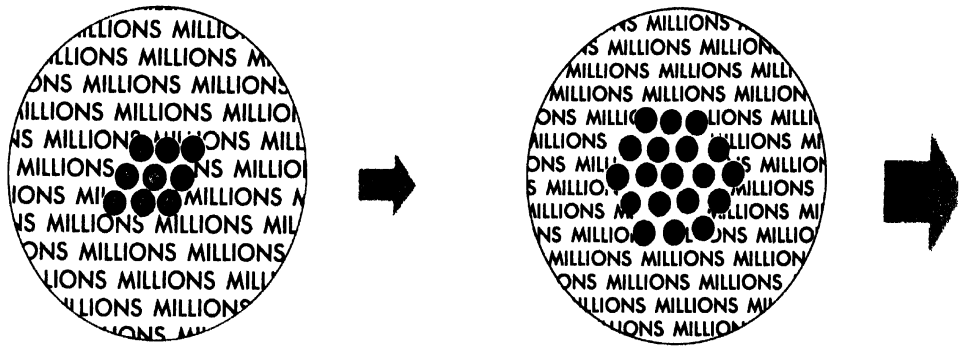
Dalton did all his eminent research in physics and chemistry in his free time. He was mostly interested in physics and meteorology. Only at the age of about forty did he direct his attention to chemistry, and he did it with the trained eye of a physicist.

He was fascinated by the way in which Nature combines her elements to form the many different compounds that were already known in his time. There was this remarkable law that elements combined only in certain proportions. He was the first who recognized this law in all its striking clarity and he lifted it out of the tables which the chemists had written up.

And then suddenly he realized that this wonderful law could only be explained by the atom.



And so Dalton began to design his famous atomic theory of chemistry. He claimed that matter consists of atoms, and that there exists an unknown force that acts between atoms to hold them together. He even drew pictures of his atoms—little dots and circles with rays indicating the forces of attraction acting between them. He also drew pictures of how atoms group together to form larger pieces of matter. Copper atoms, for instance, group together in little regular squares. When many atoms group together in this fashion, they form large sheets of atoms laid out in a regular checkerboard-type pattern. If millions of such sheets are packed upon each other—layer upon layer, and millions upon millions—they will form a tiny crystal visible under a microscope. If millions of these crystals combine, they form the copper metal

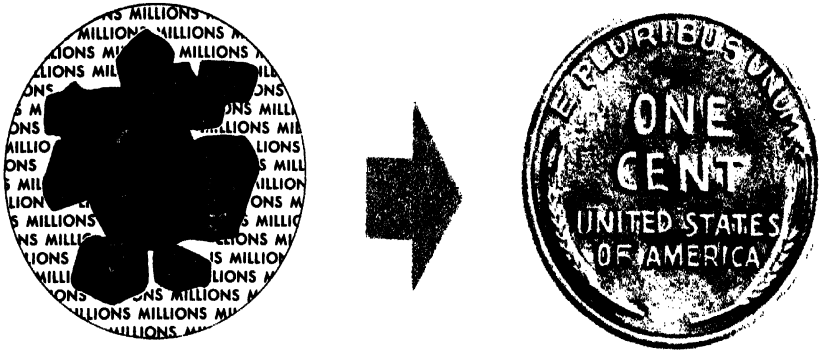


that is familiar to us from ordinary things such as the copper in a penny.

Just as there are atoms of copper, there are other kinds of atoms—one particular kind of atom for each chemical element. Since Dalton we have known that there are atoms of hydrogen, of oxygen, of iron, copper, mercury, and all the other chemical elements. All atoms of one particular element are absolutely alike. Two atoms of oxygen, for example, are more alike than two identical twins. If they were visible, nobody could tell them apart. They have the same shape and size and, above all, they weigh exactly the same. Atoms of another element are different; they have a different weight from oxygen; but among themselves they are again absolutely alike.

Actually, there is little difference between the atomic ideas of Dalton and those of Democritus, Gassendi, and Newton. All these ideas were theories and assumptions that nobody could really prove. After all, if something is too small to be visible, then you can claim just about everything about it. Nobody can prove you wrong—but neither can you prove that you are right. But Dalton was the first who had something to show in favor of his atomic theory, something that was not available to the old masters.

For one thing, there was the regular form of crystals. Dalton explained their striking regularity through the regular patterns in which atoms are supposed to be arranged. It was no direct proof of the atom, though. The microscope did show that even very tiny crystals had the same regular and orderly forms as big ones; but no microscope can actually show single atoms. It was impossible to prove that the crystal patterns really go back to regular arrangements of single atoms. This was an excellent idea, and today we know



that Dalton was right; but at that time there was no way of testing his idea.

But Dalton advanced a second, stronger point in favor of his atomic theory. By this theory he explained why most elements mix only in certain fixed amounts, as 1 ounce of hydrogen with 8 ounces of oxygen to form 9 ounces of water. Said Dalton: 1 ounce of hydrogen and 8 ounces of oxygen consist of two groups of individual atoms, just as two stacks of tiles consist of individual tiles. When the groups combine, they arrange themselves in a certain pattern—atom for atom, and tile for tile.

In the case of water, Dalton assumed that 1 ounce of hydrogen contains the same number of atoms as 8 ounces of oxygen. When 9 ounces of water are formed from these ingredients, each hydrogen atom joins one oxygen atom to form a pair—just as our tile man matched black and white tiles. In both cases—atoms as well as tiles—all units are used up because each finds a partner.

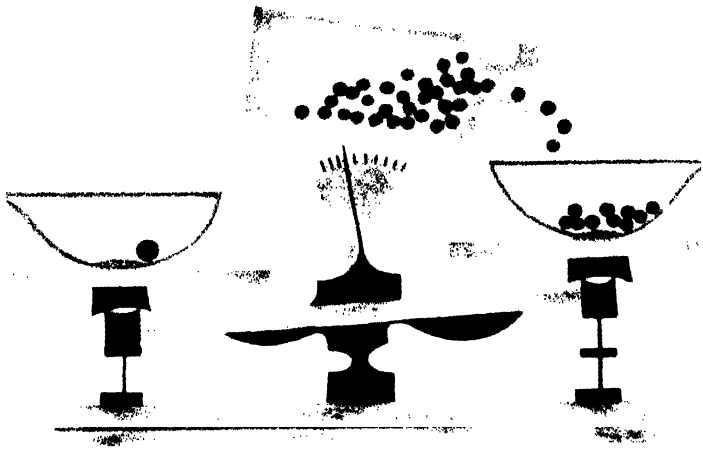
If each atom of hydrogen is represented by the symbol H, and each oxygen atom by the symbol O, then the chemical combination of the two can be written as follows:

$$\underset{(1\text{ ounce})}{H} + \underset{(8\text{ ounces})}{O} = \underset{(9\text{ ounces})}{HO}$$

According to Dalton, the symbol "HO" then stood for one atom of water.

This idea was the stroke of a genius. It brought man to grips with the invisible atom. This is why we think of John Dalton when we think of the modern atomic theory.

But—there was still something not quite right!



THE CASE OF THE MISSING CLUE

THE YEAR was 1808, and a momentous year it was. For we know today that when Dalton designed his atomic theory, he all but solved the riddle of how chemical elements combine to form chemical compounds. He was the first to express the idea that atoms of different elements stick together and form small, compound particles.

We say "all but solved"—because Dalton did not know how many atoms of each element formed any given compound. He had not one solution for the riddle but many—and he didn't know which was right.

It was a situation of the sort that happens in detective stories. There were a number of clues, pointing to different solutions; but there weren't enough clues to tell which was the right solution. In his water problem, for example, Dalton had assumed that there were as many atoms in 1 ounce of hydrogen as in 8 ounces of oxygen. That gave him 1 hydrogen atom for each oxygen atom in his water recipe. But what if 1 ounce of hydrogen contained only half as many atoms as there are in 8 ounces of oxygen? He would then have 2 oxygen atoms for each hydrogen atom in his recipe, and the water formula would be HOO or HO_2!

At this point his atomic theory was up against a certain type of problem which has been known to scientists for centuries. It was first described by the

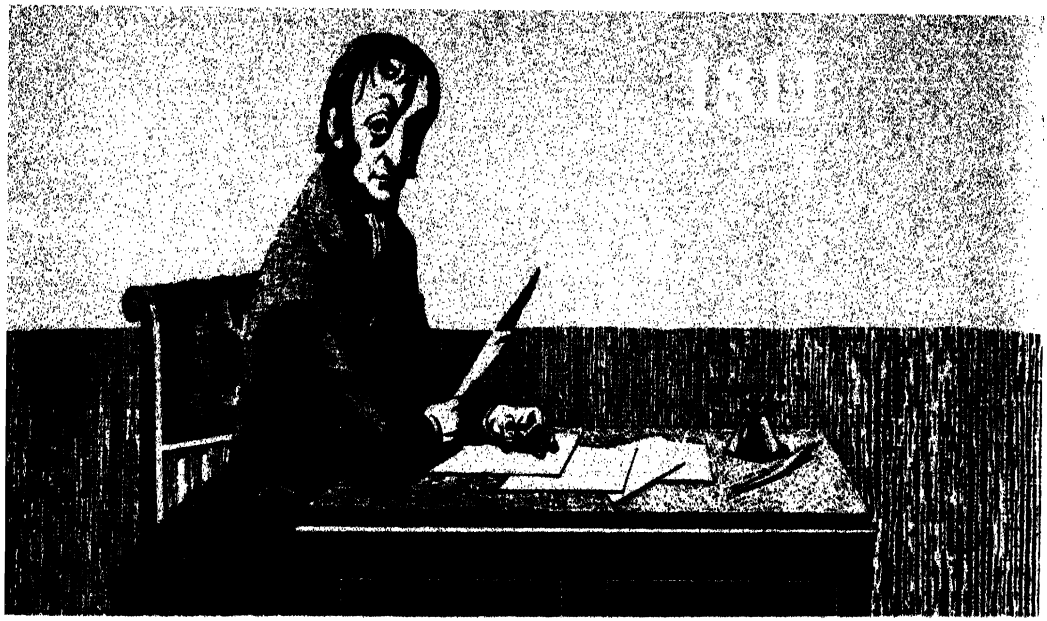
Greek mathematician Diophantus, who lived in Alexandria, Egypt, around A.D. 260. To this day a problem of this type is known under the name of "Diophantine Equation." In keeping with the lingo of the detective story we could say that Dalton was dealing with the "case of the missing clue."

Here is a simple example of a Diophantine equation: A farmer goes to town and sells 2 piglets and 4 turkeys. When he comes home he has 24 dollars, and the question is how much money he got for each of his 4 turkeys. Of course, this problem cannot be solved the way it is given. It has many solutions, and you wouldn't know which solution is the right one. For example, our farmer could have got 2 dollars for each of his turkeys, if he received 8 dollars for each of his piglets. Or, if he got 6 dollars for each piglet, we would know that he sold his turkeys for 3 dollars each. This problem has as many solutions as you want. It can only be solved if one more clue is given, such as the price for one piglet. Then the right solution can be found at once.

Fortunately for Dalton, the missing clue was found within three years of the first publication of his atomic theory. The information was supplied in the form of a marvelous law of Nature discovered by the Italian physicist Amadeo Avogadro.

Like many physicists of his time, Avogadro was very much interested in gases and how they behaved under different conditions of pressure and temperature. Since the time of Galileo, scientists had known that gases, trapped in a cylinder or closed vessel, are elastic, like springs. The air trapped inside a pump is a clear example. When you close the air outlet with a finger and push the piston handle, it is as though you were working against a coil spring. In fact, air—being a gas—is such an excellent spring that we use it in our automobile tires to get a soft, springy ride.

Since Galileo, physicists had been experimenting with this interesting springiness or pressure of air and other gases. In the course of time they had found that gases followed a set of rather simple rules. One of these gas laws had been discovered by Robert Boyle, the man who showed what a chemical element is. This law, known as "Boyle's law," was first published



by him in a paper entitled "On the Spring of the Air." It simply stated that a mass of gas trapped in a vessel doubles its pressure if it is compressed to half the space it occupied before. Conversely, the pressure of a gas is reduced in proportion as the volume of the enclosing vessel is increased.

Other gas laws were found after Boyle's time. These have to do with the temperature of gas. We all know, for example, that the pressure in automobile tires increases after a car is driven for a while and the tires get hot. These gas laws involving temperature were discovered only a few years before Dalton and Avogadro concentrated their efforts on the atom.

For many years Avogadro was professor of physics at the University of Turin, Italy. In 1811 he discovered the law that, ever since, has been linked to his name:

If gases of any kind, having the same pressure and temperature, are put into vessels of equal size, the vessels contain the same number of gas particles.

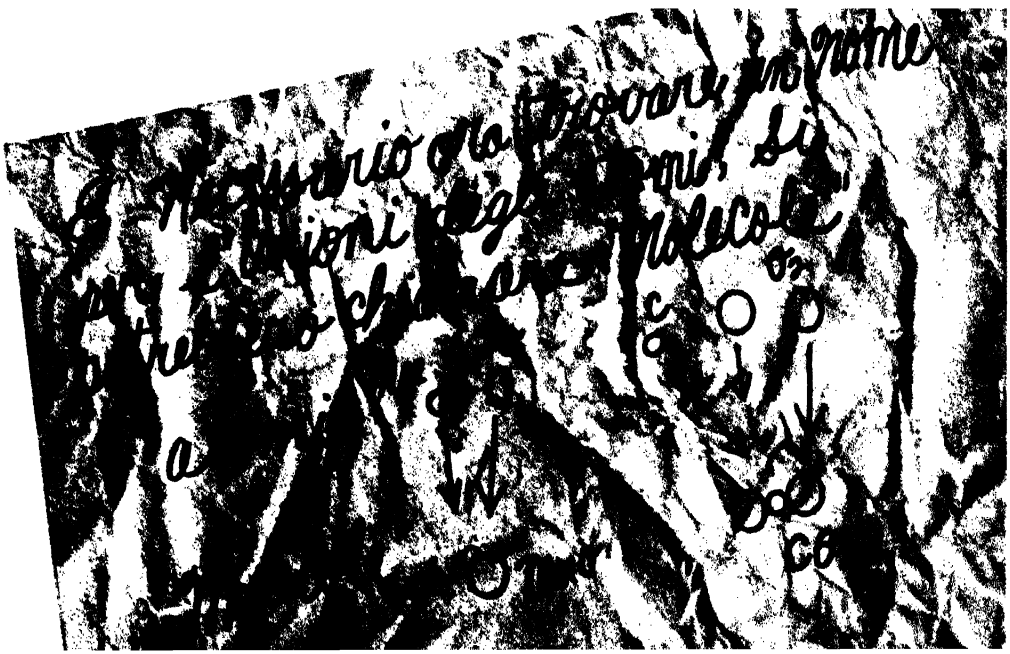
Hydrogen and oxygen, for instance, can be put into ordinary gallon bottles. The law of Avogadro states that the number of atoms found in each bottle will be the same at the same pressure and the same temperature. The

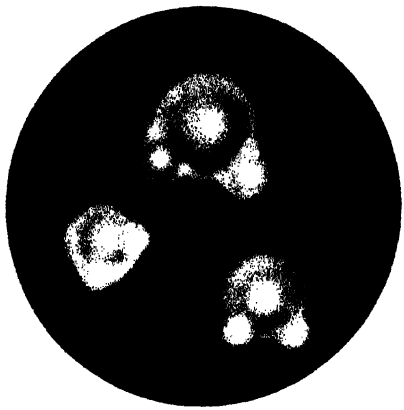
law would also hold for nitrogen and chlorine, two other gases. This law is nothing short of amazing!

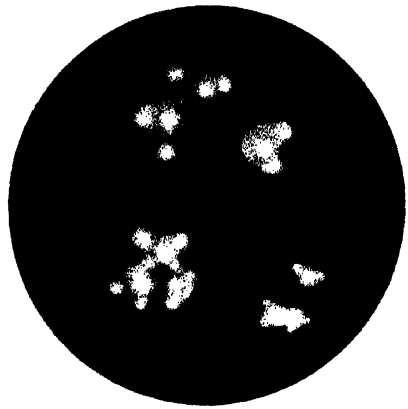
Avogadro had the missing clue, and he proceeded at once to use it on Dalton's problem. All he had to do was to look up in the tables of the chemists how much a gallon of hydrogen and how much a gallon of oxygen did weigh. The table showed that a gallon of oxygen was 16 times heavier than a gallon of hydrogen. But in each gallon there was the same number of atoms: so an oxygen atom must be 16 times heavier than a hydrogen atom! It was a simple, but very important, result.

The rest was easy. Since oxygen atoms are 16 times heavier than hydrogen atoms, one would have the same number of atoms in $\frac{1}{2}$ ounce of hydrogen as in 8 ounces of oxygen. But Dalton's water recipe called for a whole ounce of hydrogen to 8 ounces of oxygen; hence in the water recipe there must be 2 hydrogen atoms to every oxygen atom. When they combined in a chemical reaction, they formed "H_2O"—water!

Dalton had shown how chemical compounds are formed: atoms of different elements stick together and form what he called "compounded atoms." Avogadro showed how many atoms of each kind go into each compounded atom. He was also the first to see how important these compounded atoms are for the understanding of physics and chemistry. He even gave







them a name of their own so that there was a clear distinction between these compounded atoms and single ones. He called the compounded atoms "molecules," which means "little masses." The name "atom" he reserved for the single, ultimate particles which make up a chemical element.

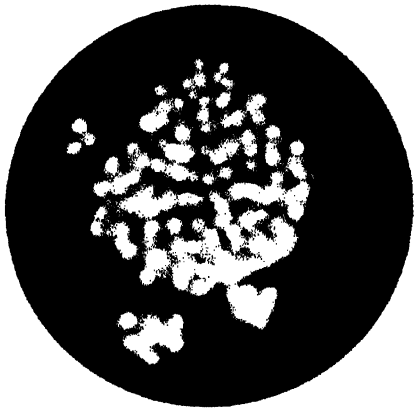
The formation "H_2O" is a molecule, according to Avogadro; it is a water molecule, the smallest water particle. If a mass of these molecules are thrown together—millions and billions of them—then we get a drop of water.

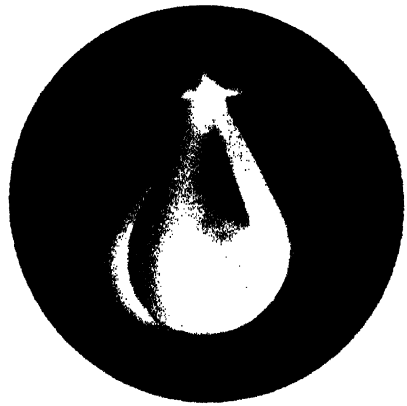
There are also molecules that consist of two or more atoms of the same kind. Oxygen, as we find it in the air all around us, is composed of small particles in which two oxygen atoms are joined like two ping-pong balls glued together. The same is true for hydrogen. If three oxygen atoms join together to make one molecule, we get ozone, a poisonous gas.

Now everything became clear. Chemical elements are composed of single atoms, or of molecules in which the same kind of atoms are glued together. Chemical compounds consist of molecules in which there are two or more different kinds of atoms.

After Avogadro had completed his work, the atomic theory of Dalton was finally accepted. Today we look upon Dalton as the father of the modern atom, and in Avogadro we see the father of the molecule.

A tremendous task remained to be done, however. It fell upon the chemists to find out how the many molecules in Nature are built—how many atoms of a kind are found in them. It became a fascinating game of numbers and combinations to solve these many questions. It was like a huge crossword puzzle that grew faster than it could be solved.



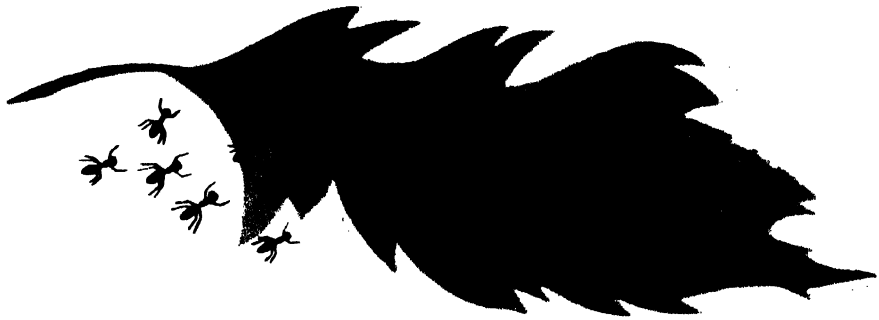


The game started with simple molecules such as are formed when sodium and chlorine atoms combine. Both these elements are highly poisonous. But when a sodium atom (Na) and a chlorine atom (Cl) join to form the simple molecule "NaCl," we get nothing else but . . . table salt. Then more complicated molecules were tackled. For example, 12 atoms of carbon (C), 22 atoms of hydrogen (H), and 11 atoms of oxygen (O) may join in a certain way to form a molecule, $C_{12}H_{22}O_{11}$, which is nothing but—sugar.

Chemists of today are still busy finding out how atoms join to form molecules. All the simple molecules have long since been analyzed; today chemists wrestle with molecules that consist of tens of thousands—even hundreds of thousands—of single atoms! Such are the molecules of which the living bodies of plants, animals, and humans are built. In 1955, Dr. Linus Pauling, of the California Institute of Technology, received the Nobel Prize in Chemistry for his study of these giant molecules.

Avogadro used his marvelous law to find out how much heavier an oxygen atom is than a hydrogen atom. The same thing can be done with all other kinds of atoms. In this way chemists found out about the so-called "atomic weights." Hydrogen turned out to be the lightest of all atoms, and so it was given an atomic weight of 1. Oxygen then has the atomic weight 16, iron 56, and the heaviest of all naturally occurring atoms, uranium, 238.

Nobody has ever seen a single atom, even to this day. At the time of Avogadro many scientists still thought there was no such thing as an atom. But only a few years later it was generally known how heavy the atom of each known element is in relation to a hydrogen atom.



ATOMS AT WORK

And so, more than a hundred years ago, scientists were already hot on the trail of the atom. Hardly a single reputable scientist remained who was not convinced that the atom exists; all believed in the atom, though nobody had ever seen one. Yet the belief in its existence was based entirely on what a lawyer would call circumstantial evidence.

It was as though the atom was the defendant in a trial. The judge, the jury, and the witnesses were all scientists. The witnesses brought to court a tremendous number of observations from the scene of the crime, and these facts could only be explained if there was such a thing as an atom. The jury weighed the facts. The circumstances were such that it could only conclude: the atom exists. A defense counsel could only have said: "Gentlemen—all this is only circumstantial evidence. Nobody has ever found a trace of an atom, nothing like a fingerprint. Nobody has ever seen the atom in action!" But the jury found the atom guilty of being in existence, because the evidence was overwhelming.

At last, in 1827, a witness did see the atom in action. This was real evidence observed with a microscope. One day the English botanist, Robert Brown, was looking at a drop of water with the highest power that his microscope could provide. There were in the water a number of very small specks of dust and some tiny bits of microscopically small plants. Brown didn't know what these little bits actually were, but he thought they were alive. They trembled, vibrated, and danced around without ever stopping. He believed they were creatures much smaller than the one-celled animals and plants known in his time. And so he misunderstood the evidence.

Only 52 years later, in 1879, was this "Brownian movement" given its correct explanation. The tiny bits of dust moved because they were constantly being kicked around by the everlasting motion of the water molecules. It was as though Brown had looked upon an anthill from the top of a high tree. He was too high above the scene of action to recognize the thousands of ants crawling around all over their hill, but he could see a number of dry leaves that had fallen there, and these were trembling, vibrating, and jiggling back and forth. Not knowing what was actually going on, he assumed the leaves were alive. But they moved only because they were kept in motion by the ever-busy ants.

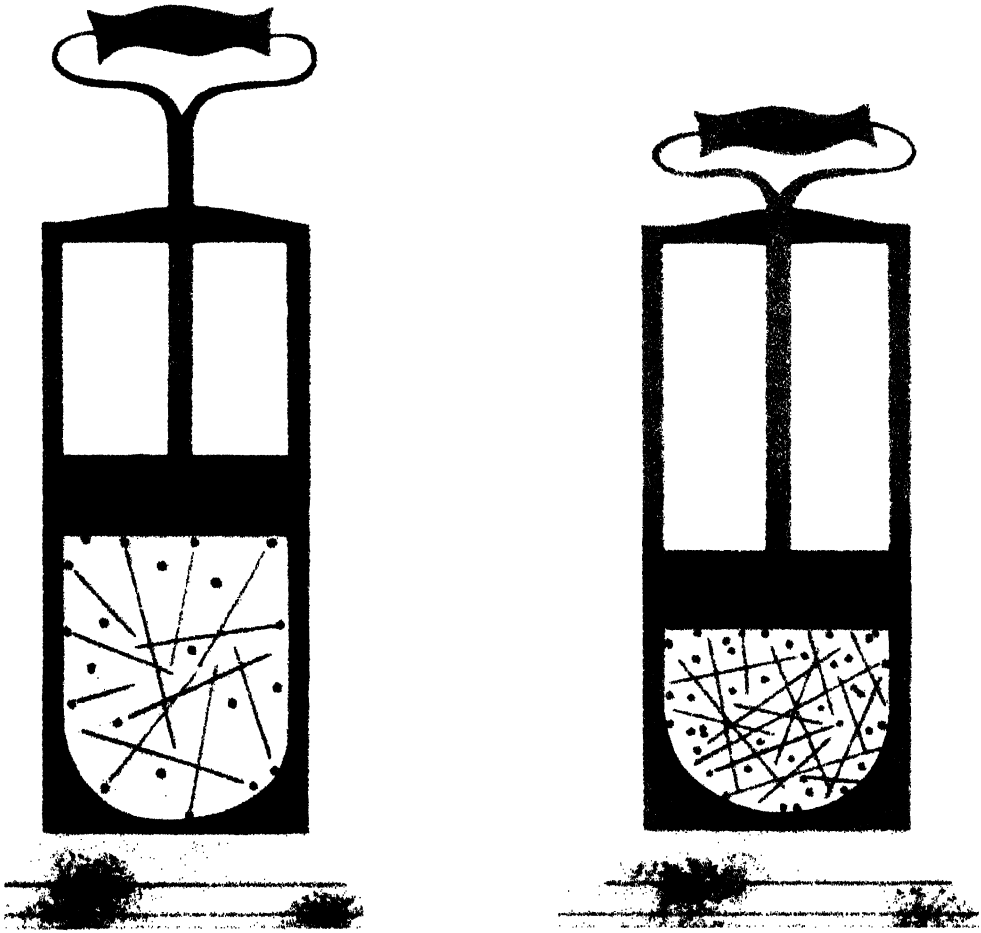
The Brownian movement proved that water molecules are in constant motion. In liquids, atoms and molecules dance around, sliding over each other without ever stopping. Molecules of which solid things are made don't slide, but they vibrate and swing around their fixed places like the coils of a spring mattress when jostled. If you could look at your table with an atomic eye, so to speak, you would recognize it as a complex network of vibrating atoms and molecules.

The atoms and molecules of a gas are likewise in constant motion. About one hundred years ago scientists were greatly interested in this concept because atomic motion presented a chance to explain the famous gas laws—the well-known laws that describe how trapped gases behave. Any law of Nature is always a great challenge, because it demands an explanation. And it turned out that atomic and molecular motion was the only correct explanation for the orderly behavior of the gases. The train of thought followed by scientists of the second half of the century was as follows:

Gases consist of atoms and molecules that are constantly in free flight, dashing back and forth in all directions like a swarm of little flies. Flies, however, usually zip around in mad circles and rarely ever collide. Not so the molecules of a gas. These dash along in straight lines until they hit other molecules that happen to cross their course. Two colliding molecules rebound like two cue balls, and each dashes off in another direction. Everyone of the molecules in a gas is constantly on the move, repeatedly colliding with many others in the game. So each molecule follows a mad zig-zag course.

The molecules in a gas also keep hitting the walls of the container which encloses the gas. When they hit, they rebound and return to the everlasting free-for-all within the gas mass. There are so many molecules hitting the walls so many times in every second that these millions and millions of little pushes amount to a constant pressure against the walls.

If a gas is compressed, all the molecules are forced into a smaller space. Then their chances of colliding with each other are greatly increased. Each molecule collides more often with its partners, and the walls, too, get a



much stronger pounding. In other words, the pressure of the gas against the walls is increased when the gas is squeezed into a smaller volume.

Now this is a proposition that will delight any physicist, particularly if he has a knack for mathematics! There are so many cubic inches of space filled with so much gas; there is a pressure of so many pounds per square inch; and the molecules can be assumed to fly around with a speed of so many feet per second. With this kind of information a student of mathematical physics can sit down and calculate how often a molecule collides with another one in each second, and how far it would travel on the average between collisions. And he can discover through calculation whether a mass of flying molecules would behave like a real gas.

Mathematics was already well developed in the nineteenth century. Newton had calculated the motions of the planets; calculus had long been in use, and mathematicians knew how to handle the tricky differential equations. These methods of higher mathematics are powerful tools of theory, and they were applied to calculating the motions of molecules in a gas.

The calculations turned out to be remarkably successful. They showed that a great mass of atoms and molecules buzzing around would indeed behave according to laws that are valid for a gas. This so-called "kinetic theory of gases" worked so well as to become final proof of the constant motion of atoms and molecules. It was also the final proof that matter really consists of atoms, even though nobody had ever seen an atom with his own two eyes.

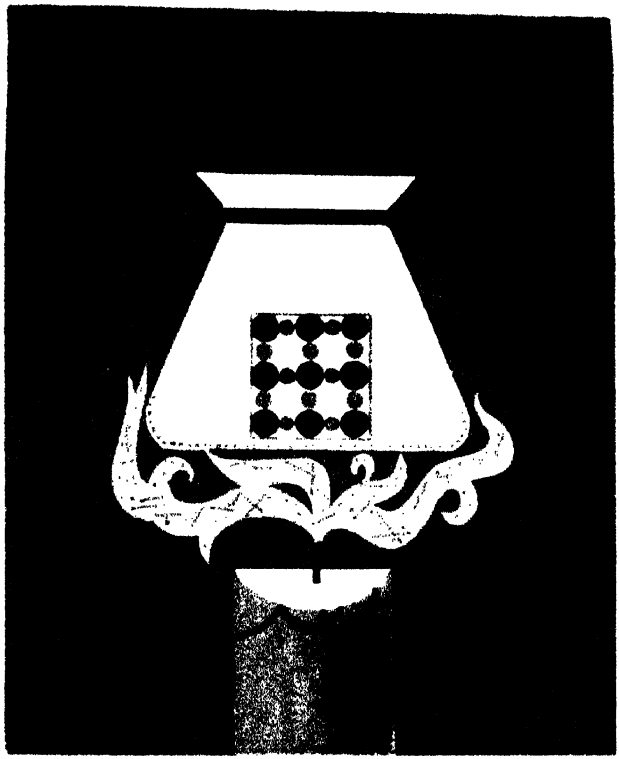
When the motion of atoms was recognized, it spelled the final defeat of Aristotle's brand of science. For one thing, it explained the nature of heat. Until almost a hundred years ago scientists believed that a body was hot because it contained heat. This was an argument true to the form of Aristotle: heat was a kind of substance that filled hot bodies. Even the great Lavoisier listed heat as one of the chemical elements in his table. Today we know that heat is motion of atoms and molecules. If a flatiron is heated, its atoms start moving faster. When we touch it, the stronger pounding of its atoms against the skin gives us the sensation of heat.

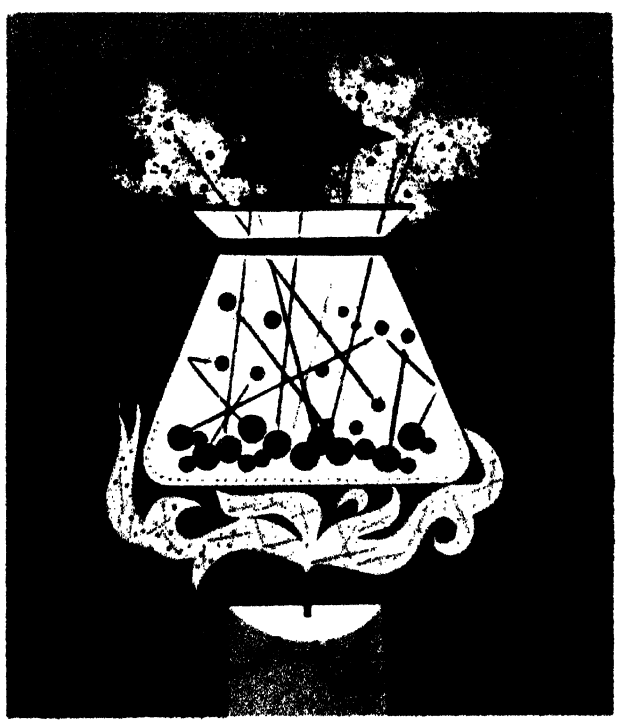
Even an ice cube contains a small amount of heat. If it could be magnified a hundred million times, we would recognize it as a huge superstructure built like a three-dimensional lattice work of single H_2O molecules. They move constantly. But they do so by vibrating slowly and sluggishly. This is why an ice cube is cold to the touch.

In a flame the motion of atoms and molecules is extremely violent. They dash around with great speed—and this is why a flame is hot. A glass jar taken from the shelf is normal to the touch. Its molecules move much more slowly, but not quite so slowly as the molecules of the ice cube. So a body's temperature is actually determined by the degree of molecular movement. But what happens if we put the ice cube in the jar and place both over the fire?

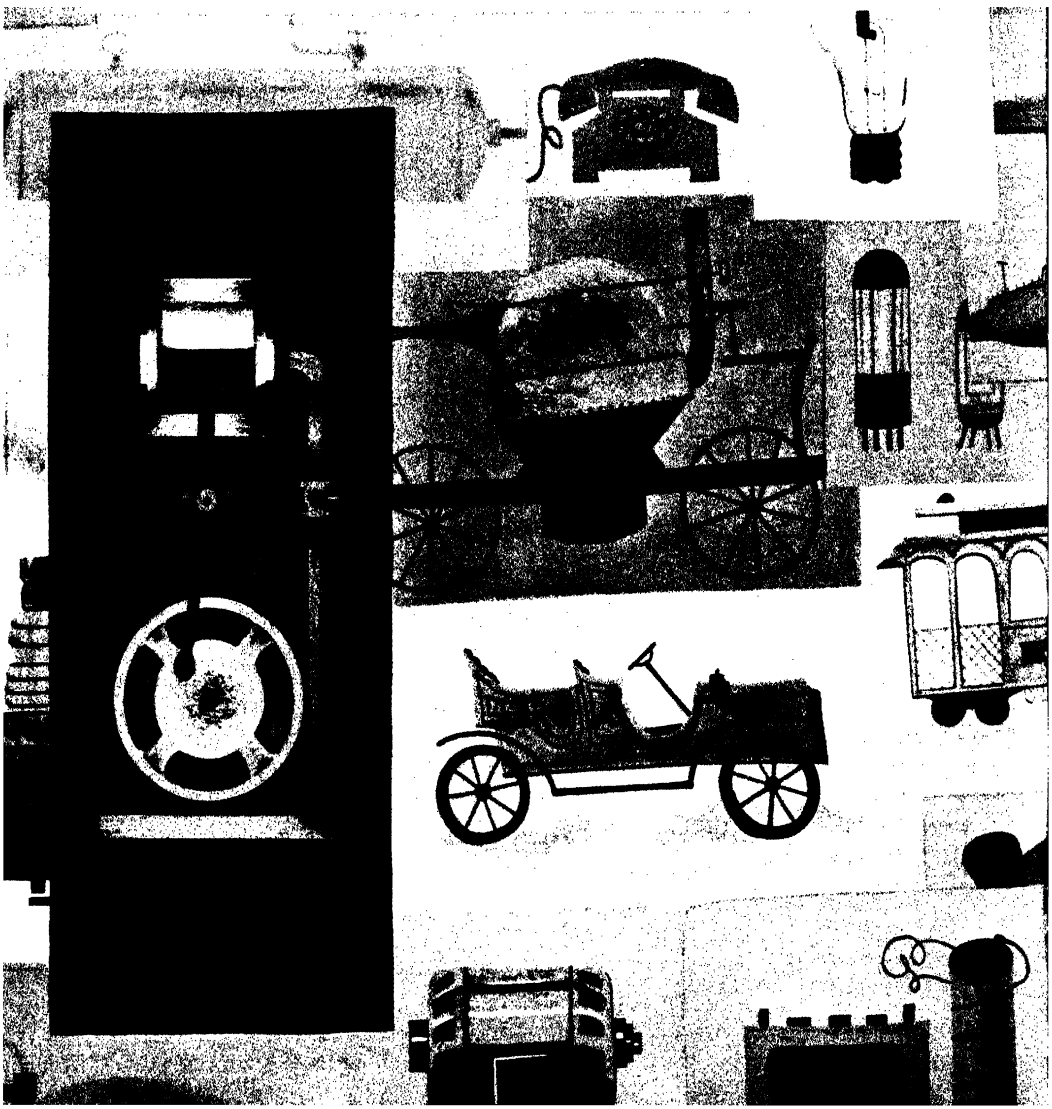
When the fast-moving molecules in the flame bounce against the molecules of the glass, the latter too, start moving faster. In turn, the glass molecules bounce against the ice molecules and start them vibrating faster, too. It's like a pool game with the balls bouncing against each other.

As more and more heat is supplied to the ice, its molecules are moving faster and faster. Finally, the ice molecules are vibrating so fast that they break loose from each other. They begin to roll around freely, forming a dense pack of ever-moving molecules: the ice has melted and has become water. The heating goes on, causing the water molecules to move ever faster. Presently a few of them are kicked above the water surface and escape into the free air. As the water is brought to boil by constant heating, the molecules will escape in great numbers: they are expelled from the water as steam. In hot steam the molecules are dashing around with their greatest force — enough force to push the lid off the jar.





We know the tremendous power in steam. When a mass of furious steam molecules are released against a piston, they push it along with great force —enough to drive a locomotive that draws a hundred cars. And so it was the power of countless moving atoms and molecules that began to drive the machines of man in the technical age. It was the power of steam that drove his engines and ships, and turned the generators that brought him from the gaslight era into the age of electricity.



Steam was a mighty servant—an almost magic servant. But it was not yet the mighty Genie of our story that dwells in the atom. Steam was a hungry servant that had to be fed constantly. It drew its power from fire, and it became necessary to keep countless fires burning all the time. The fires of the technical age cut deep into our precious resources of coal and oil.

By 1890 man was feeling pretty smug about his accomplishments in science and engineering. He thought that he had the forces of Nature at his command. He knew of the atom. He knew of its size, and he knew how much the different kinds of atoms weigh. He knew of their tremendous number, and of the great power that lay in their furious motion. But he didn't know what the atom really was. He still thought it was an indestructible and indivisible thing—just as its name implied.

What a surprise was in the offing!

METALS ALIVE!

By 1890 man had not only harnessed the power of steam; he was also well on the road to making electricity his servant in all civilized nations. As it was with the power of steam, the invisible power of electricity was first used by man without real understanding of its nature.

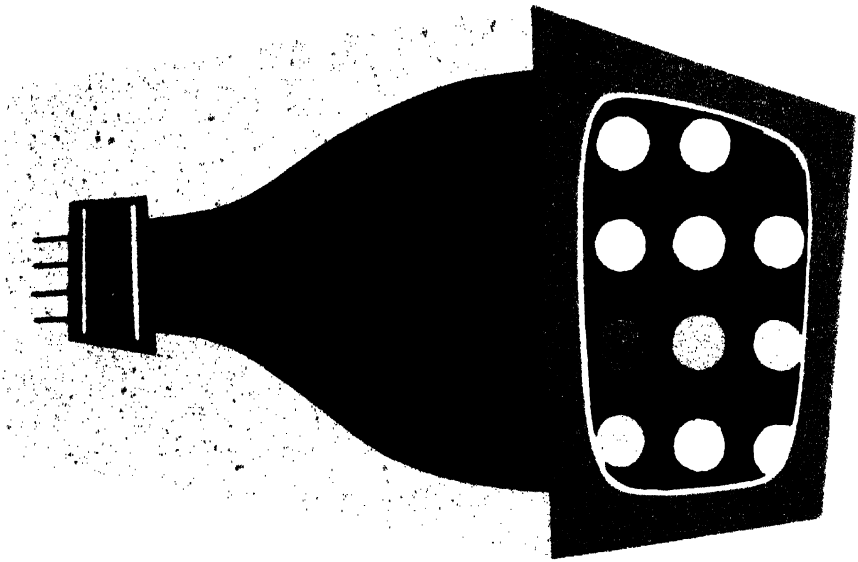
More than a hundred years ago physicists first suspected that electricity, like matter itself, is made of atoms. They thought that atoms of electricity are identical tiny bits; that all have the same tiny charge of negative electricity. If a large number of these little charge carriers are deposited on a body, it is said to be electrically charged. As early as 1874 the English physicist Stoney even invented a name for these atoms of electricity; he called them "electrons."

Like the atom, the electron had a name before it was discovered. And as with the atom, the discovery of the electron was only a question of time, because it really did and does exist.

Early experimenters discovered that electrons would flow through a tube pumped free of air. From tubes such as these came the television picture tube of today.

When scientists make a new discovery, news reporters like to say that they found something new in their "test tubes." The electron was really discovered in a tube. But it wasn't the kind of tube chemists use: it was a tube that many generations later developed into such noble great-grandchildren as the radio tube and the television tube. These latest descendants, too, bear the family name. They are still called "electron tubes," even though the bulbous eye of the TV-tube certainly looks nothing like a piece of pipe.

The ancestor of our modern electron tubes was really a tube; it was a piece of glass pipe closed at both ends. Metal wires were sealed into each end of the glass and a voltage put on these wires. At first nothing happened, just as nothing happens to the voltage that lies across the metal contacts of every wall plug in your living room. The voltage cannot discharge because the air between the contacts is a good insulator. But, knowing that in the tube the voltage is well insulated by the air between the wires, physicists pumped the air out of the tube to see what would happen. This removed more and more of the insulator between the wires, and as the air became thinner and thinner, something began to happen. A silent discharge took place: streamers of soft light stretched from one wire to the other, producing a strange, wavering glow of red and purplish colors. As more and more air was pumped out, the glow grew weaker and finally vanished. However, opposite the negative wire—which was called the "cathode"—the glass walls of the tube



glowed with a flickering light of a pale green color. It was a kind of fluorescent light like the eerie glow of rotting wood in the night.

The German physicists Hittorf and Schuster, and the English scientist Sir William Crookes, were foremost among the researchers in this fascinating field of discharge tubes. Soon they discovered that the glow was caused by a kind of radiation that was given off by the cathode wire. The rays traveled across the empty tube, and when they hit the opposite wall they caused the glass to shine with that eerie glow. Little objects put in their path inside the tube—a little cross, for example—cast a shadow on the tube walls.

Later it was found that the rays could be deflected by a magnet held close to the tube. This could only mean that the rays were not ordinary light rays; they had to be a stream of tiny charged particles that emerged from the negative wire. This meant further that they had to bear a negative charge. Crookes first called these particle rays "radiant matter," but soon they were called by the name Stoney had already chosen: electrons!

The year was 1895. In his laboratory at the University of Würzburg, Germany, Wilhelm Konrad Roentgen was making experiments with the fluorescent light produced by electron rays. He built himself a so-called fluorescent screen—a piece of cardboard painted with certain highly fluorescent chemicals. It was the forerunner of our modern television and radar screens, which also light up when electrons strike their surface. One day this screen was placed a few feet away from an electron tube which Roentgen was operating at a rather high voltage. Suddenly Roentgen discovered that the screen glowed in the dark even though the captive electron rays in his tube couldn't possibly reach over to the screen. He took a blank piece of cardboard and placed it between the tube and the screen. The screen still glowed. Excited, he ran to the workshop and selected a thin piece of sheet metal and placed it between the tube and the screen. The glow was weakened, but it was still there.

Roentgen drew his conclusions fast. The tube must be the source of a new kind of rays that penetrated cardboard and sheet metal as though they were made of glass.

Next, he placed his outstretched palm between the tube and the screen. What he saw gave him quite a start. On the screen there was visible the skeleton hand of a ghost. He could see the thin, spidery bones of the fingers. He moved his hand. The bony hand moved, too, as though it were a ghostly mirror image. Roentgen was seeing the bones of his own living hand!

The rays from the tube penetrated both flesh and bone of the living body. Because the bones are somewhat heavier and denser than the soft tissue of the flesh, they cast a shadow. Roentgen knew he had discovered a strange kind of rays unknown before. Because he didn't know what they were, he called them "X-rays"; but in German-speaking countries they were soon called "Roentgen-rays."

His discovery was a sensation, and Roentgen found himself famous overnight. Medical doctors recognized at once that X-rays permitted them to look inside the human body without cutting it open. They could watch broken bones and body organs in action. To this day X-rays remain the most

important tool in the diagnosis of human disorders. They turned out to be of tremedous benefit to suffering mankind.

It took scientists almost a decade to explore the true nature of X-rays. Somehow the electrons dashing through the tube must be responsible for them. Presently it was found that X-rays grew much stronger when the electrons were hurled against a solid block of metal. Brought to a sudden, dead stop in the metal, the electrons gave off the X-rays. What happens when electrical charges are jarred is that they produce radiation akin to light—so-called electromagnetic radiation. In the Roentgen tube the fast beam of electrons suffer a tremendous jar when they ram against the metal block. It is such jars that produce the highly energetic electromagnetic rays we know as penetrating X-rays.

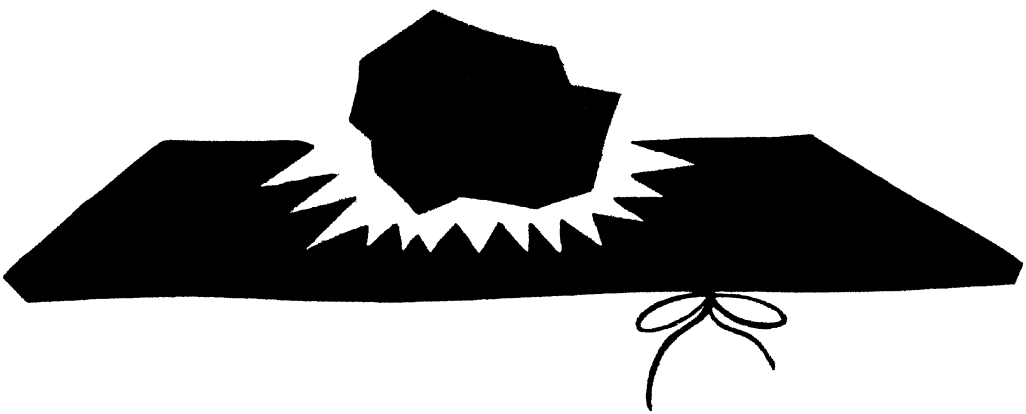
Electron tubes and how they led to the discovery of X-rays may appear to be out of place in a book that is supposed to tell the story of the atom. Both the electron tube and the X-rays were explored by scientists who actually had not made the atom the prime object of their study. But the road of science is tortuous. Frequently the men traveling it do not know where it will lead them.

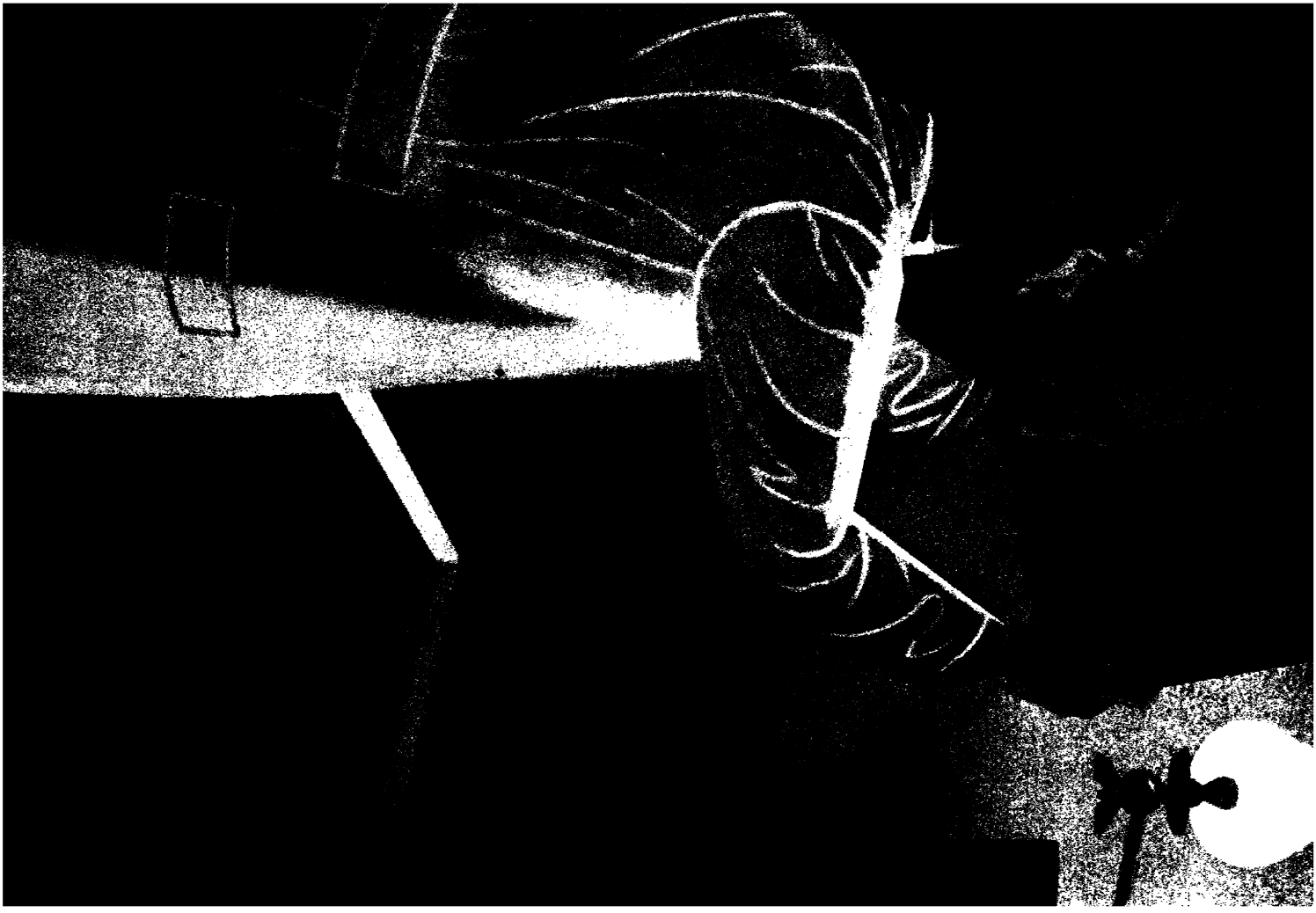
Without the electron tube there wouldn't have been any X-rays. Without the X-rays there wouldn't have been any studies by scientists trying to find out what the X-rays are. Among these studies there was one, in fact, that led into a dead-end street. This particular study did not yield the explana-

tion of X-rays, even though this was the aim. The investigating scientist could not find the correct explanation, because he had made a wrong assumption. And but for this error we might still think of the atom as a little hard, indestructible ball!

The year after the discovery of X-rays, Henri Becquerel of France became interested in a cheap metal called uranium. In a dictionary compiled at that time uranium was defined as "a heavy, practically worthless metal." Little did Becquerel know that this worthless metal was to be the star of important scientific events—then, and again fifty years later. It interested him because it was known to make materials fluorescent when added to them to form "uranium salts." He thought that X-rays were somehow related to the eerie glow that electrons or sunlight produced in fluorescent materials. Uranium salts were known to give off strong fluorescent light for a while after they had been exposed to sunlight.

So Becquerel ran a series of experiments in which he first put samples of uranium salts in the sun. Then he took the softly glowing samples and placed them on top of photographic plates tightly wrapped in black paper.





When he developed his plates, he found that the uranium salts had indeed exposed them. The plates showed foggy spots at all those places where the samples had been put. The salts had exposed the plates right through the thick wrappers, just as though they had been the source of penetrating X-rays. Becquerel thought he had something.

One day it started to rain in Paris, and it didn't stop raining for a whole week. There was no sunshine in which Becquerel could expose his samples of uranium salts. He stopped his experiments, but after three days without sunshine he got impatient. He went ahead with his experiments—without sunshine. He placed another sample of uranium salt on his wrapped photographic plates even though this sample had not been in the sun and did not show the fluorescent glow. The sample exposed the plates, anyway! The penetrating rays from the uranium salt had nothing to do with sunshine or the fluorescent light. They had nothing to do with the fact that uranium salt was used, not pure uranium metal.

Uranium, then, was constantly "alive"—giving off a strange new kind of radiation that fogged photographic plates right through their protective wrappers. It was radioactive. Becquerel had discovered a new phenomenon. To us, in the atomic age, "radioactivity" sounds familiar. Its discovery was the beginning of something entirely new, a snowball that sent a whole avalanche of atomic discoveries on its way.

TELL-TALE RAYS

RADIOACTIVITY was such a new, unheard-of thing that scientists were baffled. But uranium was only the beginning. If scientists thought uranium was hard to explain, they didn't know that their problem was soon to become more than two million times bigger.

When scientists run into a roadblock such as this, they go after more facts, often searching blindly. Among the scientists who responded to this challenge were a married couple in Paris—Pierre and Marie Curie. He was a physicist, she primarily a chemist. They turned out to be a well-equipped fact-finding team.

Their first step was to go back to the very source of radioactivity: not to uranium itself but to raw uranium ore as it is found in the earth's crust, mixed with other metals and minerals.

For some time the Curies tested the strength of radioactivity of a great number of uranium ore samples. Some samples were found more radioactive than pure uranium. But uranium was only part of the mineral mixtures they were using, other materials forming the bulk. There was only one conclusion: among these materials must exist a substance more radioactive than uranium itself.

Madame Curie went to work separating the uranium ore into its many component parts. It was a chemist's work on a grand scale. Normally chemists keep their samples in handy bottles that contain only a few ounces of chemicals. Madame Curie started out with a whole ton of uranium ore. For months their wooden building in Paris looked more like a factory than a laboratory.

Slowly her ton of ore shrank as she threw out the dead minerals and the uranium itself. With every step in the long process of elimination, her

sample grew smaller, and the strength of its radioactivity increased. In time she discovered a new element that was highly radioactive. She named this second, rarer radioactive element "polonium," after Poland, her native country.

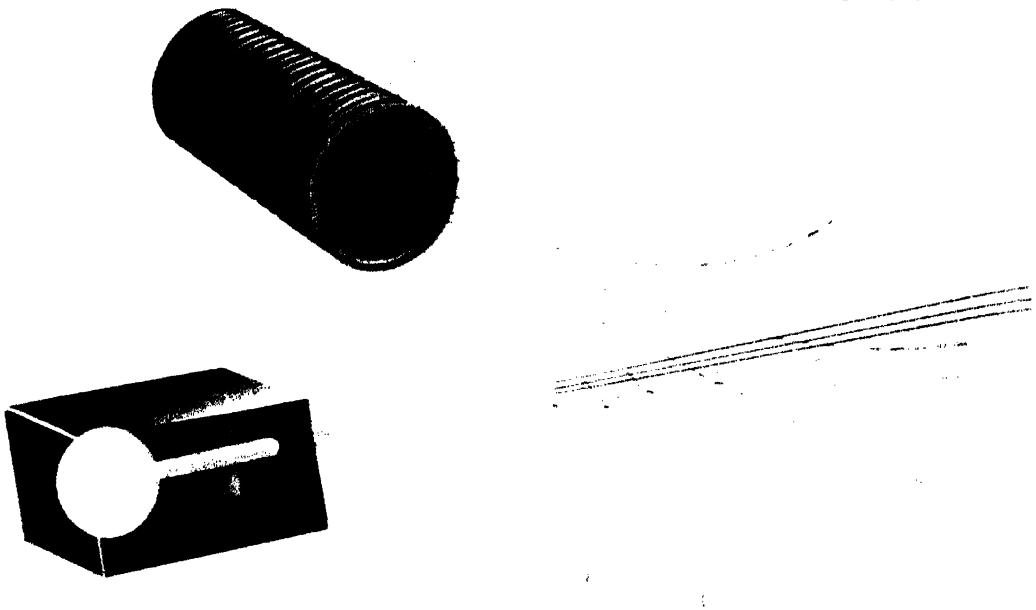
But there was still a small remainder, free of uranium and polonium, yet still radiating. It must contain still another radioactive material. So Madame Curie forged ahead. Presently she had whittled down her original ton to a tiny sample weighing less than 1/100 of an ounce. And this tiny sample was more than 2 million times more radioactive than the same weight of pure uranium! It radiated so strongly that it glowed faintly in the dark. And this sample was always a few degrees warmer than the temperature of the laboratory—it kept itself warm all the time.

This amazing sample of matter, too, turned out to be a new element. Madame Curie called it "the radiating one"—radium.

Uranium, polonium—radium! The chance discovery of Henri Becquerel and the patient work of Madame Curie now shook the firm foundation of physics. Up to now physicists had been dealing with forces of mechanics, with vibrations of sound, with heat, electricity, magnetism, and light. Everything, or almost everything, had been well understood and, together with the tiny atom, had found its place in the orderly files of physics. Now appeared this enigmatic trio—uranium, polonium, and radium. Rays and radiation became the talk of the day. What was it that emerged from the unseen depths of the atoms of which these strange metals were made?

It was several years before scientists found out about the nature of these rays that fogged photographic plates, electrified air, and—turned out to be vicious and dangerous to man! These rays slowly caused painful and dangerous burns in people who unduly exposed themselves to them. But in this battle for knowledge man was not without weapons. Studies of electron tubes had provided some experience with rays.

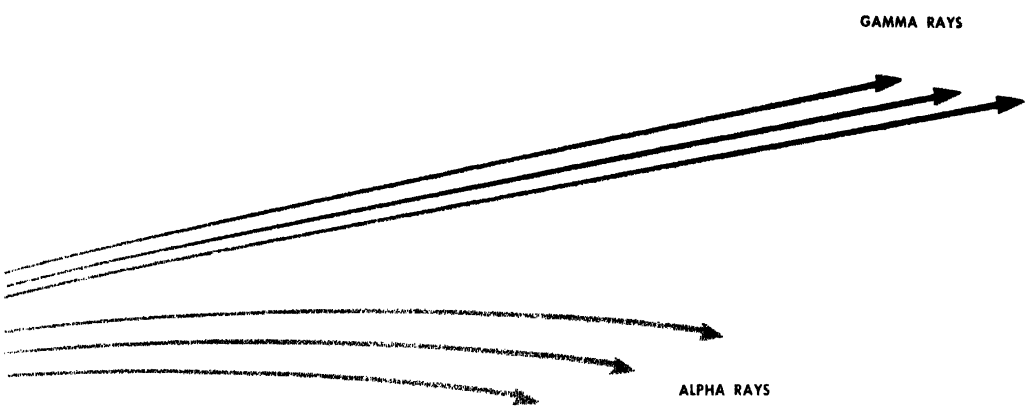
An ordinary magnet placed near an electron tube was known to bend the streams of electrons to a curve, while without the magnet they travel in a straight beam. This behavior of the electrons was well understood. A moving



electrical charge had long been known to act like a magnet. This is the basis of the everyday electromagnet used in switches and relays and in the ordinary doorbell. When an electric current is run through a coiled wire, a magnetic field is created like that of an ordinary magnet. Similarly, a moving magnet produces an electric field. This close kinship between electricity and magnetism was discovered more than a hundred years ago and led to a field of physics and engineering called "electromagnetism."

Now, the laws of electromagnetism explained why the fast-moving beam of electrons in the tube would run in a curve when a magnet was held near the tube. The electrons—little carriers of negative electricity that they are—react to the field of the magnet and are drawn over to the side.

Knowing all this, scientists went after radium with a magnet. But the test wasn't as simple as with the electron tube, in which the electrons run in beams. The rays emerging from a sample of radium fly off in all directions like rays from a miniature sun. So the first task was to produce a linear beam of radium rays. This was done by placing the radium sample in a hollow piece of lead, which is able to absorb radium rays. The hollow block of lead had a small hole through which the rays from the radium inside emerged in a thin straight beam.



Then a magnet was placed near the hole so that the rays shot through its magnetic field. It was found that some rays from the radium did indeed bend to the side. This proved that the rays consisted of streams of charged particles.

One kind of rays bent to the right. They were called "alpha-rays," after the first letter of the Greek alphabet. Another kind of rays bent to the left. They were called "beta-rays," after the second letter of the Greek alphabet. The beta-rays carried a negative charge—a fact that was obvious because the position of the magnet was such that negative charges would bend to the left side. The beta-rays turned out to be well known—they were streams of electrons. But these beta-electrons from radium were much faster than the ordinary electrons physicists had first discovered in their electron tubes. Radium shot off its electrons at a speed almost as great as that of light, which is over 186,000 miles a second!

The alpha-rays were much harder to identify. They had to be carriers of a positive charge, because the magnet bent them to the right—opposite to the bending of the beta-rays. But beyond this, the researchers were baffled; they didn't find at first any known particle that would behave this way.

Then a third variety of rays was found in radium radiation. They were logically called "gamma-rays," because gamma is the third letter of the Greek alphabet. These rays went straight through the field of the magnet without bending. Light and X-rays do the same. Gamma-rays were, indeed, found to be a particularly powerful and penetrating kind of X-rays.

The battle for knowledge went on. Next the fire was concentrated on the

particles that made up alpha-rays. Shrewd experiments were set up that put the alpha-particle on the witness stand. With their experiments scientists kept asking questions brilliant in their logic. Finally, during the first years of this century, the alpha-particle broke down under this relentless cross-examination. It surrendered its secrets, above all its personal description; weight: four times heavier than a hydrogen atom; electrical charge: positive with two charge units, each the size of the electron's charge. That meant one alpha-particle could be neutralized electrically by two electrons.

The electron, incidentally, was a co-defendant in this trial. Its weight was revealed to be extremely small: almost 2,000 times lighter than a hydrogen atom, the lightest atom known in Nature. When it comes to weight, the electron is a sheer nothing compared to the tiny atom itself.

The famous English physicist Sir Ernest Rutherford and his chemical co-worker, Frederick Soddy, did most of this fascinating detective work. In the United States, Dr. Robert A. Millikan concentrated his efforts on the electron. He measured its charge in known electrical units and could then compute its unbelievably small weight.

In 1903, Rutherford and Soddy came forth with their explanation of radioactivity. It destroyed the atom of Dalton, and the element of Boyle. It proved that the atom had been misnamed since Democritus first named it. No longer could it be considered "uncuttable." Rutherford and Soddy showed that some atoms, at least, cut themselves to pieces by their own actions.

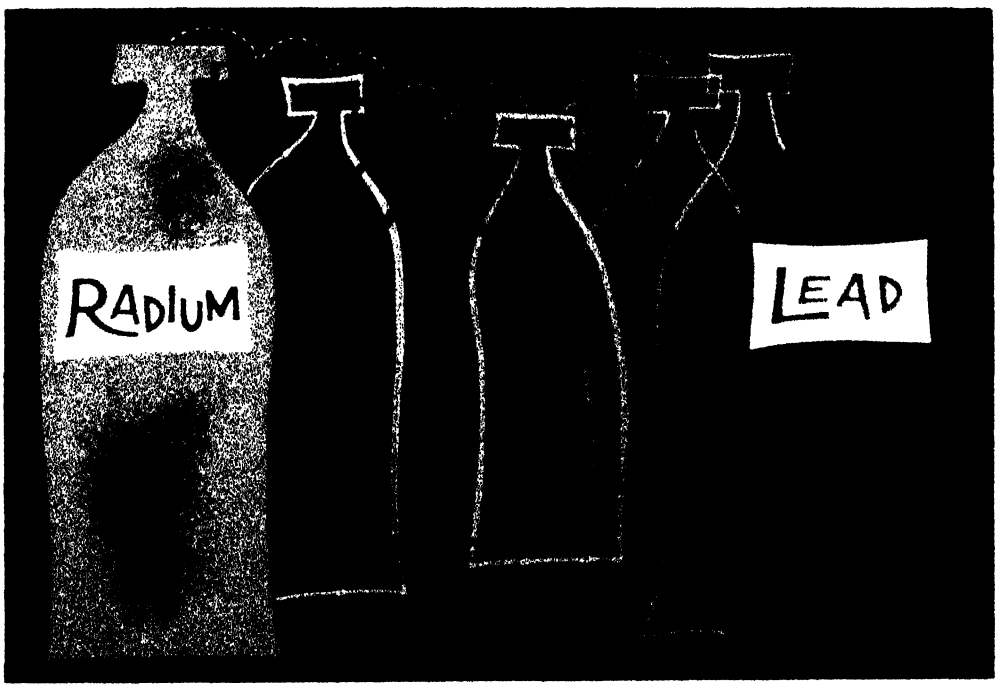
An alpha-ray is the birth cry of a new atom! Not all atoms are created eternally. New ones are created all the time.

A radium atom weighs 226 times more than a hydrogen atom; its atomic weight is 226. An alpha-particle weighs 4 times more than a hydrogen atom. So when a radium atom shoots off an alpha-particle, it loses 4 weight units in the process, and it winds up with an atomic weight of 222. That makes it a different atom. Atoms weighing 222 units are atoms of a different chemical element. Its name is "radon"—a rare, heavy gas.

By giving off an alpha-particle, then, the radium atom transforms itself into an atom of a different kind. A new element is created. Boyle was wrong,

at least in this case: for elements *can* be created from different ones. Dalton was wrong, too; for one kind of atom *can* change into another kind.

Radon also is a radioactive element. Its atoms, too, break apart and transform into atoms of still another element. Finally, by the process of successive breakdowns, the original radium atom is transformed into an atom of the metal lead. Lead atoms are stable. They remain forever as they finally emerge at the end of this so-called "radioactive decay series."



If a beta-particle is expelled from a radioactive atom, the atom doesn't lose any weight to speak of, because electrons are so extremely light. But it was found that the removal of a beta-particle with its negative charge does result in a transmutation of an atom into another one. The emission of a gamma ray, however, does not change the atom's chemical nature.

But what happens to alpha-particles, the fragments shot out of radioactive atoms? Alpha-particles have a weight of 4 atomic units. There is an element whose atoms have an atomic weight of 4. Its name is helium—the light gas

used to float balloons and blimps. When Rutherford and Soddy held a sample of the radioactive gas radon inside a sealed bottle, they found indeed a very small amount of helium. Radon atoms had transformed themselves into atoms of helium and atoms of yet another element akin to polonium!

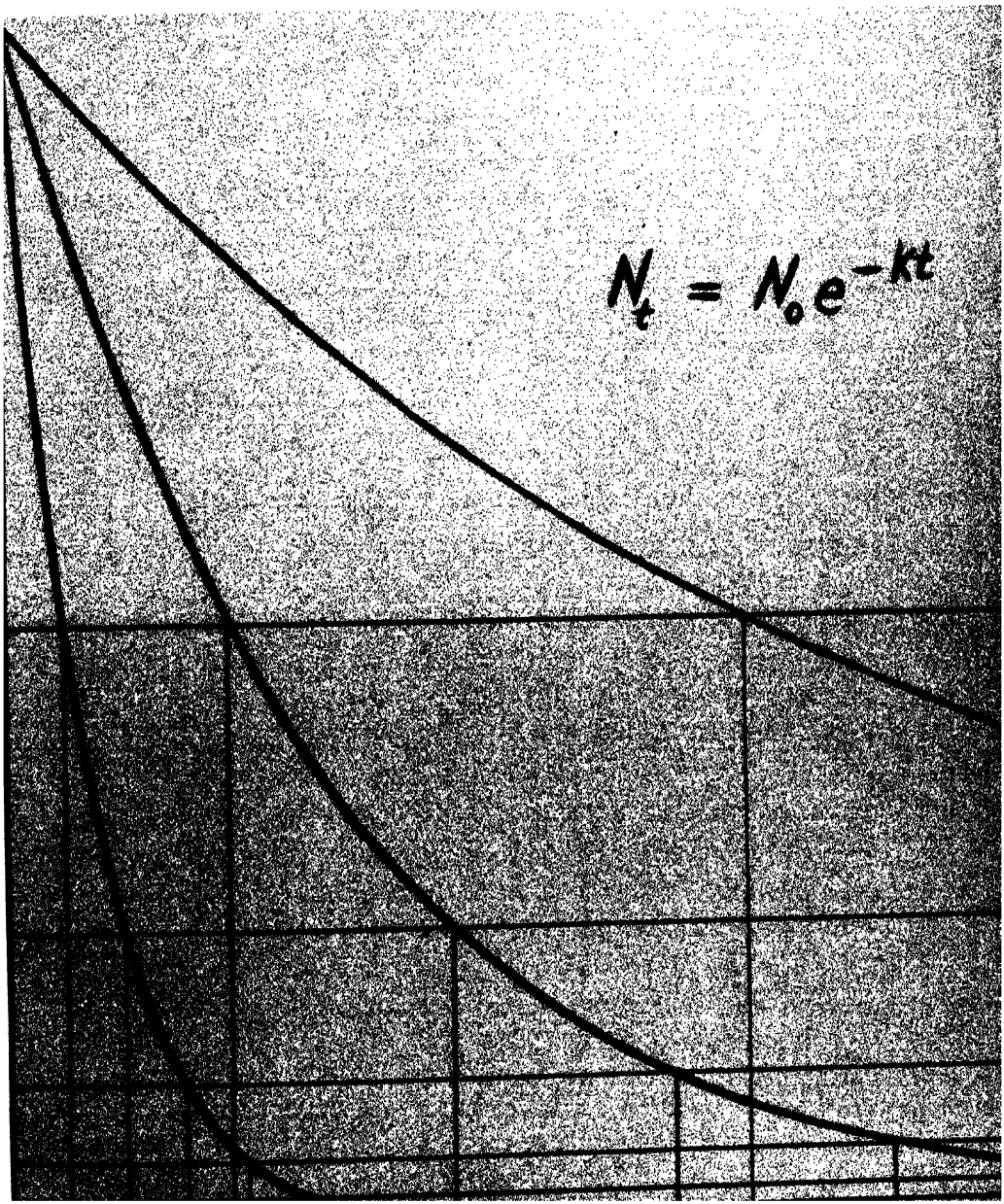
Each radioactive atom can break up only a single time in all its life. Then it becomes another kind of atom. The new one may also be radioactive, like radon, or it may be stable, like helium. Thus a radioactive atom "decays," or breaks down by stages, until finally it becomes an atom of inert lead.

In a sample of radium there is such a tremendous number of atoms that some are breaking apart all the time. Their fragments are shooting out of the sample constantly.

If you pick a single radium atom from the sample, you can't tell when it will break apart. That may happen during the next second, or you may have to wait for twenty thousand years. But the behavior of great numbers of atoms, like great numbers of people, can be fairly well predicted. Every life insurance company knows about how many of its policyholders are going to die during the next year; if it didn't, it couldn't survive. In this respect atoms and people behave alike.

Physicists know exactly what percentage of their radioactive atoms will break up during the next year. They know that 1,580 years from now exactly one half of the atoms in a sample of radium will have broken down. This span of time is the "half-life" of radium; after that time exactly one half of the original radium still is "alive." Another 1,580 years later only one fourth of the original radium atoms will still be present. Uranium, on the other hand, has a half-life of over 4 billion years. Other radioactive elements have half-lives of only minutes or even seconds.

An element with a short half-life is a much stronger radiator than one with a long half-life. In an element with a short half-life the atoms are breaking up so fast that many break-ups occur in a single second. A long-lived element loses its atoms slowly—a few at a time. This is why the short-lived radium is more than 2 million times more radioactive than the sluggish, long-lived uranium.

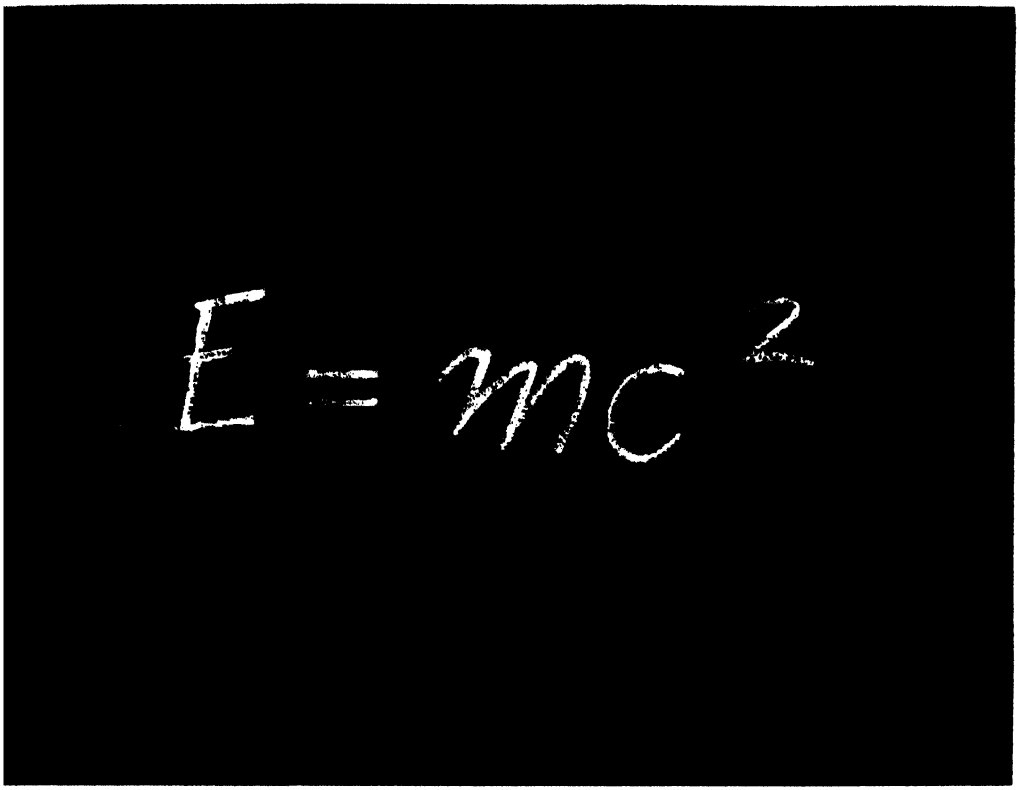

$N_t = N_0 e^{-kt}$

1905

$E=mc^2$

After Madame Curie discovered radium, scientists were fascinated most by the strange radiation that poured forth constantly from the unknown depths of its atoms. These rays, of course, were the most spectacular aspect of the radioactive elements. But the Curies also found that a piece of radium is always a little warmer than its surroundings. This property was less spectacular than the flashing rays, but no less remarkable.

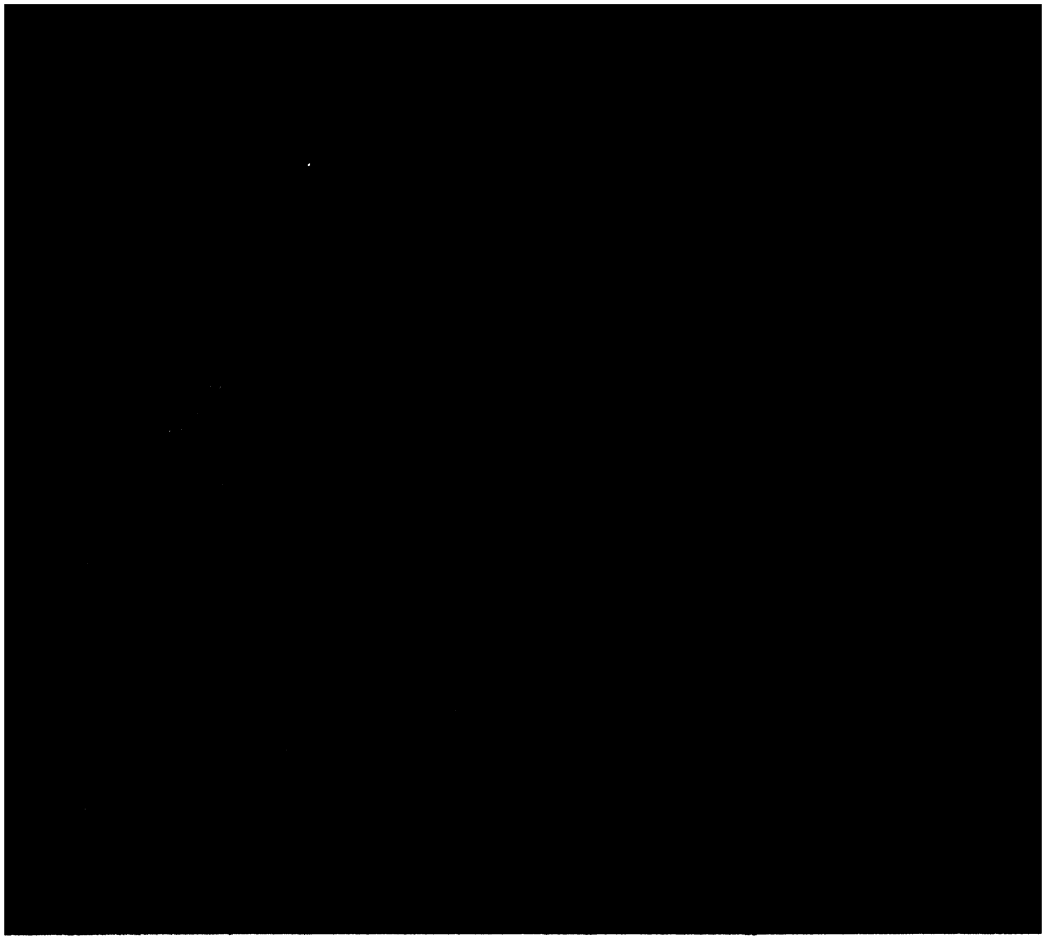
Radium turned out to be a constant and mysterious source of heat. If a bit of radium was put into a thimble full of water, the water would warm up. If the thimble was perfectly insulated to prevent loss of heat, the water became hotter and finally would start to boil. The radium could keep such



water boiling slowly for centuries. So in any tiny piece of radium there lies hidden a tremendous amount of energy that trickles out slowly.

Even before the turn of the century, therefore, the discovery of radioactivity gave science the very first inkling of atomic energy. But for a number of years nobody had even the slightest hunch where this energy came from. Radioactive energy was against all laws of science known at that time.

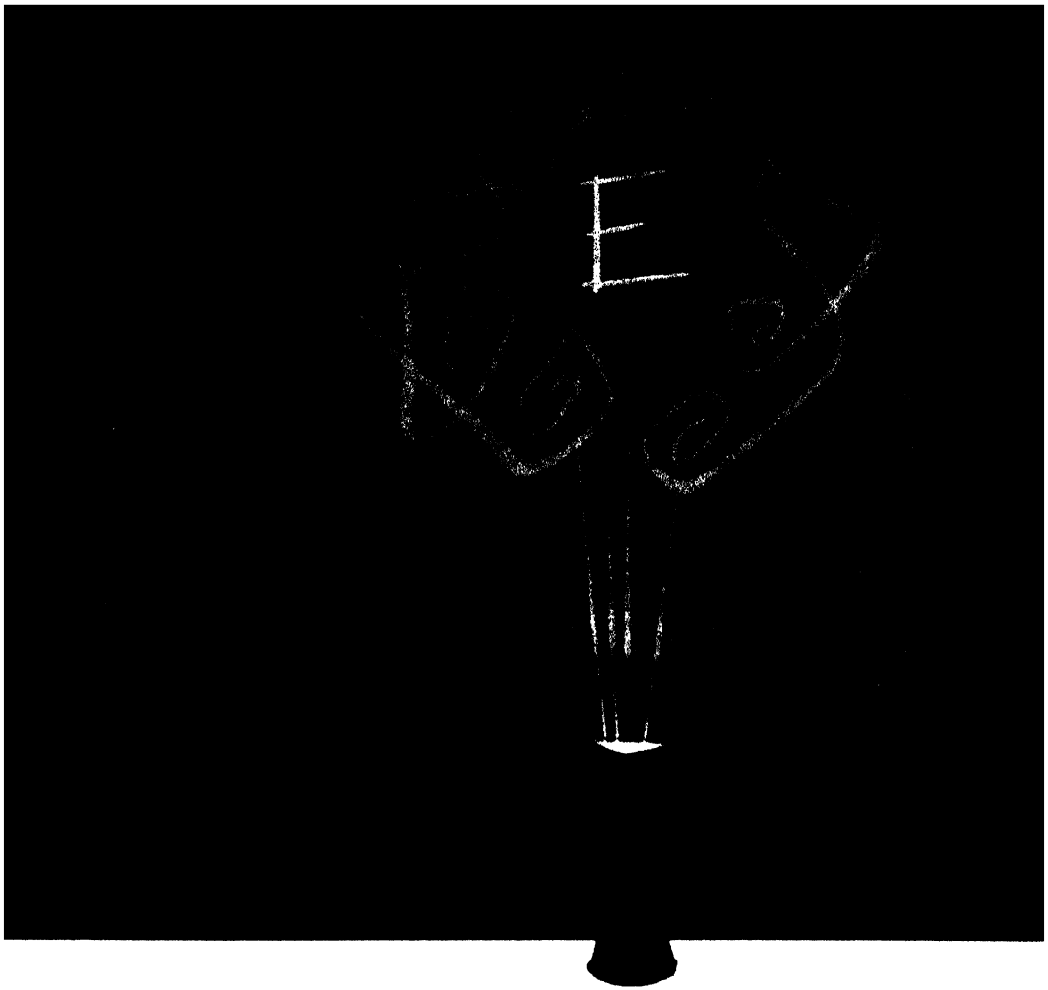
The first understanding of this mystery was achieved by the great Albert Einstein in 1905 when he discovered a new law of Nature. He was only twenty-six years old when, for the first time, he wrote down what was to become the most famous equation in science. This was part of his theory of relativity. It read: $E=mc^2$. E stands for energy, m for mass or matter, and c^2 for the speed of light multiplied by itself. The equals sign means that energy and matter are the same thing, if the latter is multiplied by the quantity c^2.



This is a cold scientific statement, but its deep meaning can be understood through our fable. The fisherman, too, had discovered that a mighty force was contained in a tiny vessel. . . .

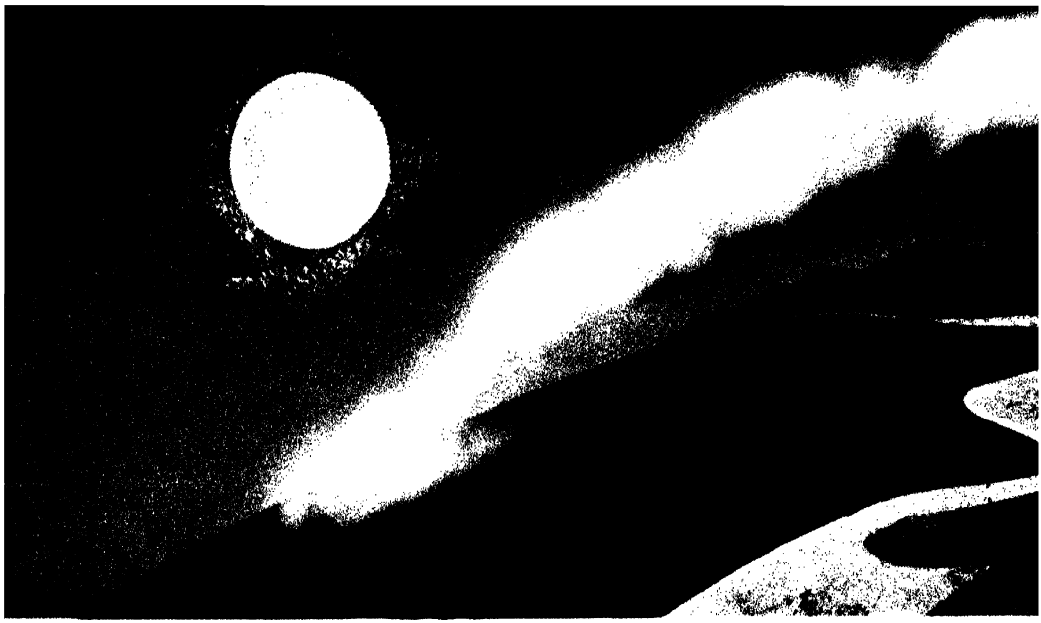
The clue to the Einstein formula lies in the quantity c^2. The speed of light is 186,000 miles per second. This great number multiplied by itself becomes 34,596,000,000. According to Einstein's equation, a mass must be multiplied by this number to find the energy that would be equivalent to this mass. It isn't necessary to tell in what units the energy would be expressed: the result is big in any units!

The Einstein equation only tells that matter and energy are the same thing in two different shapes. The equation itself doesn't tell in what way matter



could actually be converted into energy. But the formula gave scientists the assurance that there could be such a thing as a virtually endless source of energy like radium. So, from 1905 on, scientists had a formula—without instructions.

Nature herself has the instructions, and she has made use of them since the beginning of time. Today we know that atomic energy powers the universe and fires the lights in the sky. Our own sun, for example, delivers energy in the form of sunshine. In every second 4 million tons of its mass are converted into pure energy and poured into space, and this has been going on for billions of years. The millions of other stars pour out energy in like amounts. Nature, in fact, is wasteful of energy beyond comprehension.



The source of stellar energy could not possibly lie in any known chemical fuels. If the sun's energy were produced by the combustion of high-grade coal and pure oxygen, it would burn to a dead heap of ashes within a few thousand years. Like all other stars the sun shines by an atomic fire. Deep in the core of the sun, energy is broiled out of matter in fearful quantities. Slowly this energy trickles through the gaseous body of the sun and flows outward from its surface as sunshine.

A tiny portion of the sun's energy falls upon the earth and keeps us alive. All our energy resources—coal, oil, and water power—go back to the sun for their beginnings, back to the atomic fire raging deep behind the sun's gas walls. Plants that lived thousands and millions of years ago thrived in the shine of the same sun that warms us today. These plants died and were buried under many layers of earth and rock, and under this pressure were slowly transformed to peat and coal. Now we dig these up and use them for fuel. Our oil, too, comes from organisms that were once alive thanks to sunshine. Even today the sun provides us with power. Its heat evaporates ocean water and sends it across the continents to fall as rain. The rain fills the lakes behind our dams, and through broad pipes the water is directed against the blades of huge water turbines that drive generators to produce electric power for our cities, towns, and factories. It is from the

atomic fire deep in the core of the sun that our civilization gets all its power.

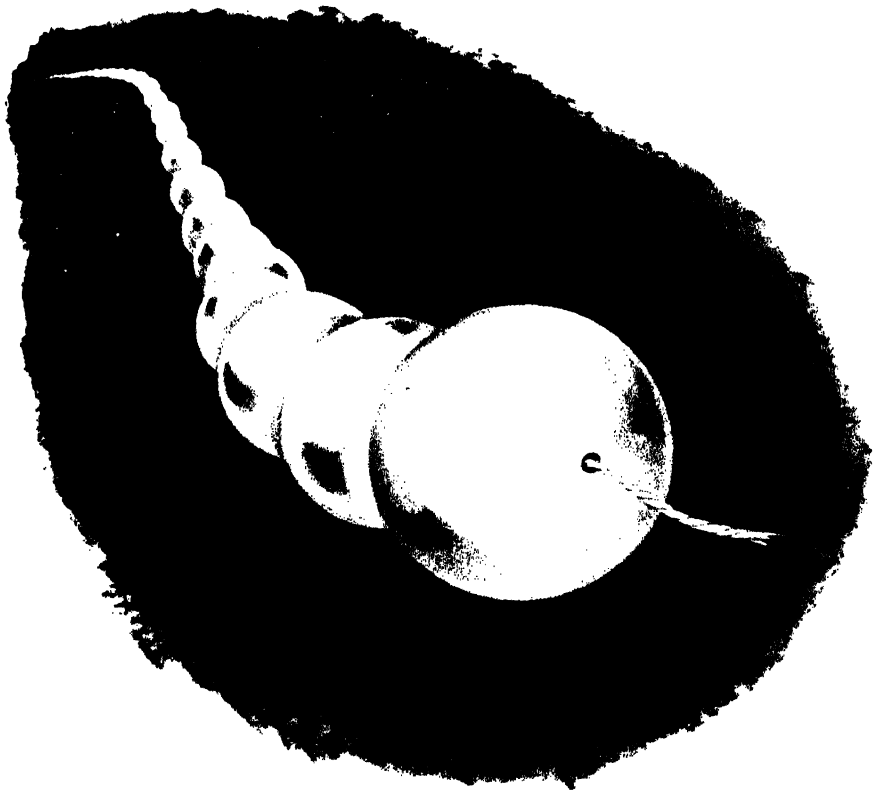
Such was the reasoning of scientists in the decades after Einstein first published his equation in 1905. However, in the beginning their reasoning could not go far beyond the recognition that there is such a thing as atomic energy. Very few scientists, if any, speculated about its practical use in the future. Too little was known about the atom at that time. Even the term "atomic energy"—so familiar to us now—was not used. A few specialists spoke of "sub-atomic" energy; they used this term to indicate that the energy of radioactive elements has its origin somewhere inside the atom.

The interior of the atom—this was the great challenge of science during the first decade of this century.

Radio-activity—atoms breaking apart! It was a great shock to all scientists. No longer could the atom be considered an indestructible, indivisible, hard ball. There were the alpha- and beta-rays: positive and negative fragments that emerged from the unknown depths of the atom's interior. As these fragments proved, the atom must consist of still smaller parts—parts that are electrically charged.

The shock of the discovery of these phenomena was quickly replaced by the excitement and promise of the next big question:

What is the architecture of the atom?



THE ATOMIC SHOOTING RANGE

SUPPOSE that atoms could be put on a string like so many pearls. A girl begins to string herself an atomic necklace 25 inches long. She is very skillful and has great endurance: she strings at the rate of one atom per second, and never stops day or night.

When will she finish her necklace?

Not before 200 years are up!

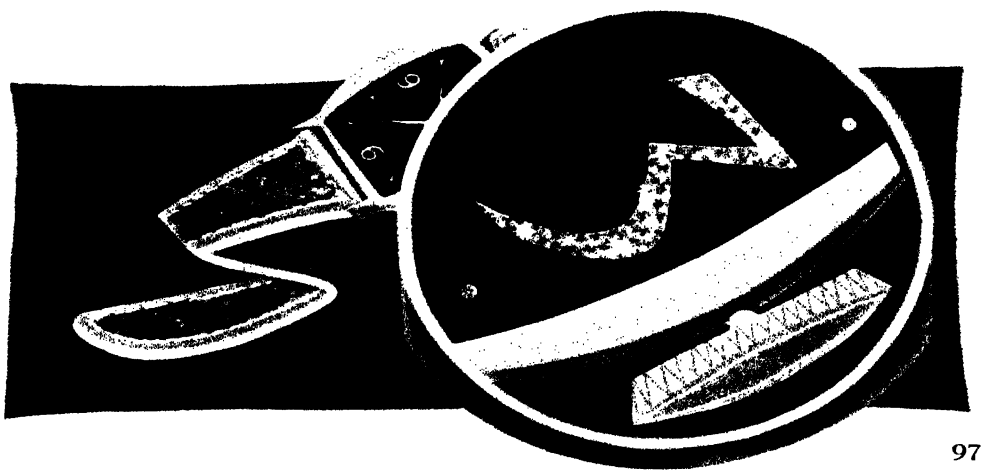
This is only another way of expressing how small atoms are. At this point of our story we must try to visualize the extreme smallness of atoms. Although this is virtually impossible, we must make the attempt because our next step will lead us into the interior of the atom.

The thought of such a step is fantastic. Here is the atom, much too small to be seen and grasped. Any ordinary method of study is doomed to failure.

But in the beginning of our century science faced the problem of probing this tiny structure and tracing its architecture. Fortunately, a method was known for tracing single atoms. It is a simple method, and not only does it trace a single atom; it even traces the tiny fragments that emerge from the inside of radioactive atoms. It's the tremendous speed of the particles of radioactive rays that makes their traces visible.

The method makes use of fluorescent screens of the type already encountered in our chapter on electron rays and X-rays. Take a single alpha-particle that dashes away from an atom of radium as the result of an atomic break-up. It has a speed of many thousands of miles per second. It crashes into a fluorescent screen with a terrific impact. The alpha-particle is a very tiny fragment of an atom, mind you—but it has a lot of wham owing to its tremendous speed. When it slams into the fluorescent screen, it causes a tiny explosion which can be seen under a microscope as a sudden minute flash.

You can demonstrate this action with the self-luminous dial of your wristwatch. The self-luminous coating on the dial is a mixture of radioactive material and fluorescent paint. In every second hundreds of alpha-particles slam into the fluorescent paint. Each one of them makes a tiny flash, and the constant sparkling makes the dial glow dimly in the dark. Under a microscope the dial looks like a display of miniature fireworks. The flashes pro-



duced by atomic particles in fluorescent materials are called "scintillations."

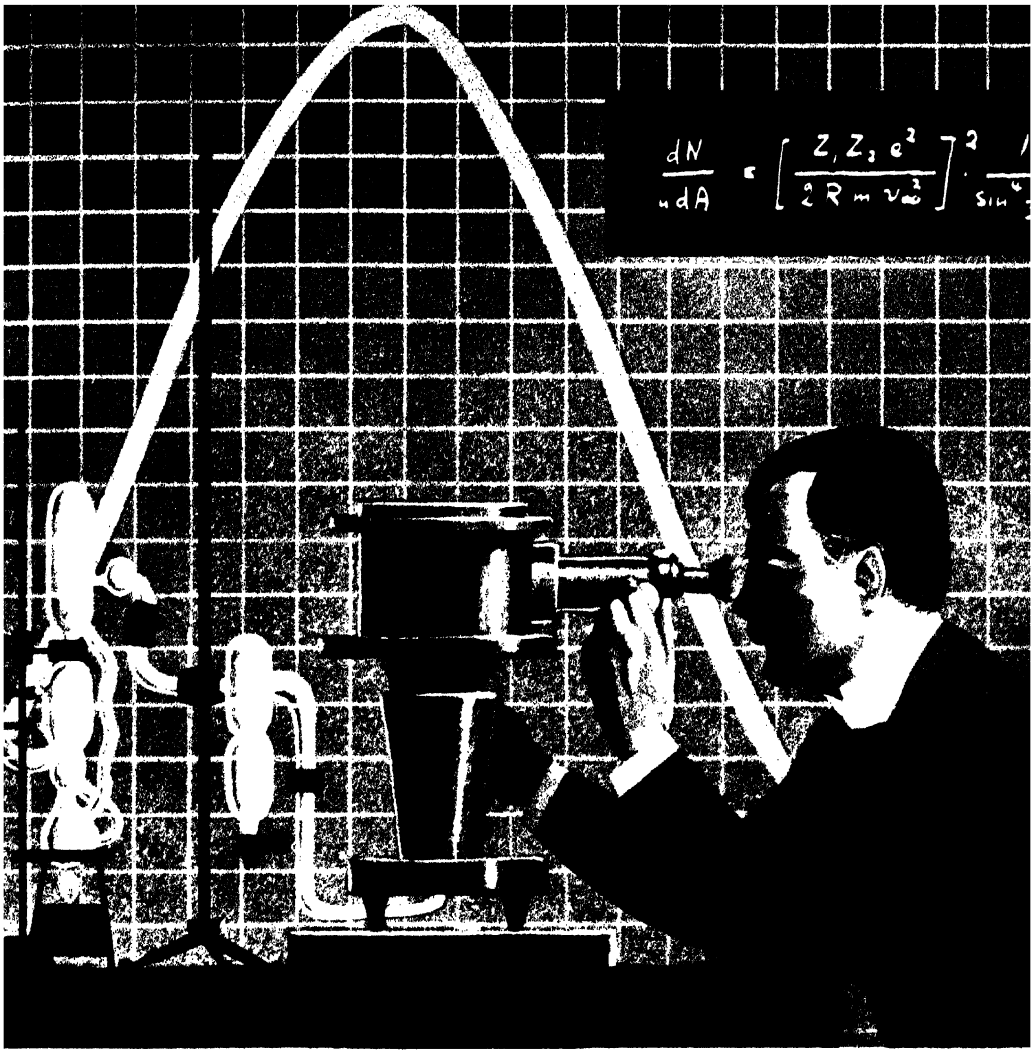
The fact that a single alpha-particle could be traced was very exciting to scientists. It meant that this particle could be used as a tool of exploration. As always in science, when a new thing is discovered it becomes a tool for discovering other things that lie around the next corner. The development of the rocket, for example, enabled man to send hundreds of miles into the upper atmosphere mechanical messengers which faithfully report back to earth what they see, hear, and feel. Likewise, early in our century scientists could shoot their alpha-particle into the atom. It was small enough to serve as a messenger, because it was known to be a fragment of the atom. To explore the atom, then, scientists used atomic bullets.

The first scientists to do so were the two German physicists Geiger and Marsden. They observed some very strange things, and their results encouraged Sir Ernest Rutherford to pursue this line of research more closely. Rutherford was the famous English scientist who had been able to explain the nature of radioactivity. He had shown that atoms break up, and through his work he had posed the question as to what the atom's architecture is. Now he began a long series of shooting experiments, for which he built himself an atomic shooting range.

His atomic machine gun was a sample of radium buried inside a block of lead with an opening for the rays to escape. This block he placed inside a glass jar that was pumped out to a good vacuum, because he did not want any interference with his bullets by air molecules. His atomic bullets traveled in a straight line, like bullets from a machine gun fired at close range.

To make the impacts of his bullets visible he used a fluorescent screen attached to the front of a microscope. First he placed the microscope bearing the screen so that his line of sight through the microscope was directly into

Rutherford's atomic shooting range



the muzzle of his "gun." On the screen he saw a constant sparkling at the point where the bullets from the gun were striking.

Then he mounted in front of the gun an extremely thin piece of gold foil—less than a hundred thousandth of an inch thick. Thin it was, but atoms are very small. For the atoms, the gold foil represented a thick wall, more than 2,000 atoms deep. And each gold atom weighed as much as 197 hydrogen atoms—the atoms of gold being among the heaviest there are. Atomically speaking, therefore, this wall of gold represented solid armor.

Again Rutherford peered through his microscope. To his amazement he saw the constant sparkling on the screen as before. It was as though his gun were shooting through a ghost: the alpha-particles were still bombarding the screen. They were pouring through the wall of atoms represented by the foil as though it were not there at all!

The wall was thick. If the gold atoms had been as big as baseballs, the wall would have been about 400 feet thick—more than a whole city block thick. And the atomic bullets went right through this kind of wall. They tore into the screen just as they did before the gold foil was put in their path. The target spot on the screen still flickered and sparkled as bright as before.

Right then and there, an age-old idea of the atom vanished into nothingness. Atoms could not be solid—they could not be the impenetrable, absolutely hard little balls they were thought to be. What, then, was really happening on the atomic shooting range?

Rutherford kept spying through his microscope, the gold foil still in place. Then he saw something. There was a tiny flash on the screen—far out to the side of the target area. Then he saw another flash, this time to the other side, right out at the rim of his field of view. . . . Then another one at still another place.

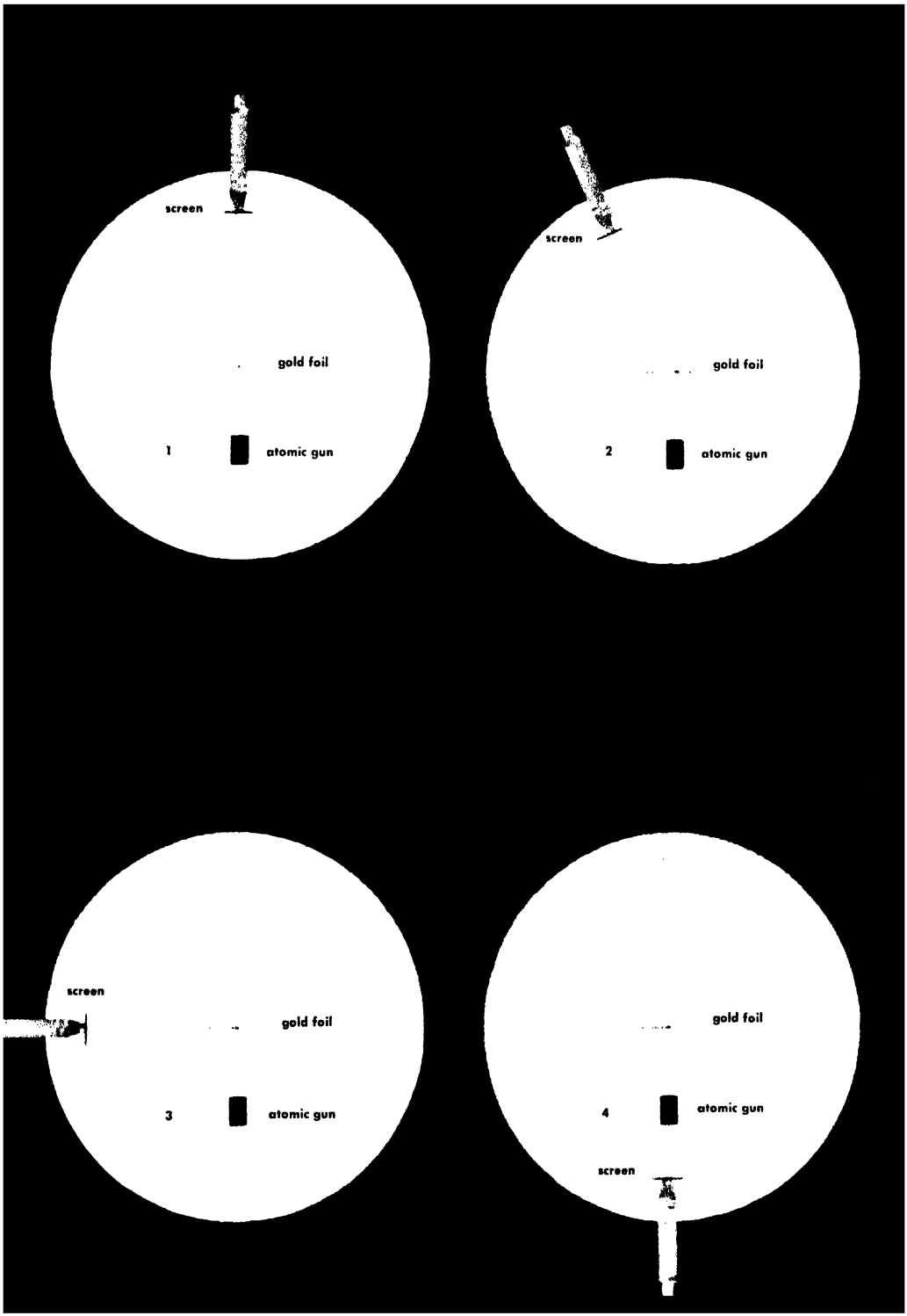
He shifted his microscope to the side, so his line of sight was no longer into the muzzle of the gun. The screen was now dark. But there—there was a tiny flash, where just a single bullet had struck!

He brought the microscope and screen around to a position at right angles to the gold foil.

His line of sight was now directly across the beam of bullets. Again a single flash on the screen! This bullet must have bounced off something; it had reached the screen by ricocheting at a right angle.

Next he moved the microscope and screen behind the "gun." His line of sight was now in the direction of his bullets, like that of a machine gunner behind his weapon. Another flash on the screen: this single bullet must have bounced right back at him like a bullet from armor plate!

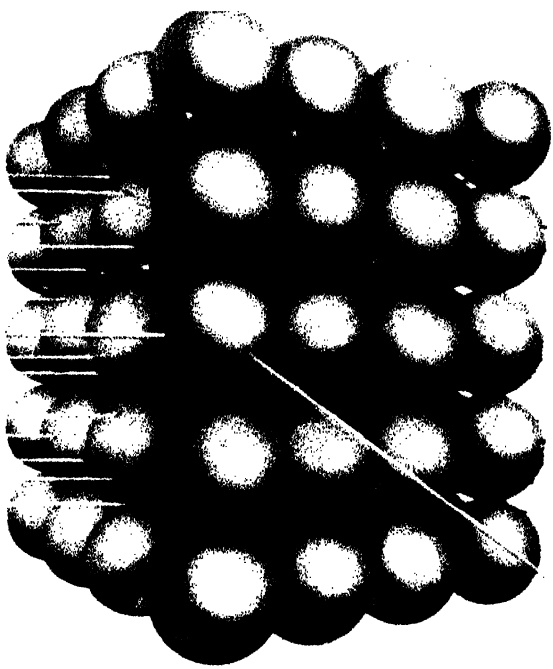
Rutherford repeated his experiments many times. He counted the bullets


screen
gold foil
1
atomic gun
screen
gold foil
2
atomic gun
screen
gold foil
3
atomic gun
gold foil
4
atomic gun
screen

that went straight through his wall of atoms and he counted those that bounced off in the various directions. The result was amazing. Only one out of more than 8,000 bullets bounced!

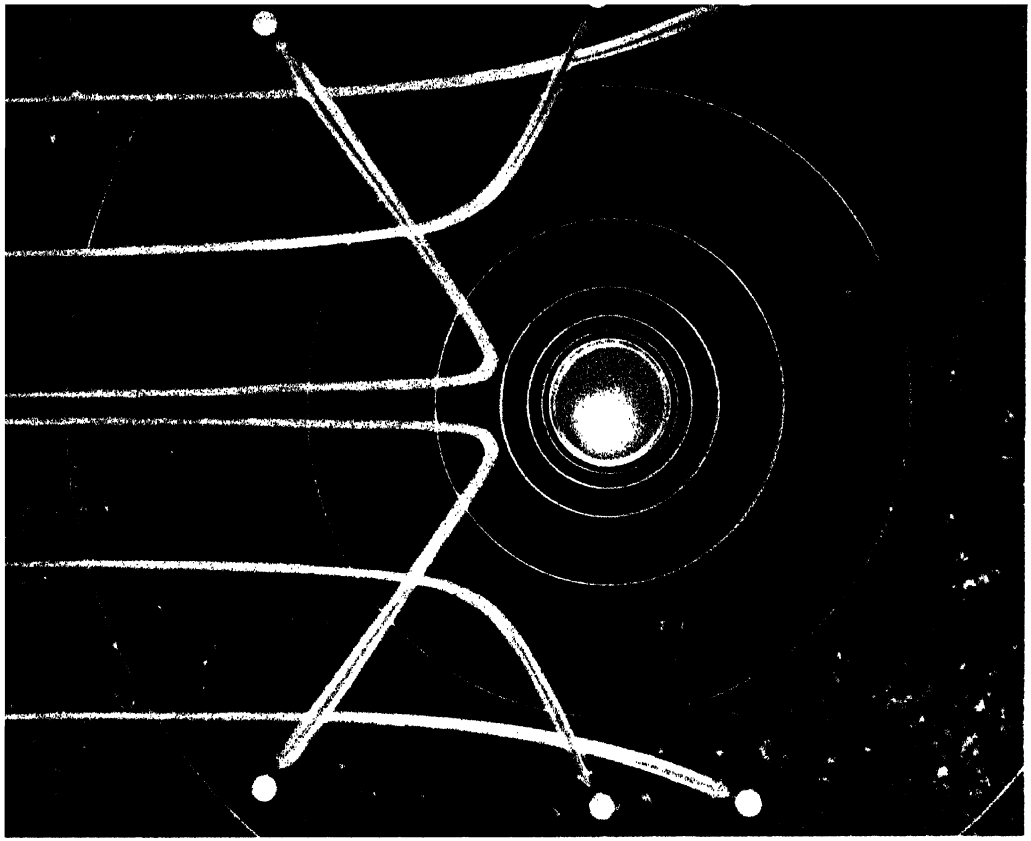
Imagine a huge stack of thousands of tissue paper boxes each containing a single small marble. When you spray this stack with birdshot, almost all of them tear right through the whole stack. Only a few will happen to strike a marble, glance off, or rebound. If the marbles are small enough, chances are that only one out of 8,000 bullets will ricochet.

That was approximately the situation encountered by Lord Rutherford. He reasoned that the heavy wall of gold atoms was actually nothing more than a stack of almost empty shells. But something *must* be inside each shell—a small center, a hard core which caused the rare ricochets. This core must be unbelievably small—much smaller than the atom itself. The core had to be very small because the chance of hitting it was so small.



Rutherford called this little core the "nucleus" of the atom. From his record of hits and misses he learned how small the nucleus is in relation to the atom: ten to fifty thousand times smaller!

The atom is indeed an empty shell—almost empty, that is. Practically the entire weight of the atom is concentrated in the tiny nucleus. The rest is empty space.



The closer the alpha-particles get to the nucleus, the more sharply they are deflected

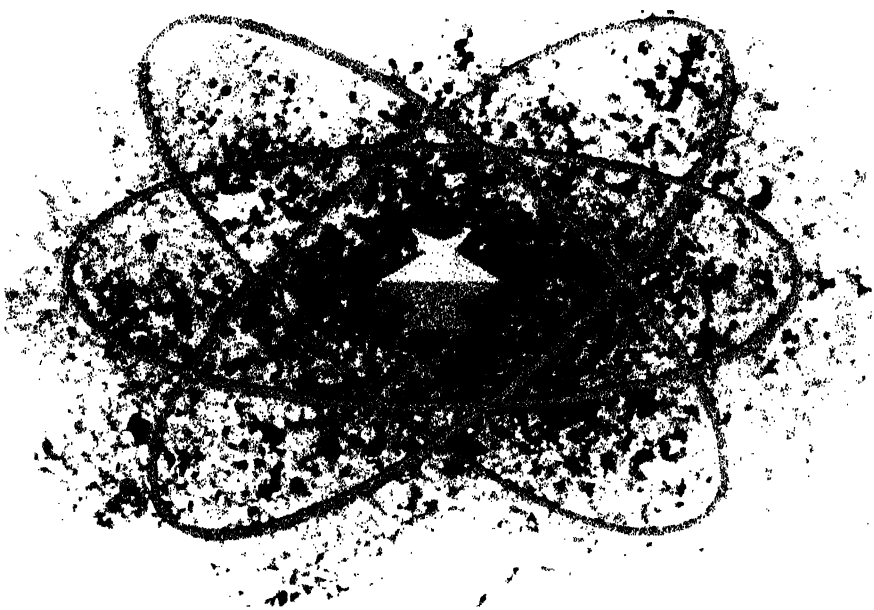
These are not the only findings that Rutherford's tiny messengers brought back from the interior of the atom. The nucleus not only is extremely tiny and fabulously heavy for its size; it is also electrically charged. This was proved by the way in which the alpha-particles bounced off the atomic nuclei —or rather, in more exact scientific terms, were deflected from their straight course.

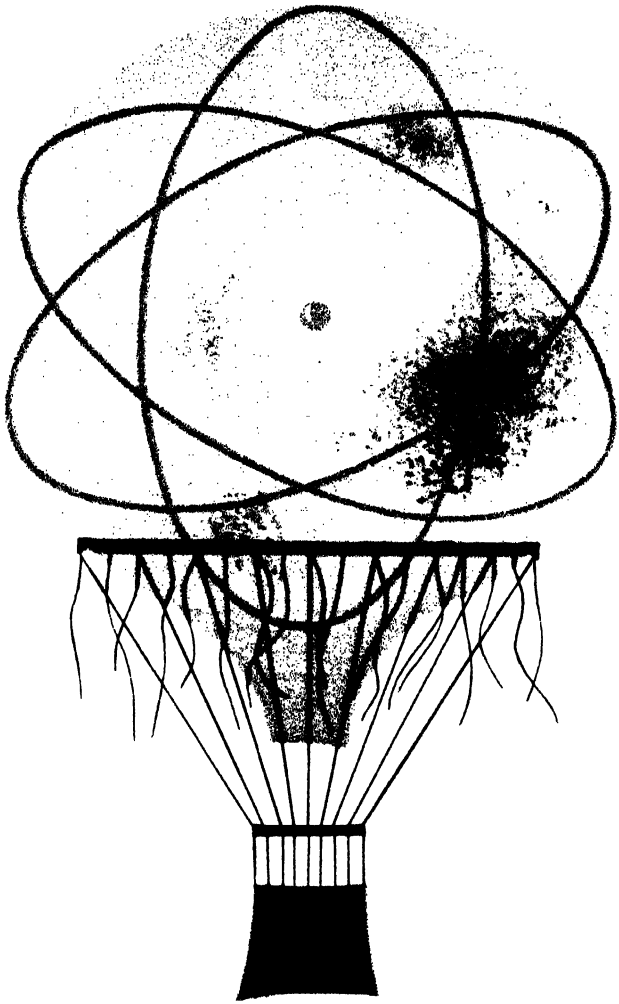
Previously we noted that the alpha-particle bears two units of positive electrical charge. The nucleus, too, is positively charged. The nuclei of gold atoms each bear a very strong electrical charge—79 units! Now, there is a force acting between two like electrical charges, a strong force that pushes them apart. Conversely, a positive and a negative charge attract each other as a magnet attracts a piece of iron. Since the alpha-particle and any nucleus are both positively charged, they repel each other. As the alpha-bullet

approaches the target nucleus, the force acting to keep them apart becomes greater and greater. As with a tiny, invisible hand, the nucleus pushes the alpha-particle to the side so that it continues its flight in a different direction. If the alpha-bullet approaches the nucleus almost dead-center, it is pushed back at a steep angle. In the case of a rare shot directly at the center of the nucleus, the alpha-particle is slowed down, comes to a stop a short distance from the nucleus, and—repelled by a tremendous force—is hurled directly back as if recoiling from a tightly squeezed coil spring.

Thus Sir Ernest Rutherford did well with his experiments on the atomic shooting range. He discovered the nucleus of the atom, measured its unbelievably small size, and proved that it is electrically charged.

The atomic nucleus was the tiny vessel in which the Genie of our story lay imprisoned. The year of its discovery was 1911.





WHY IS THE ATOM SO BIG?

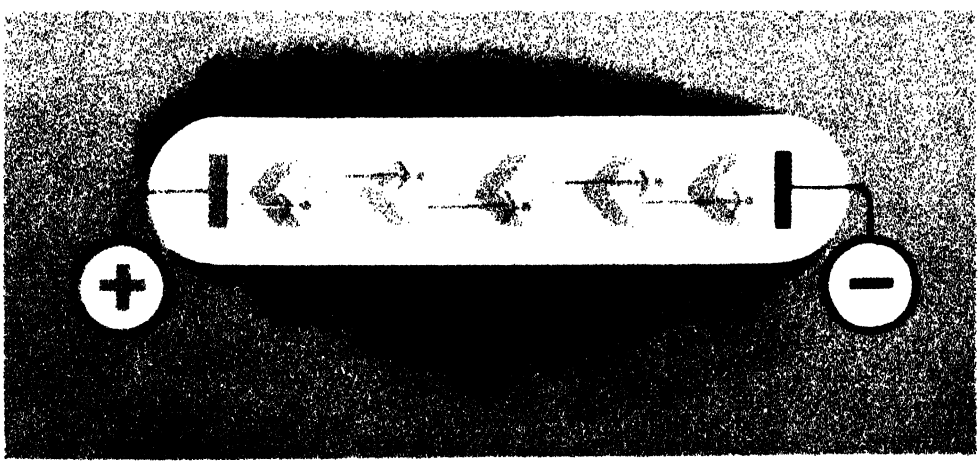
FOR A LONG time scientists had been baffled by the smallness of the atom. After the discovery of the tiny nucleus, the problem reversed itself completely. If the nucleus were enlarged to the size of a small glass marble, the whole atom would be as big as a giant balloon measuring more than 300 feet across! Scientists were hard put to explain why the atom is so big. Its architecture, that is to say, was still a mystery.

Rutherford's work by 1911 had so far unearthed only one important building block of the atom—the positively charged nucleus. Scientists now took stock of their inventory of atomic particles that could serve as atomic building blocks. The guiding idea here was to look for charged particles.

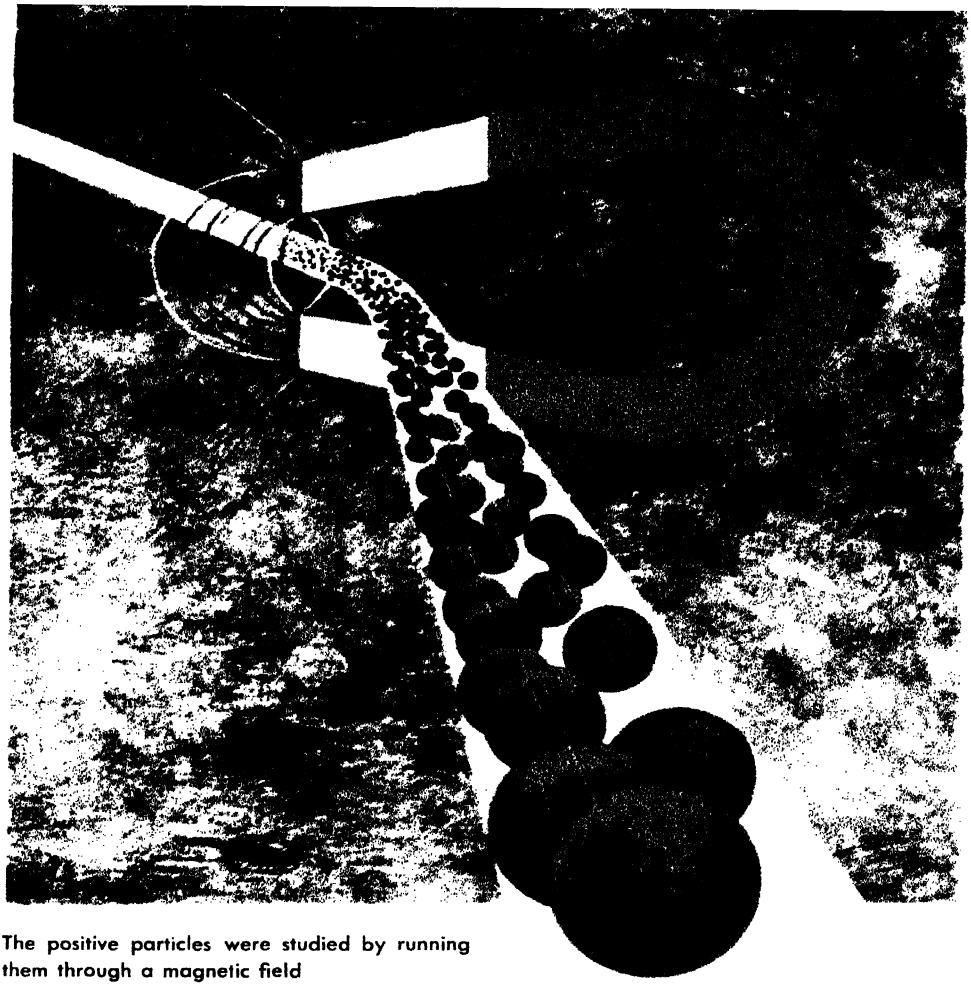
There were, of course, the electrons that had previously been discovered in electron tubes. In 1911 the electron could be put on the stock list of atomic particles as a well-known item. It had one negative unit of electrical charge, and its weight was almost 2,000 times smaller than that of a hydrogen atom having the standard weight of 1 atomic weight unit.

In searching through their stock lists, scientists were particularly watchful for positively charged particles because the nucleus was also positive. And they found one. It was a particle they had filed away under the heading of "charged atom of hydrogen." It had been in their files since 1886, when it was discovered in the electron tube.

In an otherwise perfectly empty electron tube the only particles present are electrons. If a trace of hydrogen is introduced into the tube, positive particles can be observed. Because their charge is opposite to that of the electrons, they travel in the opposite direction. They are attracted by the negative wire owing to their positive charge, just as the negative electrons



Electrons (blue stream), being negative, are attracted to the positive wire; positive particles (red dots) to the negative



The positive particles were studied by running them through a magnetic field

are attracted by the positive wire. The positive particles were studied by running them through magnetic and electric fields, as had been done with electrons and radium rays. It was found that they weighed as much as one hydrogen atom each, and they had one positive unit of electrical charge. Their weight was not surprising; they weighed as much as hydrogen atoms because they *were* hydrogen atoms that had been put into the tube in the first place. However, because they were electrically charged, they were filed away under this heading.

Now, the positively charged hydrogen atom had been standing on the side lines while uranium and radium occupied scientific attention. After the discovery of the atomic nucleus, scientists took a second look at the charged

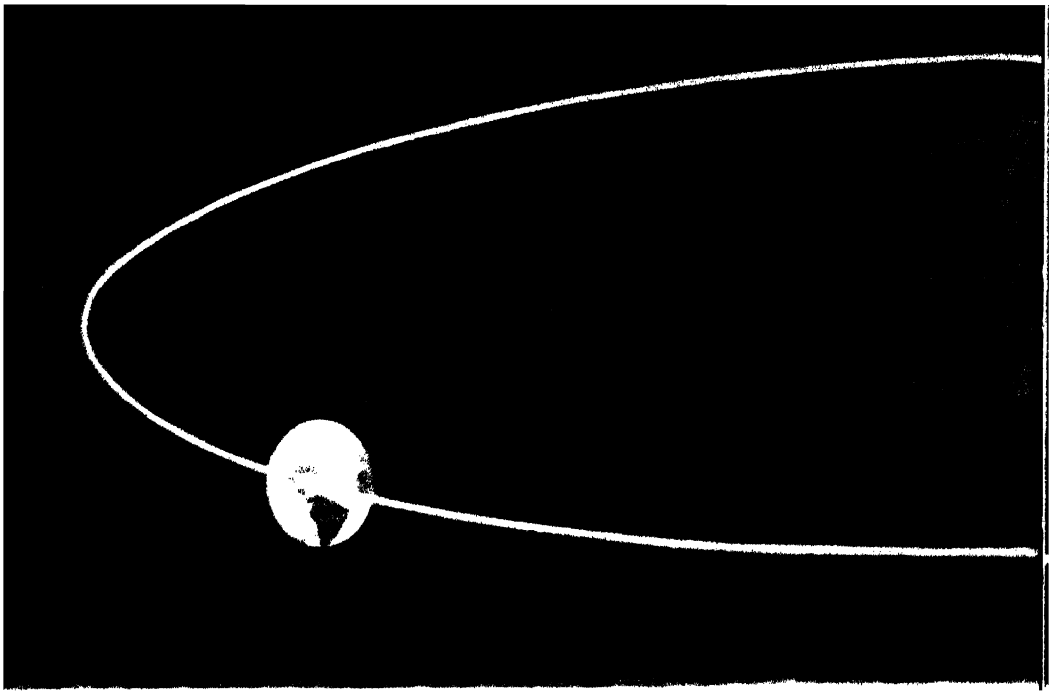
hydrogen atom. If, they reasoned, one negative electron was added to this atom, the electrical charges would cancel and we would get a normal, electrically neutral hydrogen atom exactly like the ones we find in Nature. Adding the light electron wouldn't appreciably change its weight. Could it be that the particle known as the charged hydrogen atom was nothing else but the nucleus of the hydrogen atom?

It was. In fact, the charged hydrogen atom was the most fundamental positive particle that exists. It had an electrical charge of one unit and an atomic weight of one unit. In this new light scientists felt that the "charged hydrogen atom" rated a new and better name that befitted its newly discovered importance. It was henceforth called "proton," which means "primary particle." After all, scientists owed it a flattering name after these long years of neglect.

The proton was assigned the role of the nucleus of the hydrogen atom, the simplest atom in Nature. It was one of the building blocks of this atom. The electron had to be the other, because only then could the proton's charge be canceled without measurably adding to its weight. The two together produce a neutral hydrogen atom. But where was the electron in relation to the proton? So long as the proton was still filed away under its old name, everybody had tacitly assumed that it was as small or as big as a hydrogen atom. Now that it was assigned the role of a nucleus, it had to be many thousands of times smaller. The electron itself wasn't much bigger. The question then was: How to build an atom—a huge atom, mind you—by using one proton and one electron?

We know that a nucleus is very small in comparison to the whole atom—like a marble in a balloon measuring 300 feet across. These grotesque dimensions we must keep in mind as we now proceed to build a hydrogen atom from a proton and an electron. Let's try to build it in this large scale so that the weak powers of our imagination are given something to grasp.

If we enlarge a proton and an electron to the size of marbles, we must also enlarge their electrical charge in the same proportion. This is where we run into a fantastic difficulty. For the proton has a positive and the

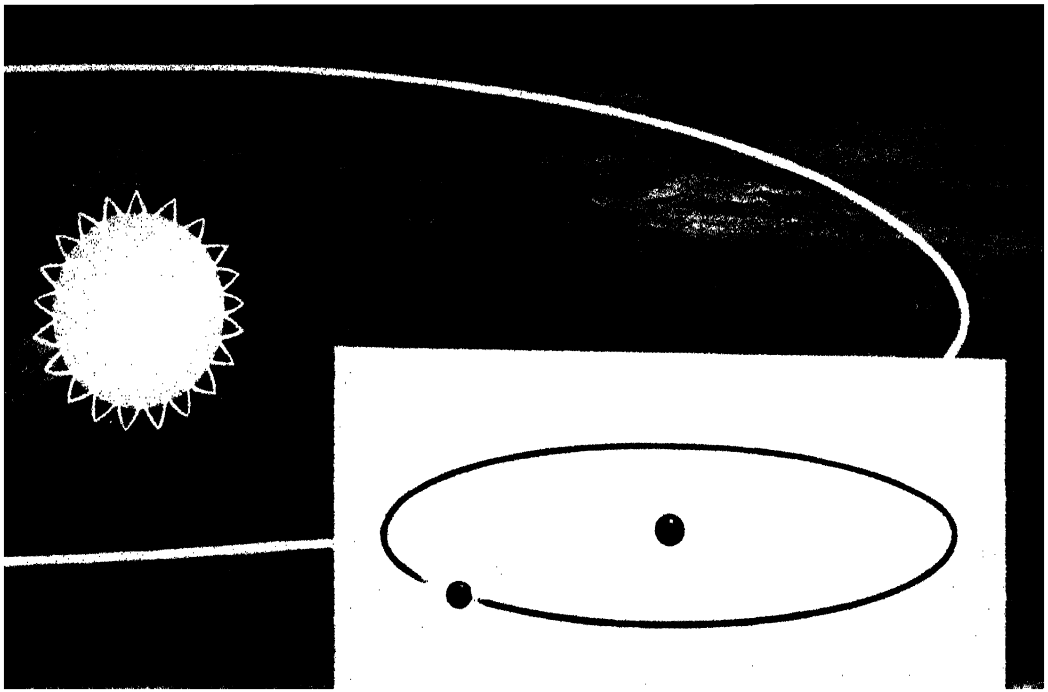


electron has a negative charge. To allow for the proper empty space within the atom, we must place the two charged marbles about 150 feet apart. However, the two opposite electrical charges attract each other. The force of attraction between the two atoms is tremendous. Even over this distance of a small city block they attract each other with the force of 400 million tons!

It is, therefore, utterly impossible to keep the two marbles apart. Even if we filled the 150-foot space between them with a solid wall of high-grade steel, they would bull their way through this wall in their devastating urge to get together. The strength of steel is much too small to resist a force of 400 million tons on an area as small as the cross-section of a marble. The toughest material would behave like butter under this kind of force.

Yet our hydrogen atom *must* be of this size. How in the world are a proton and an electron kept apart by Nature? The answer was given in 1913 by the Danish physicist Niels Bohr.

There exists a famous example of how Nature manages to keep two bodies apart even though they attract each other with an enormous force: the sun and the earth. They attract one another through the force of gravity. How-



ever, the earth doesn't fall into the sun, because it constantly swings around the sun in its almost perfectly circular orbit. Things that are swung around a center are subject to what we familiarly know as centrifugal force. Every boy knows this force from playing with a pail of water on a string. The pail can be swung around overhead without the water spilling out. The water is constantly pressed against the bottom of the pail by centrifugal force. Likewise the force of solar gravity is canceled, and the earth is kept at a safe distance. If the earth suddenly stopped swinging around the sun, solar gravity would take over and the earth would be swallowed by the flaming body of the sun after a deadly fall lasting only about two months.

The same principle works in the case of the two attracting particles that make up a hydrogen atom. When the marble proton and electron are reduced to their natural, small size, the force of attraction between them, of course, becomes much smaller, too. But in proportion to their size, the force still remains unbelievably great. You could guess that the electron must whirl around at a terrific speed to offset this force. Bohr has calculated how fast: not less than 7 million billion times in every second!

In its mad dash around the nucleus the electron is, so to speak, everywhere all the time. Whirling around at this high speed, the electron weaves a dense shell all around the nucleus, just as the blades of a spinning airplane propeller form a "solid" disk.

Bohr's theory of the whirling electron solved the problem of how the atom could be so big. It explained how a large atom could be built of two tiny particles. It indicated also how Rutherford's alpha-particle with its great speed could easily penetrate the space covered by the spinning electron, as a bullet can be shot in between the blades of a whirling propeller. If the electron is hit by the alpha-particle, it is pushed aside like a ping-pong ball by a cannon ball. In shooting atoms with alpha-particles one scores a "hit" only if the bullet happens to come close to the hard, heavy nucleus inside the atom just as Rutherford found.

If a lot of hydrogen atoms are put together inside a bottle, they behave like normal atoms. The electrons in the atoms, with their fast spinning motion, "defend"

The electron in the hydrogen atom whirls around so fast that the atom seems to have a solid shell

the space they cover. When two atoms collide, the nuclei never come into contact; the whirling electrons prevent the atoms from penetrating each other. In this sense the electron makes the atom *act* like a hard little ball.

Hydrogen is the simplest atom. It has as its nucleus one proton with one positive charge. It was soon recognized that other elements have nuclei in which two or more protons are packed together. In a package nucleus with two protons, there would be two positive charges. However, Nature always tries to keep an electrical balance in her atoms; normally they are electrically neutral. To offset the two positive charges in the package nucleus, there would have to be two whirling electrons, forming the atom's shell.

Atoms with two positive charges in the nucleus and two whirling electrons do exist. They are atoms of the chemical element helium—a light gas used for filling balloons. The hydrogen atom is like a sun with one planet; the helium atom is like a solar system with two planets.

To build the atoms of all other elements, we must add more and more positive charges to the nucleus and an equal number of whirling electrons to neutralize the nuclear charge and to build the ever more complicated atomic shells. Three charges in the nucleus and three whirling electrons will give us an atom of lithium, a metal akin to sodium.

A few other combinations are shown at the top of the next page.

Helium has two charges in the nucleus and two whirling electrons; lithium has three of each

Protons		Electrons	Element
6	and	6	for carbon
16	and	16	for sulfur
26	and	26	for iron
47	and	47	for silver
79	and	79	for gold

and finally, the most complicated natural atom:

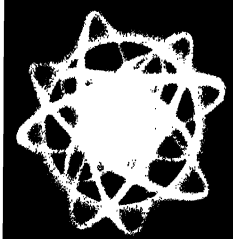
92	and	92	for uranium

For each number between 1 and 92, chemists have found an element. Defining a chemical element has been reduced to the simple procedure of calling a number.

Bohr's idea of the structure of the atom turned out to be very fruitful. Scientists went ahead to explain many facts in physics and chemistry with this new atomic theory. One important discovery was that when atoms join to form a molecule, they do it by sharing electrons of their shells. The nuclei never change in a chemical reaction; they always stay at great distances protected by their shells of electrons.

Bohr's theory gave us the familiar symbol of the atom—a drawing of a tiny solar system. But through Rutherford and Bohr, atomic theory took a very strange turn indeed. The hard, impenetrable ball of the atom turned out to be mostly—empty space! All things around us—the solid chair you are sitting in, your house, the entire earth—everything is virtually empty space, with its widely scattered, forlorn nuclei and electrons. If all the empty space could be removed from a human body—if all its nuclei and electrons could be crowded together into a solid mass—the body would shrink to the size of a tiny grain of sand that can barely be felt between

A family portrait: each atom can be recognized by the number of electrons it needs to balance the charge in its nucleus—carbon (6), sulfur (16), iron (26), silver (47), gold (79), and uranium (92)



6

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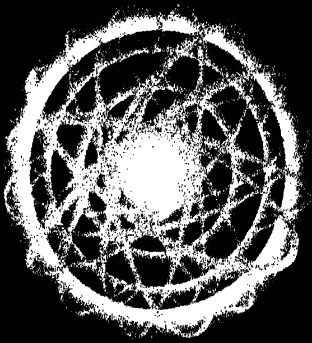

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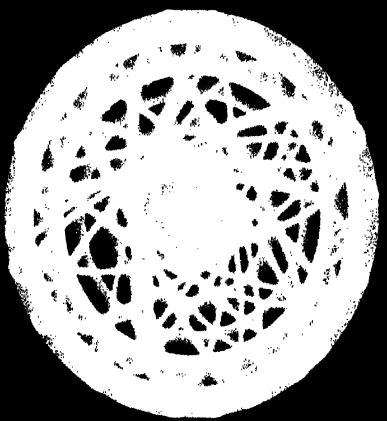

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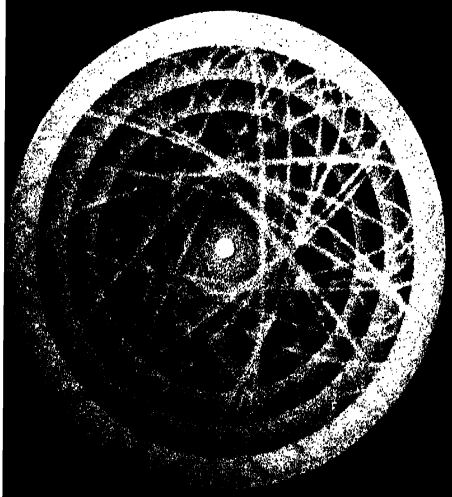
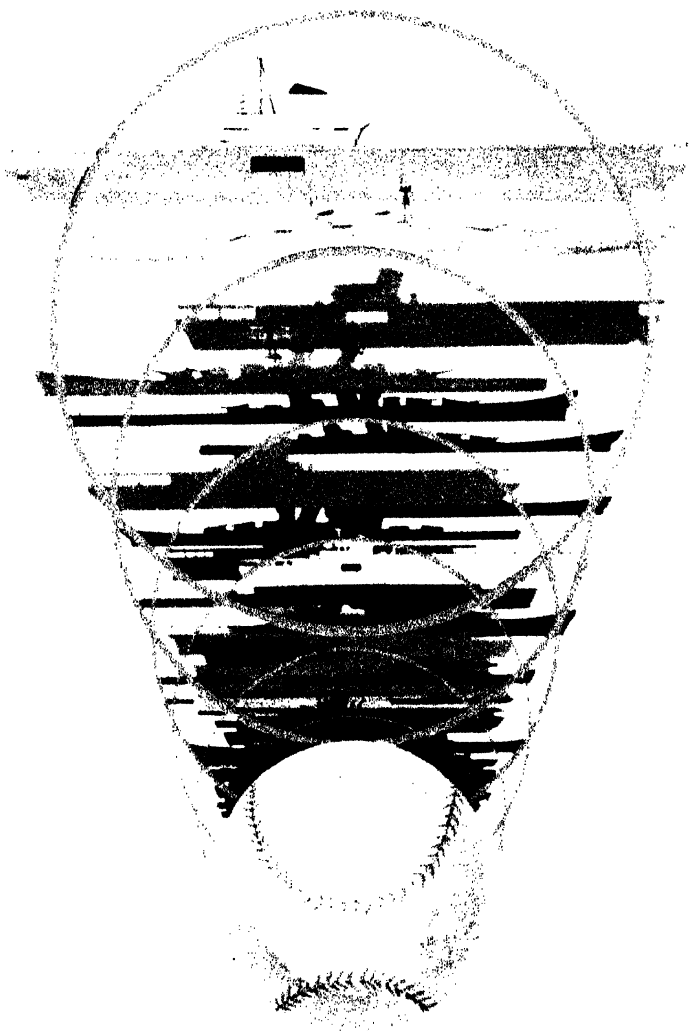


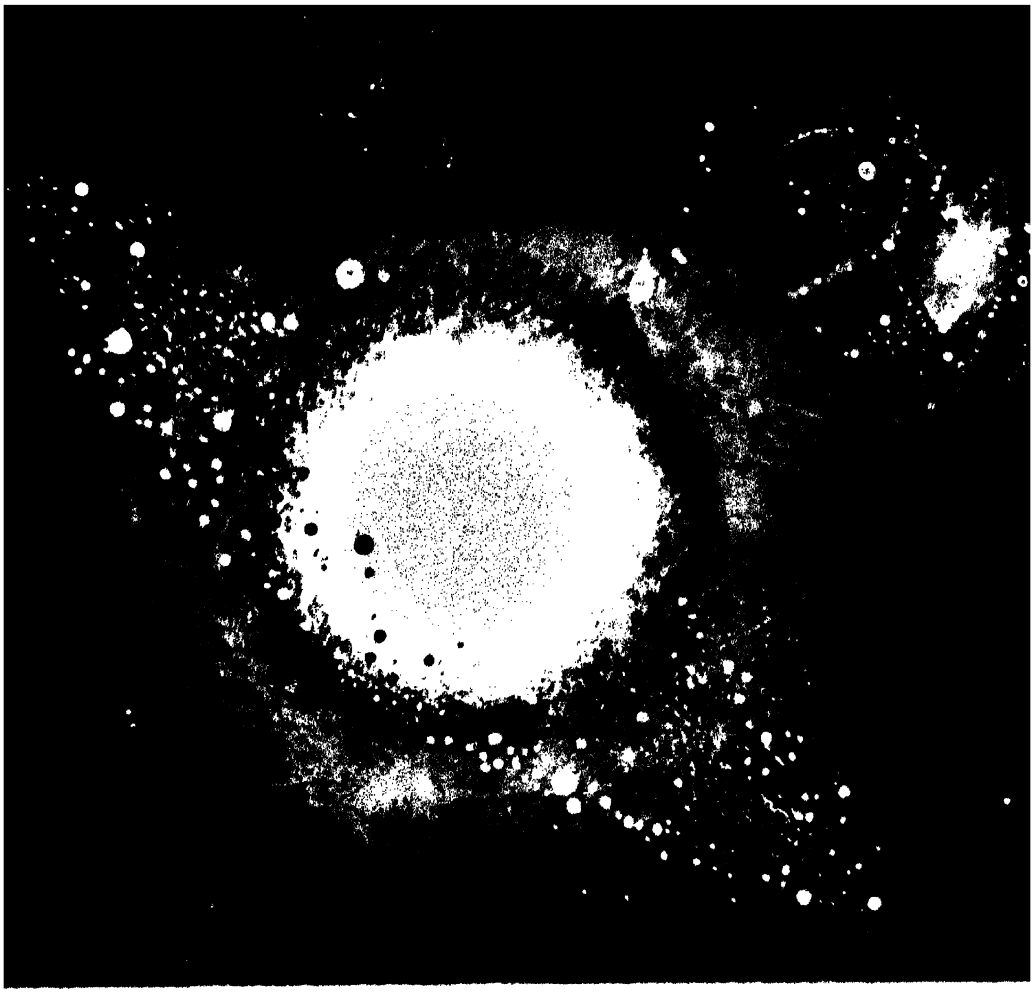
79

92

the tips of our fingers. Or, take 5,000 battleships and aircraft carriers. If all the empty space in their atoms were removed, all these ships could be crowded into the dimensions of a baseball! But this "baseball" would still weigh as much as all the 5,000 ships. It is horrifying to imagine such an object. It couldn't be kept anywhere. It would sink through the hardest obstacles and probably drill its way to the very center of the earth.

Truly, the atom of Rutherford and Bohr was a dramatically new concept!





ELUSIVE PREY

So THIS is the design of the universe—planets swirling around suns. An outer space filled with millions of galaxies of suns—countless solar systems among them, no doubt. And an inner space—filled with many more countless solar systems of atoms, electrons whirling around nuclear suns. A universe built of solar systems, infinitely big and infinitely small.

The architecture of the atom was now known and fairly well understood. But science ever progresses. The next step led into the nucleus itself. Like our Fisherman, scientists were curious about the tiny vessel they had netted —the atomic nucleus. And they probed it with every tool of research they could muster.

Again atomic bullets were used. So far, they had not touched the nucleus. The available bullets were charged—positively charged like the nucleus itself. We have seen what a tremendous force it is that pulls a proton and an electron together. A force of the same strength acts between the bullet and the nucleus—but in this case it keeps the two apart. Because like charges repel each other, the nucleus was as if cased in almost invincibly strong electrical armor.

Science needed better bullets. But a better bullet was simply a faster bullet. So scientists got busy building huge machines to create faster and faster bullets.

Now, it is fairly easy to strip the electron from a hydrogen atom. In fact, this is what happens in the electron tube. The electron rays that sweep across the tube hit the hydrogen atoms that are put inside. They crash into the atoms and knock the electron out. The naked proton remains. And thereby hangs an important result. For if a proton is put between two metal plates with opposite charges, it is attracted by the negative plate and starts to run for it. If the voltage between the plates is high, the proton picks up great speed. The greater the speed, the better the bullet. And that was what scientists wanted.

Physicists built all kinds of machines that created voltages in the millions. The fast protons that emerge from these high-voltage machines are similar to the powerful radium rays. But they are faster, and there are many more particles in their beams. What comes out of radium or polonium is like a thin trickle, while the proton beams from the machines are like the powerful burst from a firehose.

In thousands of experiments, scientists hurled their artificial rays at the atom. The protons slammed into the nuclei of many elements, and a great

number of things happened. Consider, for example, a piece of the metal lithium, which has three charges in its nucleus. It is put at the business end of an atom smasher and shot at with a beam of fast protons. Most of the bullets miss their target because the nuclei are so small, but let us consider one of the protons that happens to be on dead-center. With its great speed it pierces the electrical armor of the nucleus, crams inward, and gets stuck. The newly created nuclear package now contains 4 charges, and it immediately breaks down into two nuclei of 2 charges each. The new nuclei are helium nuclei, because helium atoms have 2 charges in their nucleus. Thus it is that one element is changed into another—an achievement dreamed of by the alchemists of the middle ages.

When scientists started thus to ram their bullets into atomic nuclei, a new field of science was born: nuclear physics. A lot of things were learned during this interesting and important period of the atom smashers. But the prize discovery was made with "old-fashioned" bullets—with the thin trickle of alpha-particles from radioactive elements. They could be used against lightly charged nuclei whose armor wasn't strong enough to ward them off.

For a number of years two German physicists, Bothe and Becker, used alpha-particles in their nuclear studies. One day they selected the metal beryllium as a target. Beryllium is a very light metal closely related to aluminum; its atoms have 4 charges in their nuclei; in the long list of elements beryllium occupies the fourth place, after hydrogen, helium, and lithium. Now, when the alpha-particles slammed into the beryllium nuclei, something baffling happened. For some time nuclear physicists were at a loss to explain it. Finally, in 1932, the English physicist Sir James Chadwick was able to round out the story.

This is what had happened: The alpha-particle with its 2 charges slammed into the beryllium nucleus with its 4 charges. The alpha-particle got stuck, and a nucleus was produced having 6 charges—the nucleus of a carbon atom. But this was not all. The newly created carbon nucleus released a particle that flew away with a great speed. The particle had no electrical charge—it was neutral! This was something entirely new and unexpected.

So far all known atomic particles had been electrically charged. Suddenly science found a neutral one. And there was only one logical name for it: "neutron."

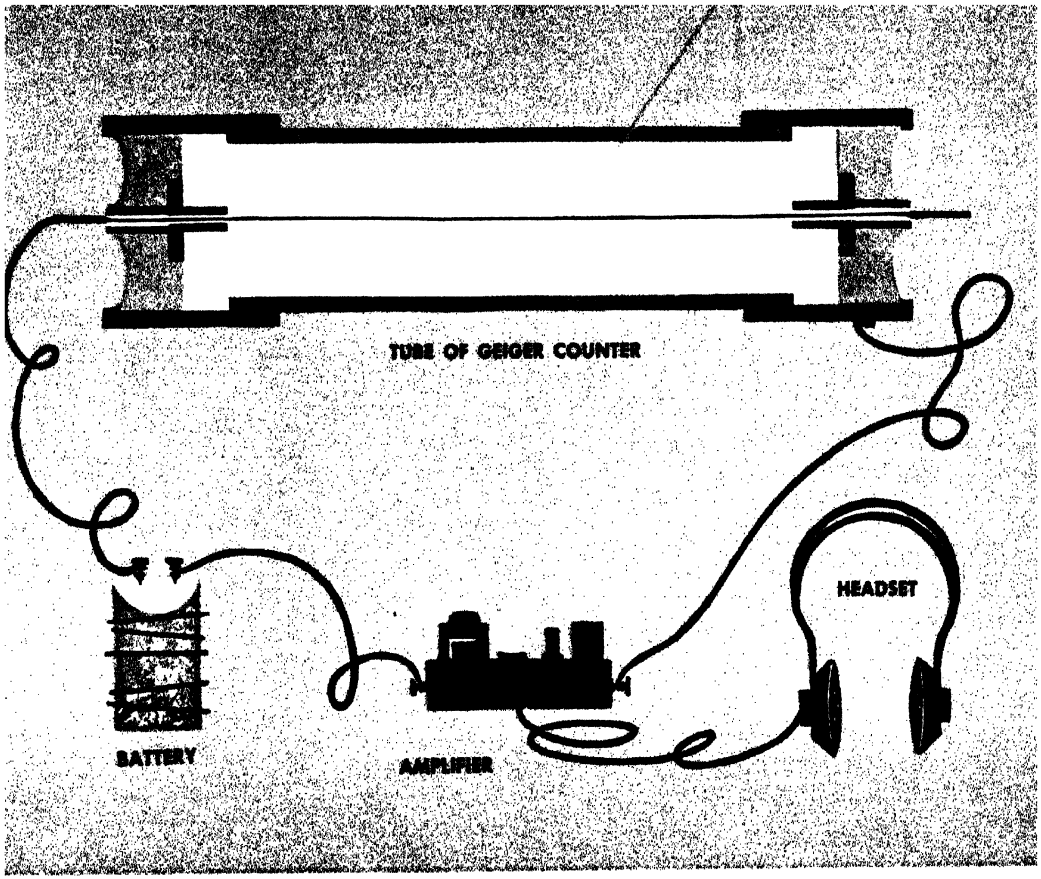
The neutron turned out to be as heavy as a proton. Its atomic weight was also 1. It was like a proton without a charge.

The neutron was discovered after more than 20 years of nuclear research. It had managed to escape the hunters this long because it has no tell-tale charge. It is because of their strong electrical charge that protons, electrons, and alpha-particles can be traced easily.

As nuclear physics grew, scientists invented a number of instruments for detecting atomic particles. The fluorescent screen was the first device in this line. Later, another radiation detector was invented—the famous Geiger counter, named after the German physicist Hans Geiger.

A Geiger counter is a small metal tube with an insulated wire that runs along its axis. To put the counter into operation, a voltage is put across the wire and the tube walls. The inner space of the tube is filled with a thin gas, so that in its normal state the voltage cannot discharge because of the insulation provided by the gas. Now, an alpha-particle or a proton shoots into the counter. It slashes its way through the gas atoms, and with its strong charge it knocks a number of electrons from the shells of the atoms. The freed electrons make a run for the positive wire. They pick up speed and ram into further gas atoms, knocking out more and more electrons, which in turn also run for the wire; and so a thick avalanche of electrons is created. The avalanche of electrons dives into the wire and causes a small discharge. This is run through an amplifier and transferred to a loudspeaker or a headset. Thus a single alpha-particle or proton snowballs into a shower of thousands and millions of electrons that can be recorded easily. The electric impulse can also be used to trigger a numbered counter drum built like the mileage counter in a car. If a Geiger counter is rigged up in this way, it automatically counts up every single particle.

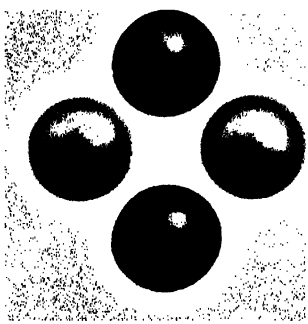
Only a charged particle can trigger an ordinary Geiger counter. A neutron is without charge, and so it travels straight through the electronic shells of



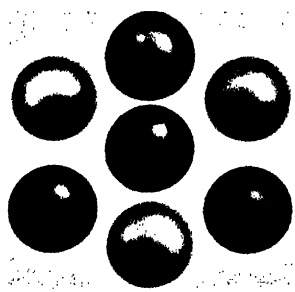
atoms. It exerts no force on the electrons and so cannot knock them out of their places. A neutron cannot start an electronic avalanche by itself.

A neutron can only do one thing. While it travels freely through the inner space of the atoms, it may by chance hit the nucleus of an atom and kick it on its way as one cue ball tees off another. The nucleus then slashes into other atoms and, because it is charged, it triggers an electronic avalanche and makes the counter click. Today neutrons are recorded with counters of a special kind that give them the best possible chance of hitting nuclei; these will then fly off and do the recording for the neutrons. Originally, of course, these special counters didn't exist, and this is why the neutron was able to slip through undetected for a long time. But finally scientists smoked it out of its hiding place in the nucleus.

The neutron was found to be one important building block of the atomic nucleus. The proton was the other. Nuclei are built of protons and neutrons tightly fused to a tiny, dense ball. The only single nucleus in nature is the proton itself, which serves as the nucleus of the hydrogen atom. All other atoms have both protons and neutrons in their nuclei. Helium, for example, has 2 protons and 2 neutrons. All four particles have the same weight of one unit, so that the atomic weight of helium comes out as 4, while the protons give it a nuclear charge of 2. When chemists speak of helium, they use the abbreviated symbol "He." Nuclear physicists are more specific; they write the helium nucleus like this: "$^{4}_{2}$He"—weight 4, charge 2. From the two numbers we can see at once that it must consist of 2 protons and 2 neutrons.



HELIUM NUCLEUS



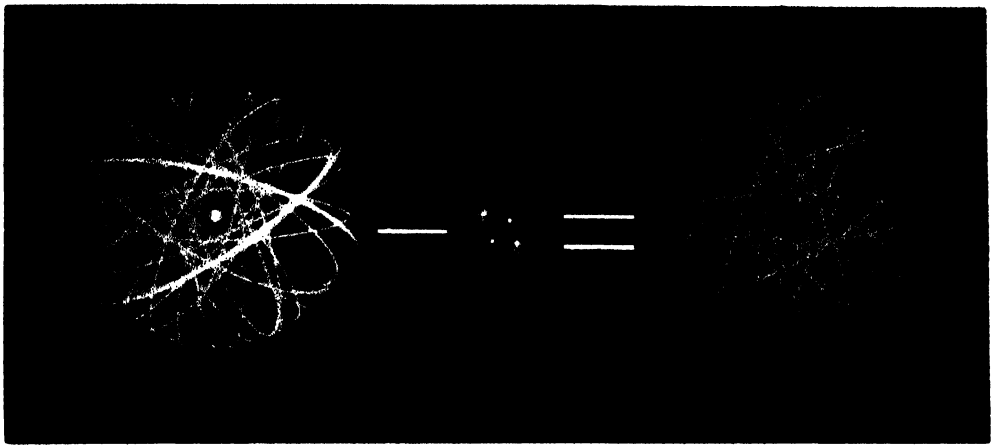
LITHIUM NUCLEUS

The next in line is lithium. It is "$^{7}_{3}$Li"—3 protons and 4 neutrons. This combination gives a nuclear charge of 3 and an atomic weight of 7. Oxygen is $^{16}_{8}$O; iron is $^{56}_{26}$Fe. Uranium is $^{238}_{92}$U—it has 92 protons and 146 neutrons in its nucleus. Radium, too, has a crowded nucleus—88 protons and 138 neutrons.

Crowded conditions are the reason why the heavy atoms are radioactive. Their nuclei are "top-heavy," unstable, likely to break apart after a while. By shooting out an alpha-particle they rid themselves of excess weight and excess charge. In a previous chapter we saw how radium (Ra) transforms itself into radon (Rn) when an alpha-particle—or, what is the same, a helium nucleus—is thrown out of the radium nucleus. There is a simple way

of saying all this. For this long sentence physicists simply write:

$$^{226}_{88}\mathrm{Ra} - ^{4}_{2}\mathrm{He} = ^{222}_{86}\mathrm{Rn}$$



Nuclear physics thus became a simple, but fascinating, game of numbers!

Protons and neutrons have a way of sticking together tightly to form atomic nuclei. What would happen if a single neutron should stick to a single proton? The two would form the nucleus of an atom with charge 1 and weight 2. This nucleus could string up with a single electron to form a little solar system like a hydrogen atom. Chemically such an atom would behave like genuine hydrogen, because the chemistry of an atom depends only on the number of electrons in its shell. In 1932 this "heavy" hydrogen was found by the American Nobel Prize winner Harold Urey, of the University of Chicago. It is found everywhere mixed up with normal hydrogen. About 1 out of 5,000 hydrogen atoms is a heavy one. In nuclear symbols normal hydrogen is $^{1}_{1}\mathrm{H}$, while heavy hydrogen is $^{2}_{1}\mathrm{H}$.

When scientists took stock of their atoms, they found that there are many with one or even more extra neutrons packed away in their nuclei. Of 10,000 atoms of oxygen, 9,976 will have 8 neutrons besides the 8 protons in their nuclei; but 4 of them will have 9 neutrons, and 20 will even have 10 neutrons. These rare oxygen atoms have an atomic weight of 17 and 18, respectively. But all of them have 8 protons and 8 electrons; this is what makes them oxygen atoms.

PERIODIC TABLE OF THE

1 Hydrogen H—1 2 1*				
3 Lithium Li—7 2 1*	4 Beryllium Be—9 1 3*	5 Boron B—11 2 2*	6 Carbon C—12 2 4*	7 Nitrogen N—14 2 4*
11 Sodium Na—23 1 5*	12 Magnesium Mg—24 3 2*	13 Aluminum Al—27 1 4*	14 Silicon Si—28 3 2*	15 Phosphorus P—31 1 4*
19 Potassium K—39 2 1** 4*	20 Calcium Ca—40 6 5*	21 Scandium Sc—45 9 9*	22 Titanium Ti—48 5 4*	23 Vanadium V—51 2 5*
29 Copper Cu—63 2 9*	30 Zinc Zn—64 5 8*	31 Gallium Ga—69 2 9*	32 Germanium Ge—74 5 8*	33 Arsenic As—75 1 11*
37 Rubidium Rb—85 1 1** 12*	38 Strontium Sr—88 4 10*	39 Yttrium Y—89 1 12*	40 Zirconium Zr—90 5 7*	41 Niobium Nb—93 1 14*
47 Silver Ag—107 2 15*	48 Cadmium Cd—114 8 9*	49 Indium In—115 2** 16*	50 Tin Sn—120 9 1** 13*	51 Antimony Sb—121 2 21*
55 Cesium Cs—133 1 13*	56 Barium Ba—138 7 11*	57-71 Rare Earths (See below)	72 Hafnium Hf—180. 6 7*	73 Tantalum Ta—181 1 12*
79 Gold Au—197 1 14*	80 Mercury Hg—202 7 6*	81 Thallium Tl—205 2 3** 8*	82 Lead Pb—208 4 5** 8*	83 Bismuth Bi—209 5** 14*
87 Francium Fr—223 8*	88 Radium Ra—226 4** 5*	89 Actinium Ac—227 1** 6*	90 Thorium Th—232 6** 5*	91 Protactinium Pa—231 3** 9*

RARE EARTHS

57 Lanthanum La—139 2 12*	58 Cerium Ce—140 4 10*	59 Praseodymium Pr—141 1 8*	60 Neodymium Nd—144 4 10*	61 Promethium Pm—147 6*
62 Samarium Sm—154 6 1** 6*	63 Europium Eu—152 3	Gadolinium Gd—157 7 4*	65 Terbium Tb—159 3 10*	66 Dysprosium Dy—162 7 4*
67 Holmium Ho—165 1 10*	68 Erbium Er—167 6	69 Thulium Tm—169 3 9*	70 Ytterbium Yb—173 6 8*	71 Lutetium Lu—175 1 9*

This table lists all chemical elements known at this time. The top line in each box shows the element's name and the number of protons in its atomic nucleus—the so-called atomic number. If atomic numbers are arranged in horizontal lines, elements of similar chemical behavior fall periodically into vertical columns as shown by the color scheme. This is why this table is called a "periodic table." The "rare earths" and the "elements beyond uranium" (having atomic numbers greater than uranium)

ELEMENTS AND THEIR ISOTOPES

					2 Helium He—4 2 1*
8 Oxygen O—16 3 3*	9 Fluorine F—19 1 3*				10 Neon Ne—20 3 2*
16 Sulfur S—32 4 3*	17 Chlorine Cl—35 2 5*				18 Argon A—40 3 4*
24 Chromium Cr—52 4 3*	25 Manganese Mn—55 1 5*	26 Iron Fe—56 4 4*	27 Cobalt Co—59 1 11*	28 Nickel Ni—58 5 5*	
34 Selenium Se—80 6 1** 11*	35 Bromine Br—79 2 13*				36 Krypton Kr—84 6 17*
42 Molybdenum Mo—98 7 8*	43 Technetium Tc—99 21*	44 Ruthenium Ru—102 7 6*	45 Rhodium Rh—103 1 12*	46 Palladium Pd—106 6 7*	
52 Tellurium Te—130 6 2** 17*	53 Iodine I—127 1 19*				54 Xenon Xe—132 9 17*
74 Tungsten W—184 6 11*	75 Rhenium Re—187 1 1** 9*	76 Osmium Os—192 7 10*	77 Iridium Ir—193 2 9*	78 Platinum Pt—195 6 6*	
84 Polonium Po—210 7** 9*	85 Astatine At—211 14*				86 Radon Rn—222 3** 5*
92 Uranium U—238 3** 8*					

ELEMENTS BEYOND URANIUM

93 Neptunium Np—237 9*	94 Plutonium Pu—239 9*	95 Americium Am—241 8*
96 Curium Cm—242 5*	97 Berkelium Bk—243 1*	98 Californium Cf—244 1*
99 Einsteinium E—247 1*	100 Fermium Fm—254 1*	101 Mendelevium Mv—256 1*

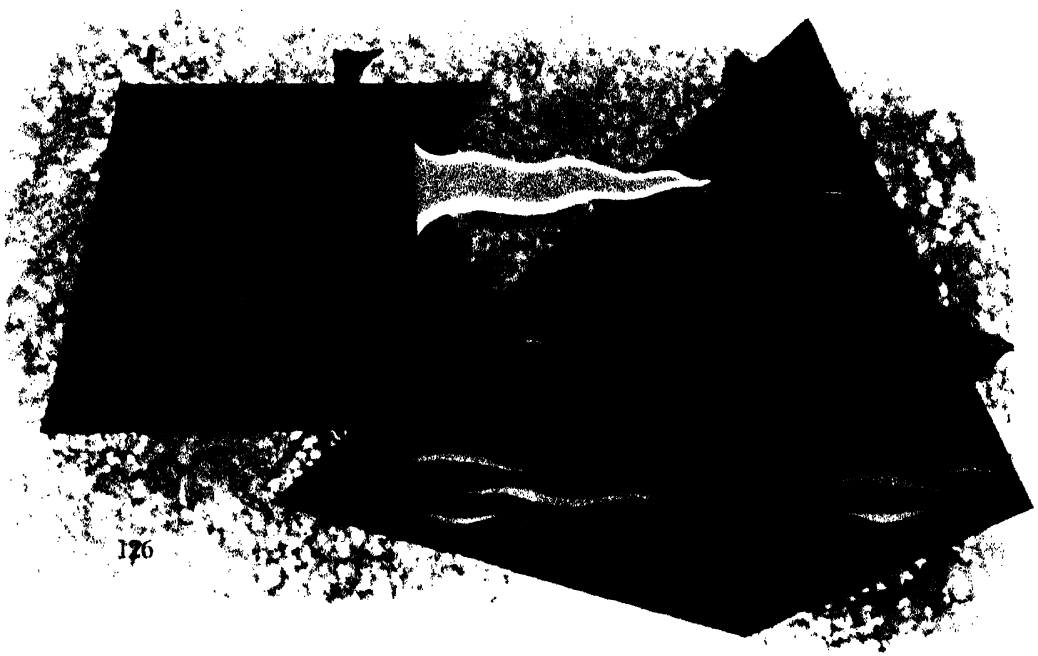
form special groups of highly similar elements. The middle line in each box gives the chemical symbol of each element and the atomic weight of its most common stable isotope. The bottom line shows for each element the number of its stable isotopes, the number of its natural radio-active isotopes (**), if any, and the number of its artificial isotopes (*) made so far—the so-called "radio-isotopes." Element 101 was named after the Russian chemist Mendeleyev, who discovered the periodic system.

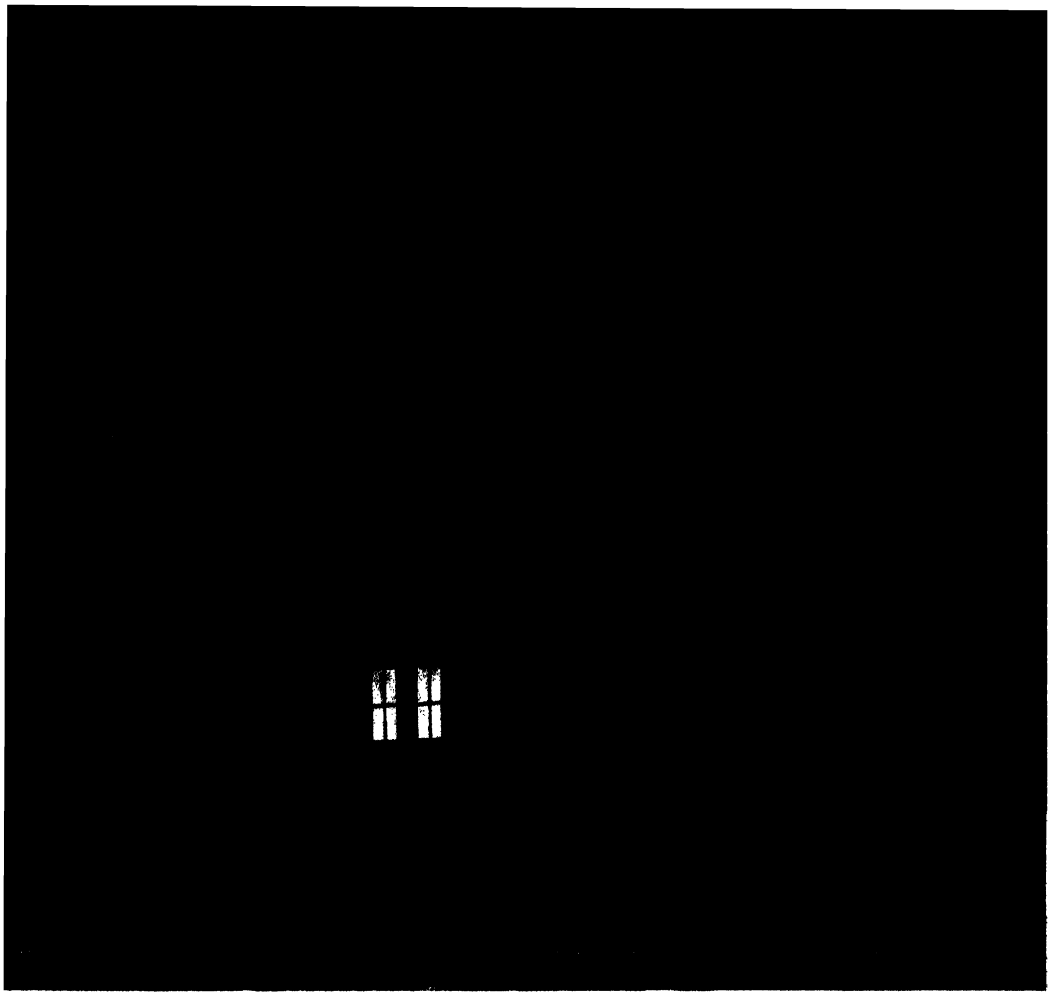
An atom does not change chemically if one or more extra neutrons are added to its nucleus. Extra neutrons don't change the charge of the nucleus and, by the same token, the number of electrons in the shell remains the same. The extra neutrons only add to the atom's weight. All these different kinds of atoms belong in the same place in our list of chemical elements, because they have the same number of electrons. Physicists have a special name for atoms that differ only in their number of neutrons; they call them "isotopes," from the Greek word meaning "in the same place."

Most elements are mixtures of isotopes. In fact, only a few elements in nature consist of only one kind of atoms all having the same weight. Others consist of two kinds, like chlorine. Oxygen has three kinds as we have seen —$^{16}_{8}O$, $^{17}_{8}O$, and $^{18}_{8}O$. The metal tin has ten kinds!

With the discovery of the neutron, the last piece of the atomic puzzle was fitted into place. The composition of the nucleus itself was now known. Radioactivity and the isotopes had found their logical explanation. But little did scientists know that their neutron was soon to become the star in a dramatic series of events in nuclear science.

The neutron turned out to be the knife by which the Fisherman broke the seal of the magic vessel.





The Kaiser Wilhelm Institute of Chemistry, Berlin

THE ATOM SPLITS

You will recall how, after the alpha-particle was discovered, Lord Rutherford used it in his classic exploration of the atom's interior. The neutron, shortly after its discovery, was used likewise to pry further into the secrets of the atomic nucleus. And what a tool it was!

Having no electrical charge, the neutron is not affected by the negative electrons in the atomic shell. What is more, it is not affected by the strong, forbidding charge of the heavy nuclei. Take uranium, for example, in which 92 protons are crowded together in a small, tight package. A charged bullet

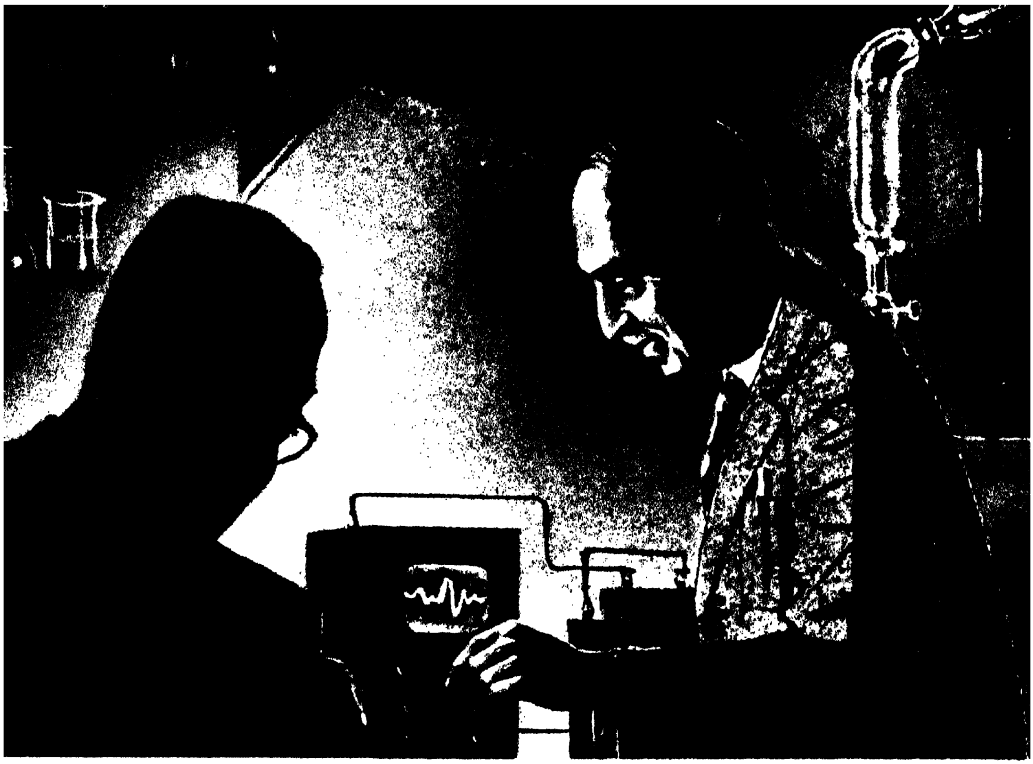
such as a proton or an alpha-particle would have to be extremely fast to overpower the strong repulsive force of the 92 protons working together. Before the bullet got near the nucleus, that force would bring the bullet to a dead stop and hurl it back. A charged bullet, then, has no chance of even touching the uranium nucleus unless it has a tremendous speed.

But the neutron is different. Since it has no charge, there is no force to stop it. It easily floats through the inside of the atom, and if it happens to touch even the most highly charged nucleus, it is swallowed up by the nucleus as readily as a tiny drop of mercury is sucked in by a bigger one.

First to attack the atom with neutrons were the brilliant Enrico Fermi, of Italy, and his co-workers. For a number of years they stuffed extra neutrons into the heavy nuclei of radioactive atoms. Then, in 1935, a group of researchers in Germany also entered this field. Working under the chemist Otto Hahn, director of the Kaiser Wilhelm Institute of Chemistry in Berlin, they concentrated on uranium. Finally, in December 1938, Hahn and his co-worker Fritz Strassmann witnessed a downright sensational event. They split the uranium atom in two!

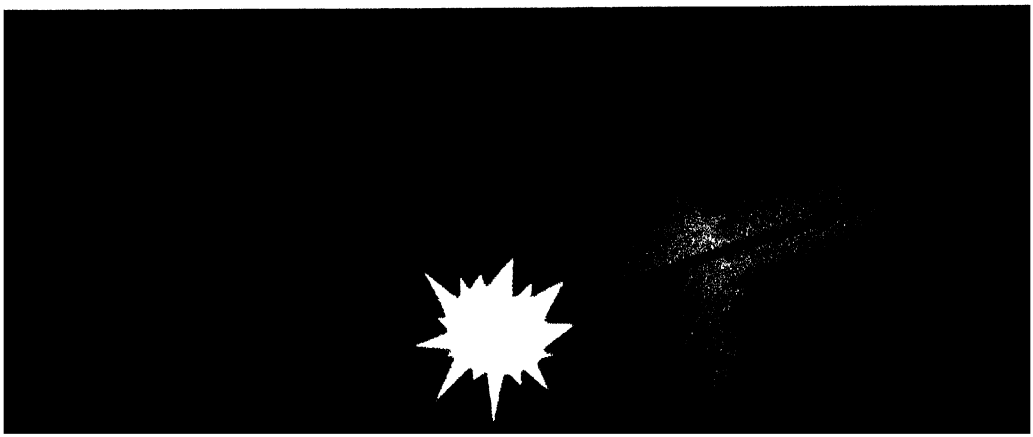
Hahn and Strassmann were actually expecting something else. In fact, after their discovery they had the wrong explanation for it. Even in their second publication they didn't dare to admit fully what they had found. A short time later, Otto R. Frisch and Lise Meitner, another co-worker and close friend of Hahn, offered the right explanation: nuclear fission.

Radioactive atoms had been known to chip, but not to split. They had been known to break apart by ridding themselves of chips not greater than an alpha-particle—a package of 2 protons and 2 neutrons. These were the biggest pieces that chipped off. But here was something new: the uranium nucleus, on swallowing the neutron, immediately splits, like a glass marble that is dropped on the floor and cracks in two. For an infinitesimally brief moment the two nuclear parts lie side by side. Then—because both fragments contain dozens of protons that repel each other with a giant force—the fragments are driven apart in a terrific recoil. The tremendous speed is equivalent to an excessive heat—the heat of atomic fission!



A glass marble breaking in two may split in many ways. Rarely are the two pieces equal in size. Uranium nuclei split in a similar way: the fragments vary in size, depending on how this violent nuclear event happens to tear the nucleus apart. The fragments then form all kinds of nuclei. For example, a uranium atom may split in such a way that 56 of its 92 protons

A neutron (trail at left) splits a uranium atom into barium and krypton. Two neutrons shoot off to right



wind up in one fragment, while the remaining 36 protons are found in the other. We then get two nuclei with these charges. The first is a nucleus of the element barium, which is akin to calcium; the other is a nucleus of krypton, a rare gas related to helium and neon. There are other ways in which uranium can split and divide its protons: 57-35, 55-37, 54-38, and so on. Mostly, one fragment gets about half again as many more protons as the other, even though some nuclei split evenly.

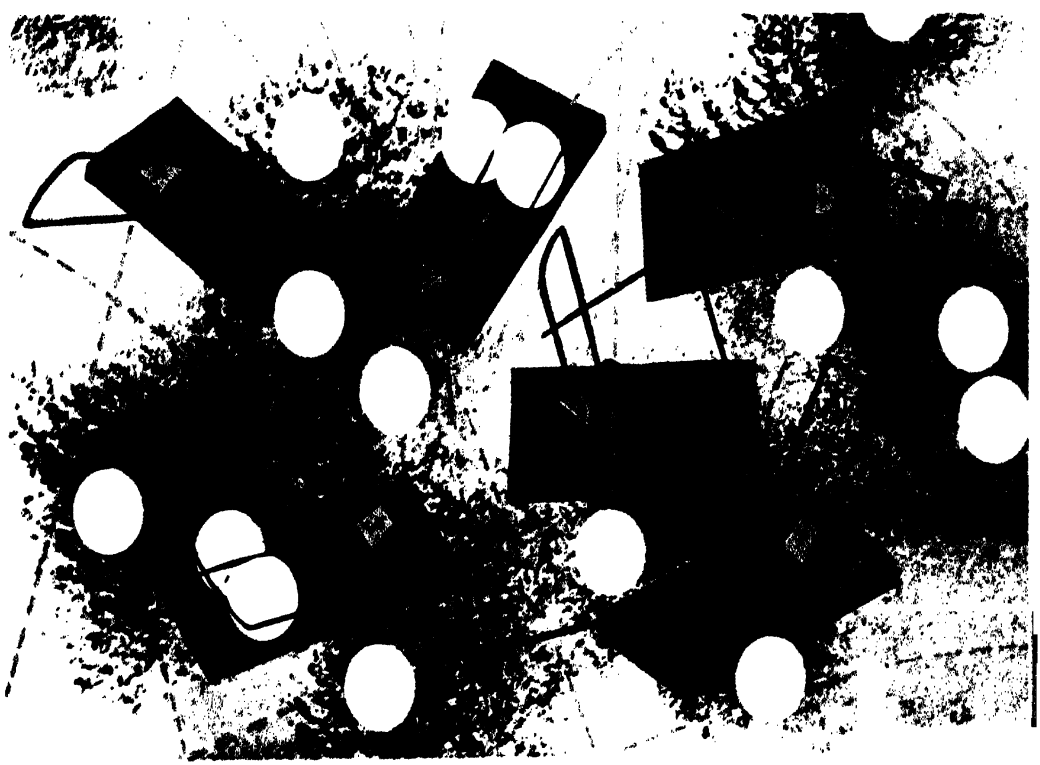
When the nucleus splits, it also gives off an extremely powerful flash of gamma-rays, the penetrating kind of radiation akin to X-rays. But there is still more to atomic fission. When a glass marble cracks in two, you are likely to find a few tiny slivers of glass that have chipped off the sharp edges. In a way, the same thing happens to a nucleus when it cracks; it, too, leaves a few tiny slivers in the process. There are one, two, or even more pieces of nuclear debris falling off when the nucleus breaks. They are single neutrons that fly away from the center of the tiny explosion.

It took physicists only a short time to recover from the shock that atomic fission had given them. They were, of course, greatly interested in studying in detail what nuclei are found among the fragments, and how fast they are driven apart. They measured the intensity of the gamma-rays which the splitting atoms sent on their way. But what fascinated them most of all was the slivers—the neutrons that were discharged every time a nucleus tore apart. These extra neutrons held a fabulous promise: the possibility of an atomic chain reaction. It was the dawn of the atomic age.

Anyone can simulate a chain reaction with a number of mousetraps. A set mousetrap and a uranium atom have one thing in common: both contain trapped energy. You supply the energy for the trap when you bend the spring; Nature supplied the energy when she created the uranium atom, forcing the rebelling protons together in the uranium nucleus and locking them up tightly. Like the coiled spring of the mousetrap, the tense nucleus lies waiting to cut loose. When the mousetrap pops, it is like a uranium atom that splits. The energy is released and the mousetrap jumps up with a sudden start, somewhat as the fragments are kicked apart in nuclear fission.

To make the mousetrap act even more like the uranium atom, we can load it with two ping-pong balls. These are flung away by the popping trap. They are like neutrons that are discharged by the atom when it splits.

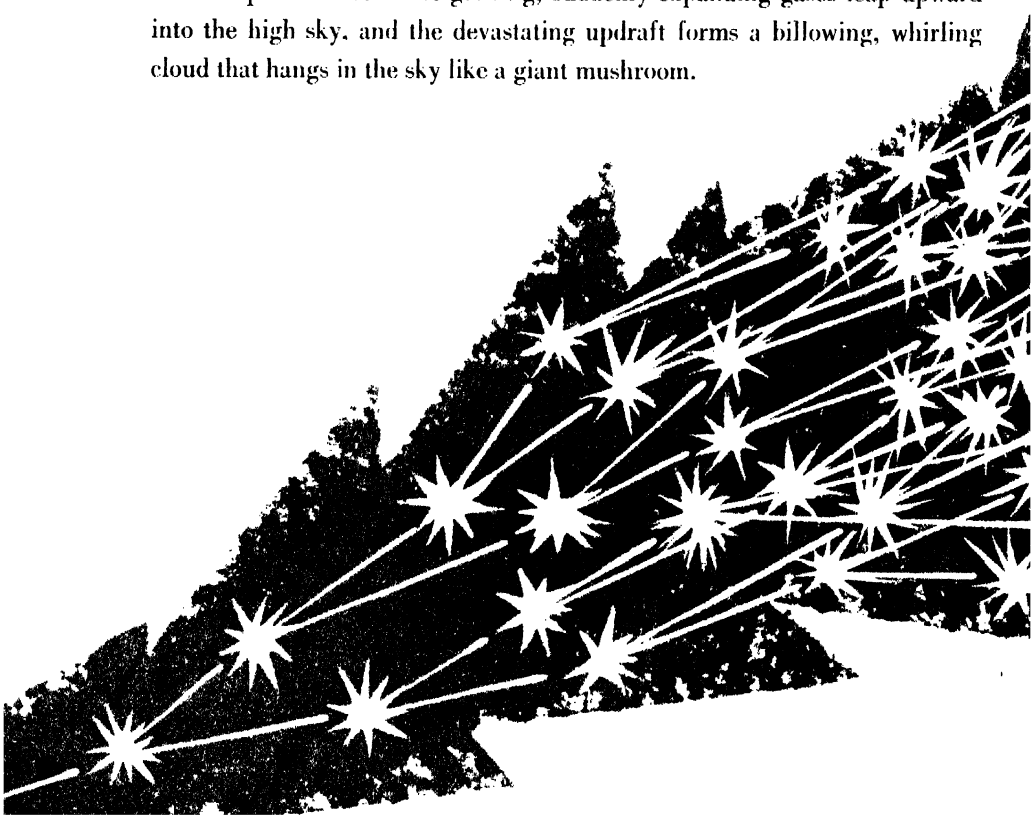
With a couple of hundred mousetraps, all set and loaded with ping-pong balls, we can make an excellent demonstration of a chain reaction. The mousetraps, placed side by side on the floor, would represent a small piece of uranium. Now, like uranium atoms, the mousetraps need a trigger to release their energy: one ping-pong ball is enough. Thrown into the heap of traps, the ball will trigger at least one trap. That pops, jumps up, and lets go with its two balls. Now there are two ping-pong balls on their way doing more triggering. They pop two other traps and out come four ping-pong balls. These in turn pop other traps, more balls are flung out, and within a few seconds the whole room becomes a racket of jumping mousetraps and flying ping-pong balls. It is quite spectacular!

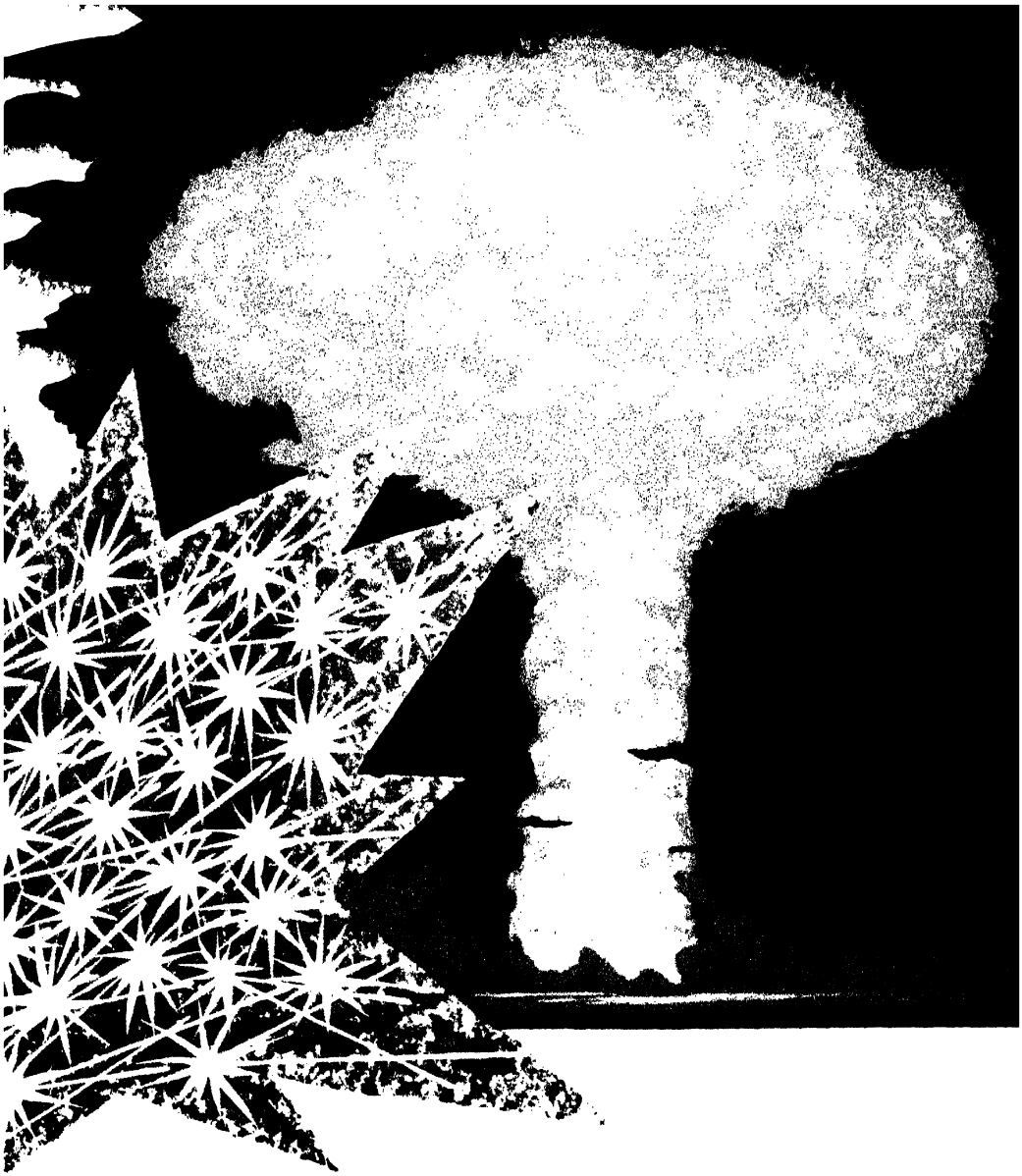


This sort of thing is what physicists had in mind when they learned of the neutrons discharged in atomic fission. Could these neutrons not dive into the nuclei of the atoms near by, make them split, and release additional neutrons to split other atoms . . . and so on?

They could do just that.

The result is fantastic. It is terrifying. It takes the mousetraps several seconds to pop. But it takes only a tiny fraction of a second for the millions and billions of atoms to split in an explosive atomic chain reaction. They split at the very same time—as human time standards go. Billions and billions of atomic fragments fly apart with a tremendous speed. A white-hot body of gas is created whose particles tear around with devastating speed. A heat of millions of degrees is created on the spot. It brings forth a monstrous explosion accompanied by an eye-searing flash. Millions of tons of air are pushed aside; a roaring shock wave hurtles in all directions. The billions of splitting atoms combine their bursts of gamma-rays, which penetrate deep air masses. The glowing, suddenly expanding gases leap upward into the high sky, and the devastating updraft forms a billowing, whirling cloud that hangs in the sky like a giant mushroom.



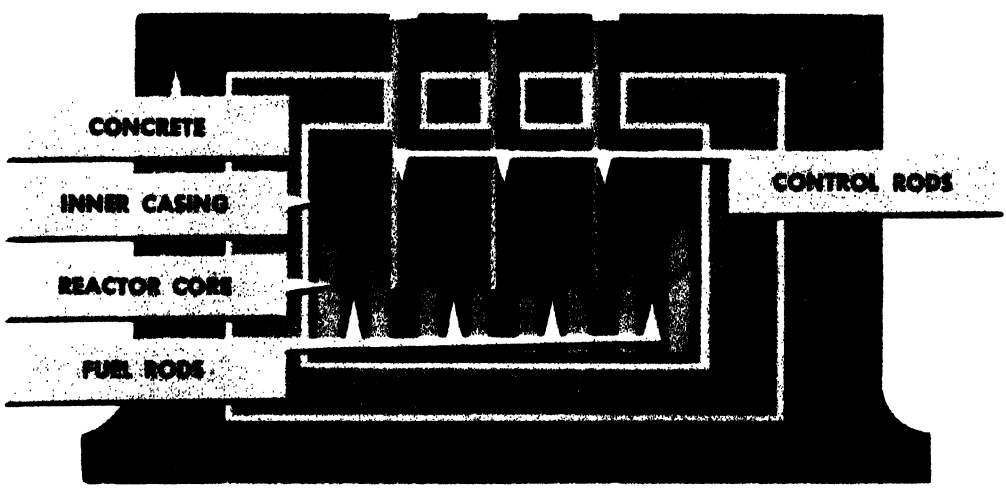


Behind this awe-inspiring cloud we recognize the terrifying form of the Genie of our fable . . . *with eyes blazing like torches, and fiery smoke whirling about him like the simoom of the desert* . . . and his thundering voice promising us death in the most cruel form.

When the Fisherman first beheld the frightful form of the Genie, he wished that he had never discovered the vessel. But our fable had a happy ending; the Fisherman had his means of making a friend of his enemy. Fortunately, science has its way of doing the same thing.

An atomic blast is more than a deadly threat; it is also a regrettable waste of energy. Heat and radiations are precious things—valuable assets to our civilization, better used for creation than for destruction. What happens during a split second in an atomic explosion must be slowed down to last for months or even years. Then the atomic Genie will not throw his energy at us in a torrent of heat and radiation; rather he will give us energy as a gently flowing spring gives us water.

Atomic physicists produce slow nuclear chain reactions through a special device of nuclear engineering—the famous atomic reactor. It is an enclosed space filled with atomic fuel, usually uranium, whose atoms are splitting in a carefully controlled chain reaction. A number of different types of atomic reactors have been built, differing in design and operation but all having one thing in common: a device to control the speed of the energy-giving

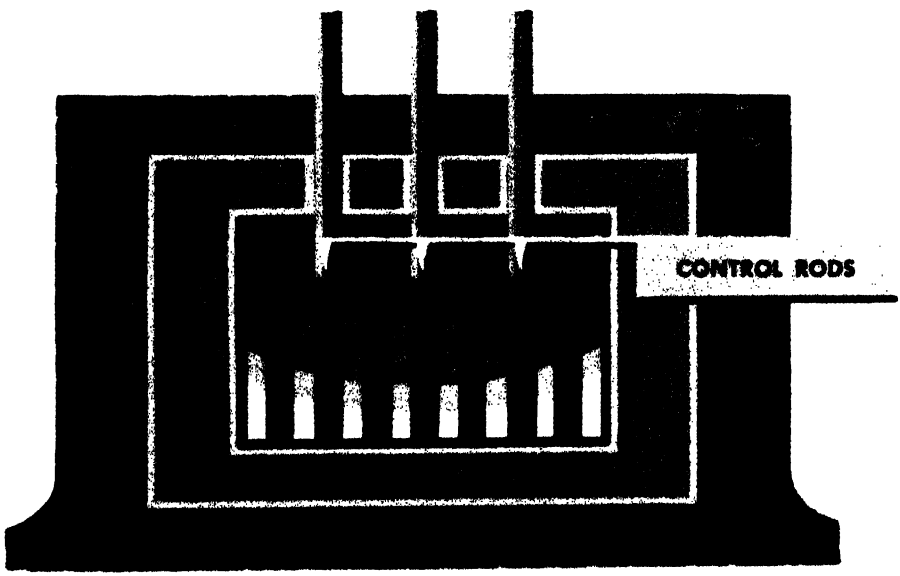


In an atomic reactor, cadmium rods absorb neutrons and slow down the chain reaction

chain reaction. The principle of this control device is actually quite simple.

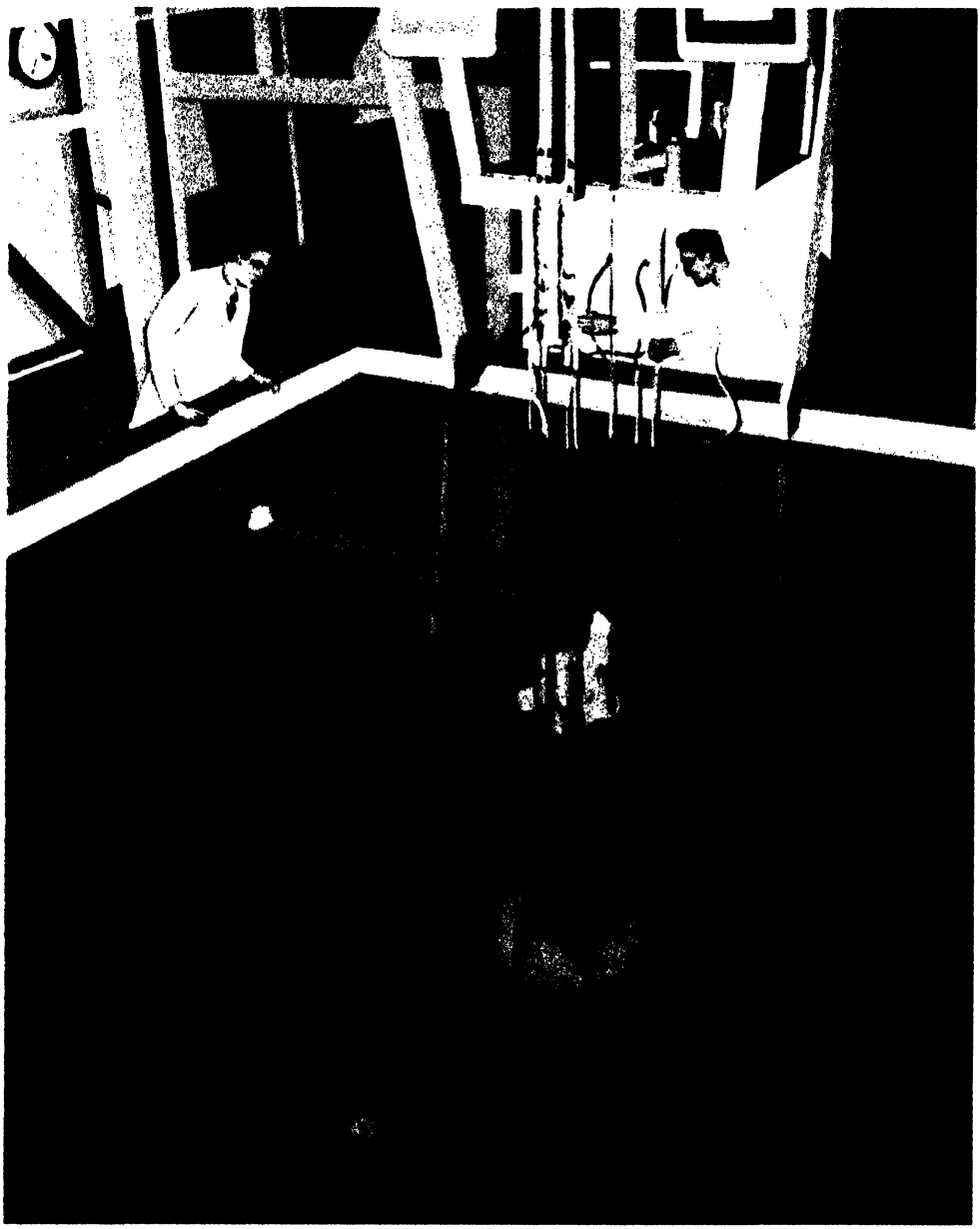
Consider once more our mousetrap chain reaction. It could be slowed down if we employed someone to catch a number of the ping-pong balls and take them out of the game. Fewer balls would remain to pop other traps, and there would then be fewer traps going off in each second. To slow down an atomic chain reaction we must, then, look out for a neutron catcher. Such catchers fortunately do exist.

Several chemical elements, among them boron and cadmium, are very efficient at the job. Their nuclei soak up neutrons as easily as a sponge soaks up raindrops. If rods of cadmium metal, for example, are placed so that they can be extended into or withdrawn from the reactor, they will provide effective control. If these control rods are pushed all the way into the reactor, so many neutrons are absorbed that the chain reaction comes to a complete stop. As the rods are pulled out, and more neutrons stay in the game, the rate of splitting increases, and the reactor gets hotter and hotter. The rods work like the accelerator of a car—or the bridle on a horse.



As rods are withdrawn, more neutrons stay in the game. The chain reaction is underway!

With the device of the reactor we hold the atomic Genie under safe control. He comes forth at our beckoning. He promises to grant us three wishes. The decision is ours. What should we wish for? What do we need most . . .?



In this reactor "pool" water shields the men from stray neutrons

OUR FIRST WISH: POWER

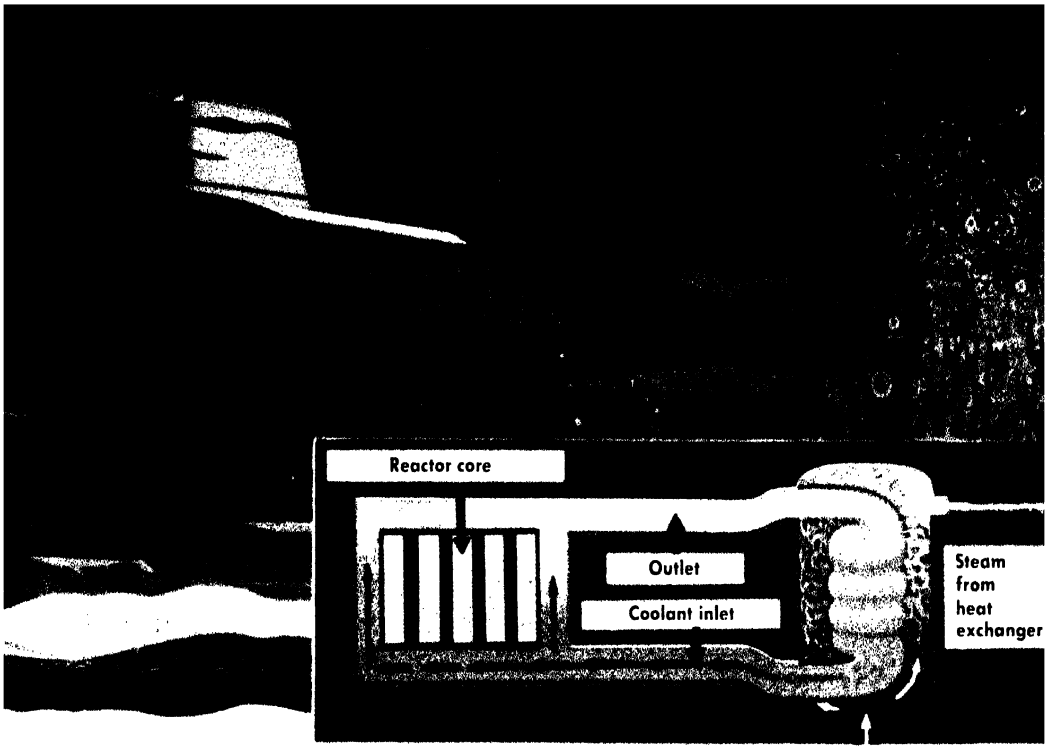
The coal and oil resources of our planet are dwindling, yet we need more and more power. The atomic Genie offers us an almost endless source of energy. For the growth of our civilization, therefore, our first wish shall be for: POWER!

DURING the past hundred years we have taken a gaint bite out of our natural fuel resources. Big though these are, they are dwindling, and every year the energy demands of the world are increasing. It won't be long, historically speaking, before we reach the bottom of our pile of cheap coal and oil. It has been estimated that our reserves will last another 200 or 300 years. But as early as 1975 even the rich United States will reach a point where cheap coal from rich deposits will be scarce; thereafter we shall have to fall back on low-grade coal. This means that our fuel bill will go up.

In the perspective of the earth's history, these prospects are truly alarming. It took Nature millions of years to create fuel reserves. These treasures were long buried, awaiting the advent of the technical age. Then man started to dig them up—and after a single century he already sees the bottom of the supply. It is as though a thrifty man saved a great fortune over a whole lifetime, and his son comes along and spends it all in a day!

But now there is offered to us a new source of power. The era of atomic power has already begun.

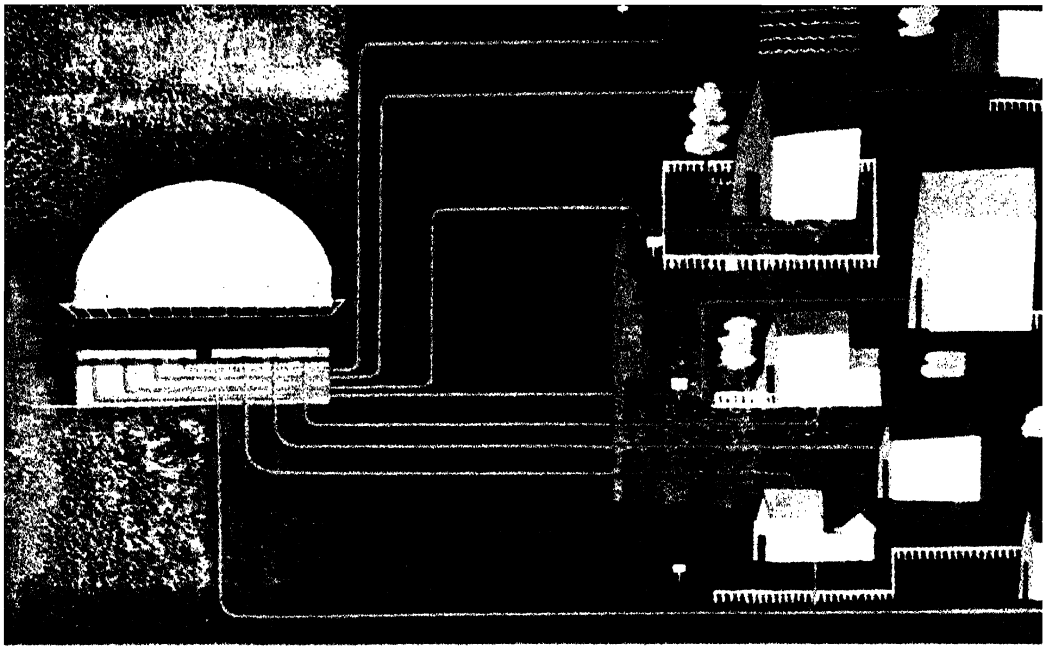
In January 1955, the clean and silent power of the atom pushed a sleek



ship of the United States Navy out of the harbor and onto the high seas. The ship's name was "Nautilus," like Captain Nemo's submarine of the immortal tale *Twenty Thousand Leagues under the Sea.* Like its famous namesake the real "Nautilus" is driven by an inexhaustible source of power. It is the first atom-driven ship of the world.

The prop shafts of the "Nautilus" are driven by a turbine, and the turbine in turn is driven by a beam of hot steam that blasts against its blades. In power plants of this type the steam is produced by atomic energy.

Inside the small reactor of the atomic sub a carefully controlled chain reaction runs its silent course. In every second, billions of atoms are torn in two by billions of neutrons that criss-cross in all directions. The nuclear fragments fly apart and slam into other atoms, causing them to bounce around in all directions. The motion of atoms is heat. Water under pressure is piped through the inside of the reactor and picks up this heat. The hot water is then piped through a tank, where its heat is used to create steam. The steam, in turn, is directed against the turbine blades and drives the prop shafts.



This is only one way of using the heat of an atomic reactor to drive an engine. During recent years a number of different types of atomic power reactors have been developed. Although they differ in design details, they all work with a fluid that is pumped through the reactor core and comes out at high temperature. In some way or another, the heat is transferred to water in the so-called heat exchanger. The heat exchanger has the same function as the boiler in an ordinary steam engine; it becomes the source of steam—the same steam that has been driving the machines of man for more than a hundred years. Only the ultimate source of heat is different. In the conventional steam engine it is a fire of coal or oil; in the reactor it is an atomic fire that drives the engines of the atomic age—engines for locomotion, for mechanical power, and for electricity.

There is a tremendous amount of energy in a little chunk of uranium. While a conventional steam engine must be fed with tons of coal or oil, an atomic power plant runs on a few pounds of uranium. It has been estimated that 20 pounds of uranium could provide enough power to light 25,000 average American homes for a whole year. One pound of refined uranium, ready to go in a reactor as fuel, costs about 35 dollars.

Will energy of the future, then, be as cheap as dirt? Unfortunately, not quite. In a power plant, fuel costs are only one item among many. In

nuclear engineering, operating costs are particularly high. Including everything, one kilowatt-hour of electricity produced by the atom still costs more than one kilowatt-hour produced by coal or oil. The "Nautilus," too, could be operated more cheaply on oil than on the atom. Of course, an atomic sub doesn't need air, and so it can run under water almost indefinitely.

We have been producing power from coal and oil for many years, but we are just beginning to tap the atom's energy. American engineers and business men have the habit of being extremely successful in cutting costs. They will do it again. They will soon bring the atom into line as a competitive source of power.

American industry is determined to make the atom the leading force of the future. The international "Atoms for Peace" conference held in Geneva, Switzerland, in late 1955, was a most optimistic foreshadowing of the coming atomic age. It was conducted in the peaceful spirit of the far-reaching "Atoms for Peace" plan which was proposed in 1953 to the United Nations by the President of the United States.

The Geneva conference was attended by delegates from many nations. The United States was represented by scientists from universities and industry, by medical research workers, by industrial leaders, and by experts in nuclear engineering and reactor design. To the scientists of the world this meeting offered a cherished opportunity for exchanging their views, experiences—and their common hopes. And from Geneva there emerged a bright picture of the atom. For the first time the world was shown that the future of the atomic age holds something better than ever more destructive weapons, ever wider danger from fall-out and radioactive ashes. The hopeful Geneva conference presented the atom for what it actually can be: a powerful force in the service of peace and progress.

In this spirit big corporations in the United States are at present building atomic plants for commercial electric power. There are plans for many more. Near Chicago a huge steel sphere houses an atomic power reactor and a big turbogenerator. This $45,000,000 installation will produce 180,000 kilowatts of electric energy. For New York a $55,000,000 nuclear power

plant is slated to produce 236,000 kilowatts. Britain, France, Russia, and other countries are busy building their own plants. The atom is on its way to light our houses, to toast our bread, to run our television sets and vacuum cleaners. The Atomic Energy Commission estimates that by 1975 about 10 per cent of all the electric power in the United States will come from the mighty atom. Up to now, just about all our civilization's energy has come from the atomic fire in the core of the sun. Soon it will be coming from man-made atomic fires right here on earth.

That does not mean we will soon be driving atom-powered automobiles.

An atomic reactor is still a fairly clumsy piece of machinery that wouldn't fit under the hood of your car as snugly as the sleek gasoline engine of today. And, of course, there is the danger of radiation from the reactor in case of a crash. Atomic power plants are better suited for heavier machines of transportation such as ships. Yet a bulky atomic power plant is still a tight package of power. It runs for months on just one filling of atomic fuel.

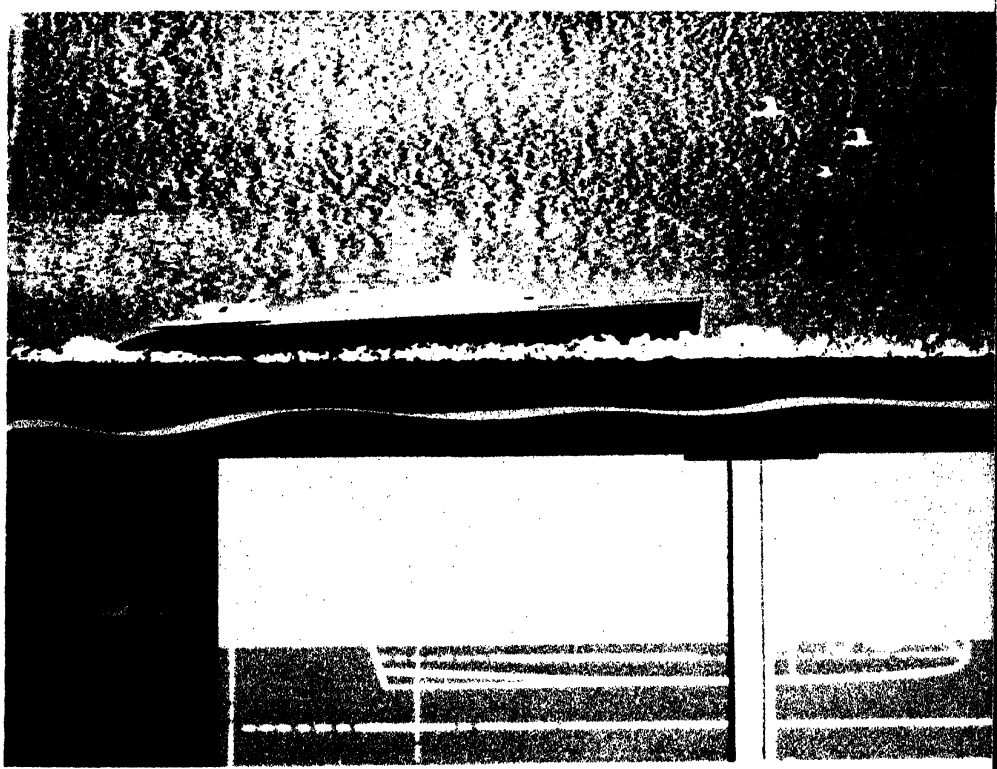
An atomic merchant ship would have no need for large, space-consuming tanks of fuel and oil; it could call on many ports all over the world without ever worrying about its fuel supply. Whereas in the past many tons of coal and oil have been burned to haul a few more tons of goods from one place to another, in atomic traffic of the future the fuel will be in pounds, but the payloads will still be in tons.

One of the most enchanting prospects of the atomic revolution in the transportation field is the atomic airplane. In aviation, the weight of fuel has always been a discouraging limitation. Only in recent years have non-stop, cross-country flights become routine. The engines of an airplane drain the tanks fast; even our latest planes must make a refueling stop after 8 to 12 hours. In military aviation the range of airplanes is extended by means of in-flight (plane-to-plane) refueling—a daring and ingenious operation, but still basically a clumsy method of keeping a plane in the air beyond its normal capacity. An atomic airplane will need no refueling—at least not during the time the crew can possibly stay on the job.

Several aircraft companies in the United States have government con-

tracts for atomic airplanes. They will be different in design to fit different purposes. Probably the first atomic airplanes will be rather large—something like 75 feet long and weighing close to half a million pounds. In existing plans, the atomic power reactor supplies heat. Part of the heat drives a set of turbo-compressors. Great quantities of air, scooped up by broad intakes in front of the power plant, are squeezed by the compressors into a special heat-exchanger that heats the air by atomic energy. The hot air escapes as a stabbing jet at the rear end of the airplane. The recoil of the escaping air pushes the plane forward, as in an ordinary jet plane.

The atomic power reactor is encased in a heavy lead shield to protect the crew against dangerous radiations. Crew and passengers are positioned at a safe distance forward of the power plant. The cabin is at the forward



end of the ship's big nose. The crew is further protected by plastic shielding and by double-walled windows. The free space between the window walls is filled with water, which absorbs any stray radiation from the reactor.

This heavy plane will need a runway miles long. But once airborne, it will cruise at nearly twice the speed of sound. It will circle the earth many times without ever landing for fuel. It will fly as long as its crew wants it to fly.

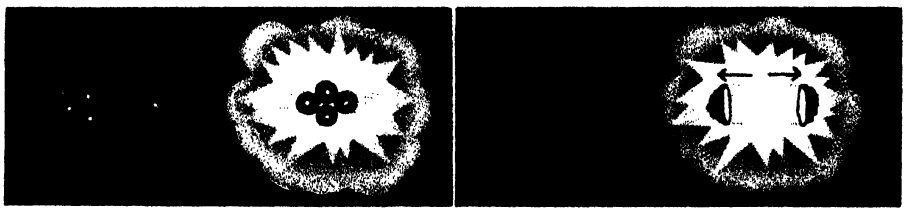
And, some day in the future, atomic power will help us to cast off the shackles of gravity that still hold us bound to our planet. The atom will then help us fly freely through the vast reaches of space. . . .

Before the end of this century the atom will largely replace coal and oil as a source of power. It must! For coal and oil are far too valuable to burn up. They are precious raw materials out of which our chemical industry makes an endless list of useful products—textiles, plastics, dyes, drugs. In the future much of our power will be created inside clean, silent reactors; water power and solar energy will supply the rest.

But how about the resources of uranium—raw material of the atomic

age? There is much less uranium on our earth than coal and oil, ton for ton. In each ounce of uranium there is, of course, much more power than in a ton of either coal or oil. It has been estimated that the world's known resources of uranium should give us about 15 times more power than all the coal and oil that still lie in the ground. More will be discovered by uranium hunters. There is, then, a lot of uranium, but our great-grandchildren will want some, too. If our children dig into their supplies as fast as we have, uranium too will some day be short. What then?

We come back to the Einstein equation. It tells that each piece of matter is a treasure chest of energy. But a splitting uranium atom releases only a tiny fraction of its energy. If the fragments and neutrons discharged in nuclear fission were collected and put together on a scale, they would weigh only a tiny fraction less than the whole uranium atom before it split. Only this minute difference in weight has been converted into energy. It is found in the gamma-ray and in the energy of motion of the fragments and neutrons. All we get out of the uranium atom is a tiny fraction of the energy it contains.



Fusion of light elements

Fission of heavy elements

Now, we have seen that when heavy atoms come apart, energy is released. With light elements, it is the other way around: they release energy when put together. In exact numbers, 2 protons and 2 neutrons weigh 4.033 atomic weight units. If fused together to form a helium nucleus, they weigh only 4.003 weight units—0.030 weight units less. This amount of mass is transformed into energy every time a helium nucleus is formed from its component parts. Obviously this process holds greater promise of virtually inexhaustible energy than the fission of uranium.

Fusion of light elements is what actually happens in the deep core of the sun. This is the secret of solar energy. The fusion occurs in the terrific heat of the sun's core—many millions of degrees. There the protons of hydrogen dash around at tremendous speeds, great enough for them to overcome the electrical forces of repulsion that tend to keep them apart. When they crash into each other, they fuse and form nuclei of helium in several steps. The energy that powers the sun is released in these processes. Slowly the sun uses up its enormous reserves of hydrogen and transforms them into helium. Hydrogen is the fuel and helium is the ash of the sun's atomic fires. But there is enough hydrogen in the sun to last countless billions of years into the future.

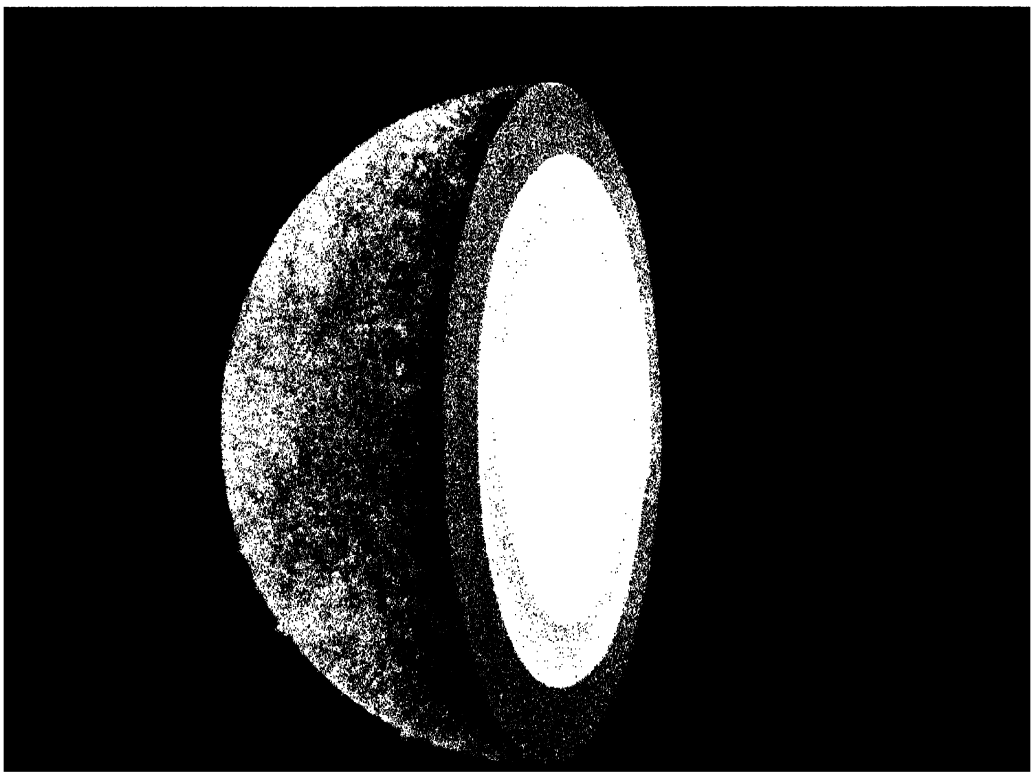
Fusion of hydrogen nuclei can take place only at temperatures of millions of degrees. Only then do the nuclei move fast enough to break through one another's electric armor, come into contact, and fuse, releasing energy in the process. This is why physicists call such nuclear fusion a "thermonuclear reaction."

It is from such thermonuclear processes that the hydrogen bomb gets

its awesome power. In an H-bomb explosion the high temperature necessary is supplied by a normal A-bomb. In the heat of the initial flash, hydrogen fuses in a blast of incredible proportions. Uranium thus becomes only the trigger for the release of more energy than uranium itself could provide.

So far, nuclear fusion has been achieved only in the form of the devastating H-bomb blasts that have shaken the very soul of man. Everybody agrees that explosive release of such energy does not belong on this planet. It belongs where Nature first put it: deep inside the stars.

To make the power of fusion useful, it has to be tamed like the power of fission, but it is vastly more difficult to build a fusion reactor than a conventional fission reactor. As we have seen, the fusion of nuclei requires temperatures of millions of degrees, and a body of gas heated to such temperatures would exert a tremendous pressure against the walls of its container. The hot gas would vaporize the walls instantly and escape in a violent explosion. There is only one way around these hard facts of physics: using



a highly diluted gas—so thin that its pressure would remain within bounds and its heat energy would not be great enough to vaporize the walls.

But now a second problem arises. We have made the gas so thin that it cannot overheat the walls; yet if the walls are not hot enough, they will cool the gas so that nuclear fusion cannot take place. Now we see how beautifully Nature has solved this problem in the case of the sun. The sun's core is a fusion reactor and its walls consist of hot layers of gas thousands of miles thick. This gas shell can withstand tremendous pressures, and since it is hot it cannot cool the core. So this is our task: to find a wall that performs the same tricks. It is obvious that no ordinary materials could do the job.

The hopes of nuclear physicists are kept alive through a strange and fortunate coincidence. A gas can be heated to millions of degrees: namely, by running a strong electric current through it. This procedure automatically produces a "wall" of a special kind. The electric current surrounds itself with a strong magnetic field; this field acts like a wall that the electrically charged nuclei cannot penetrate. The magnetic field also compresses the current into a narrow cylinder which holds the particles of hot gas together. This is the famous "pinch effect," and the invisible walls of the magnetic field are called a "magnetic bottle."

At present our only hope of taming the power of fusion lies within the magnetic bottles, even though they are very difficult to produce and to maintain. They are highly unstable and they collapse after a few thousandths of a second! In the United States, in England, and probably in Russia scientists are doing their best to improve techniques of maintaining magnetic bottles and pushing the temperature inside higher and higher. In the spring of 1958 British scientists announced that they had produced atomic fusion with heavy hydrogen on a very small scale. Final success is still a long way off, but the first step has been taken.

Heavy hydrogen will truly be the "ultimate fuel." Each gallon of water contains enough heavy hydrogen to produce the same amount of energy found in 350 gallons of gasoline. There are oceans of fuel all around us!

All this, then, may be granted to us through our first wish.

OUR SECOND WISH: FOOD AND HEALTH

Mankind has long suffered from hunger and disease. The atomic Genie offers us a source of beneficial rays. These are magic tools of research which can, above all, help us to produce more food for the world and to promote the health of mankind. Our second wish, therefore, shall be for: FOOD AND HEALTH!

FOR COUNTLESS centuries man has been using fire. He has known that fire can keep him warm, but it can also burn his hand. He has long since learned to harness fire, to put its benefits to use, but to avoid its dangers. With the atomic fire, man faces the very same situation all over again. The atom is a source of invisible radiation, whose dangers are infinitely more subtle than those of fire. By the same token, its potential benefits to mankind are also more subtle. The atom's rays hold a great promise for research and medicine.

Inside a reactor is confined a slow, continuous "explosion." It smolders mildly, like softly glowing embers. With each splitting of an atom there is a fierce burst of gamma-rays, and neutrons are constantly produced in great numbers. Both gamma-rays and neutrons are dangerous to man. Undue exposure to these rays causes radiation sickness and shortening of life. To protect personnel working with atomic reactors, the entire core is encased in heavy walls of concrete that absorb the dangerous radiation and prevent it from escaping. Against neutrons, thick layers of water are a good protection. In addition to these basic precautions, all people and equipment are under constant supervision. Medical supervisors monitor atomic installations with Geiger counters to detect stray radiation that could accumulate and become dangerous.

Danger is foremost in our minds when we think of atomic radiation. It makes us forget that the atom's rays have done much good. For many years radioactive rays have been used to treat dread diseases like cancer. Before atomic reactors were built, the only practical source of atomic radiation for medical use was radium. Today the reactor is not only a source of raw power; it is also a device that can be used to make many elements radioactive like radium itself. Since reactors have been in operation, natural radium in hospitals has been largely replaced by artificial radioactive elements.

As we have seen, the neutron is the key to the release of the atom's energy. The same neutron is also the magic wand that turns a normal, natural element into a radioactive one. Here is how it happens:

A tremendous number of neutrons are constantly on the move inside a reactor core. Many million million neutrons fly through each square inch

of the core's cross-section in every second. A piece of material sunk into the reactor core is shot through constantly by this dense shower of neutrons. They seep through the atoms of the material as so many millions of raindrops fall through the foliage of a forest. Every so often a neutron hits the nucleus of an atom and—it gets stuck.

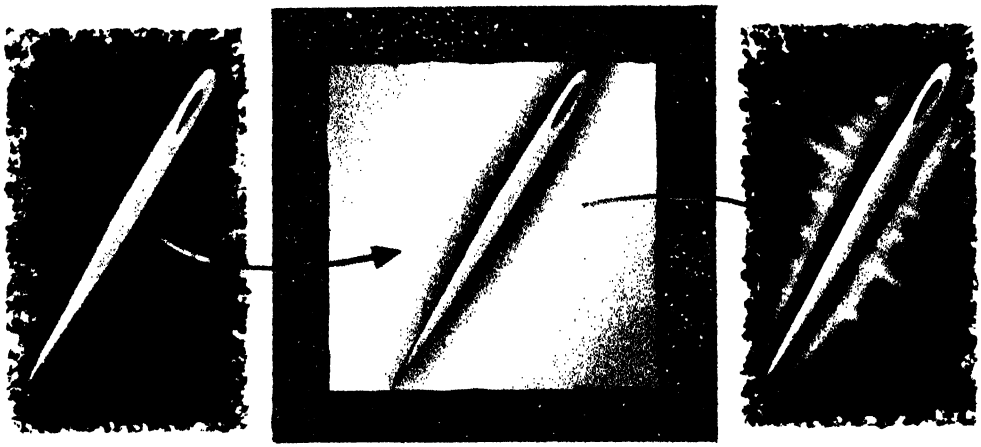
Take the element cobalt, for example. It is a metal closely related to iron and nickel, and one of the few elements in Nature that have only one isotope. All cobalt atoms, as they are found in the earth's crust, are of one kind: $^{59}_{27}Co$—that is, 27 protons and 32 neutrons in the nucleus, giving the atomic weight of 59. If a chunk of cobalt is put into a reactor and exposed to the bombardment of neutrons, a large number of its atoms each capture an extra neutron. These atoms now have 33 neutrons in their nuclei. The new nucleus is written $^{60}_{27}Co$. A simple equation describes the whole process that takes place in the reactor:

$$^{59}_{27}Co + ^{1}_{0}n = ^{60}_{27}Co$$

$^{1}_{0}n$, of course, is the symbol for the neutron, with its weight of 1 and charge of 0. The newly created $^{60}_{27}Co$ is still a cobalt atom, because the number of protons in its nucleus has not changed. It is an artificial isotope of cobalt with the atomic weight of 60. Such an atom is not found in Nature; it can only be made artificially.

But this is not all the story. The extra neutron in the nucleus makes the neucleus unstable, like the nuclei of the natural radioactive elements radium and uranium. After a while the cobalt-60 nucleus gives off a gamma-ray. Thus, by putting cobalt in the reactor, we made it radioactive. It is an artificial radioactive isotope—or, as physicists say, a "radio-isotope."

A chunk of cobalt coming out of the reactor contains actually only a small percentage of the radio-isotope cobalt-60. Most of the atoms have not captured a neutron and thus remain normal cobalt-59 atoms. But even these few radioactive atoms mixed up with many more normal cobalt atoms are enough to make the chunk of cobalt strongly radioactive.



The radio-isotope cobalt-60 has a half-life of 5 years and 3 months. After this time half of its atoms have given off their single bursts of gamma-rays, and the radioactivity of the whole chunk of cobalt is exactly one half of its original intensity.

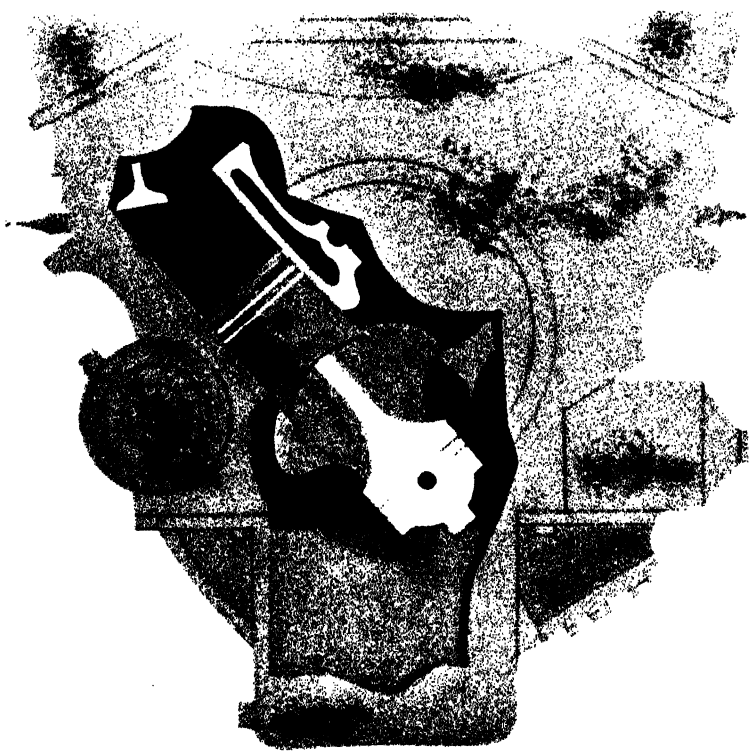
Many other elements can be put into an atomic reactor and made radioactive artificially. A score of radio-isotopes are available today for use in science and medicine. They have opened up a fascinating new area of research and have become one of the most astonishing tools of science in the atomic age. An important aspect of their usefulness is that they can be traced; a Geiger counter will easily tell their presence anywhere, even in amounts too small to be visible or to be traced by ordinary chemical means. This is why radio-isotopes are also called "tracer-atoms."

Take an ordinary needle and put it into an atomic reactor for a short while. Some of the iron atoms contained in the steel will capture a neutron and be transformed into a radio-isotope of iron. When the needle is pulled out, it will radiate mildly. It will cause a Geiger counter to click. Now that needle could be found in the proverbial haystack without any trouble. The Geiger counter would lead us directly to its hiding place.

Making a sample of material mildly radioactive is like putting a bell on a sheep. The shepherd traces the whole flock by the sound of the bell. In the same way it is possible to keep tabs on tracer-atoms with a Geiger counter or any other radiation detector.

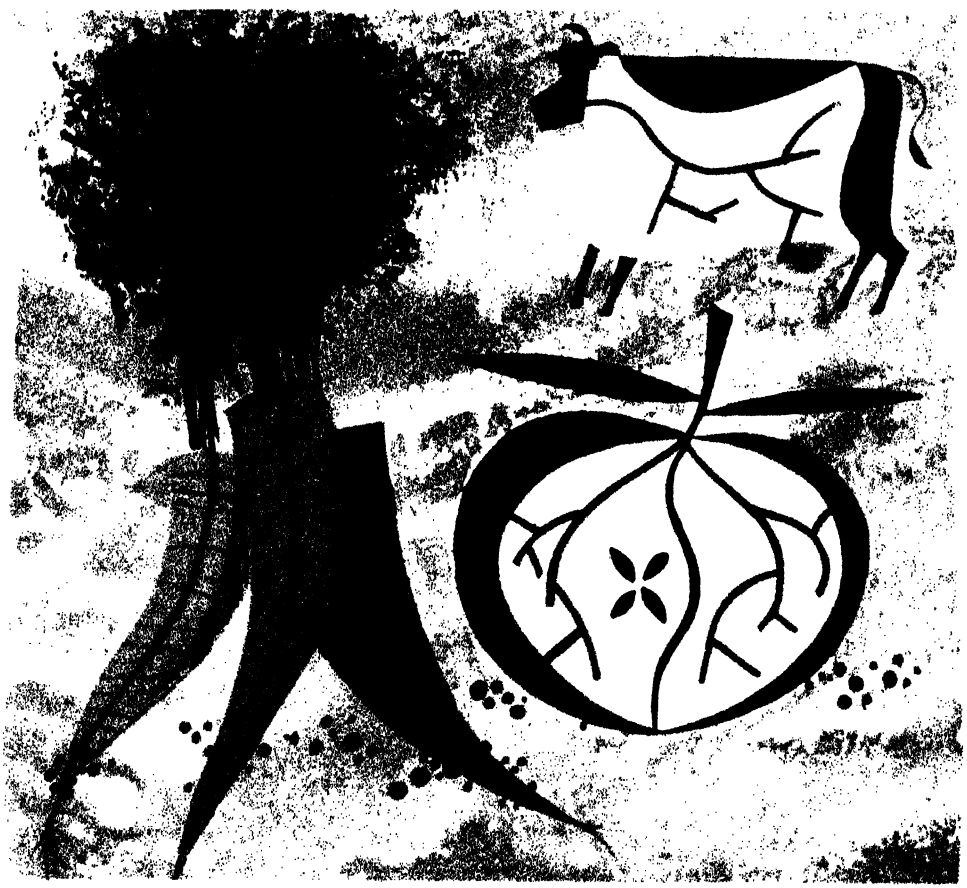
This wonderful arrangement makes the radio-isotopes a boon to science, engineering, and medicine. Tracing of small amounts of matter is extremely helpful in all kinds of research. An engineer, for instance, wants to test how well a new type of piston ring wears. So he mixes up a small amount of iron radio-isotope in the steel and runs the ring in an engine for a few hours. Tiny bits of steel rub off in the process, and there will be a few of the tell-tale tracer-atoms among them. These are washed down into the oil pan. By testing the oil with a Geiger counter, the engineer can tell how much steel is rubbing off—in other words, how well his piston ring wears.

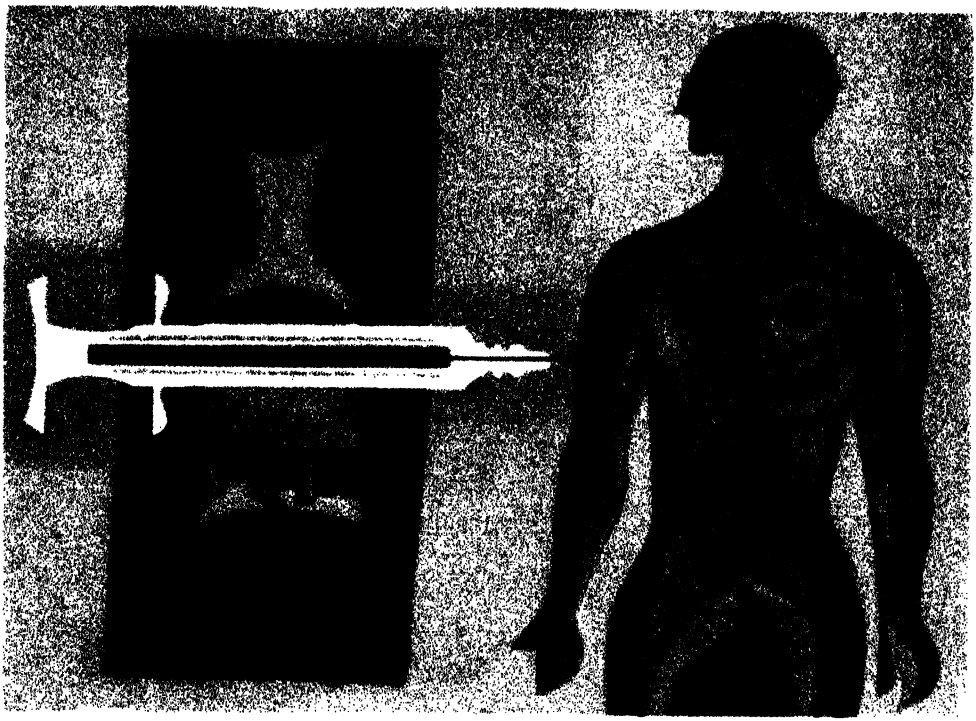
In oil refineries, radio-isotopes can be used to trace oil along the pipelines. By adding a few tracer-atoms to the oil, batches of different grades of oil can be "labeled" and followed wherever they go. Hidden leaks are easily discovered; they are betrayed by the presence of radioactivity outside the pipes.



However, by far the greatest value of the radio-isotopes lies in biology. Before biologists had tracer-atoms it was difficult for them to study the chemistry of living organisms. They had to kill their test animals, and plants had to be cut up. With tracer-atoms they can now study the living body in action. They can follow the movement of matter through the pipelines of life.

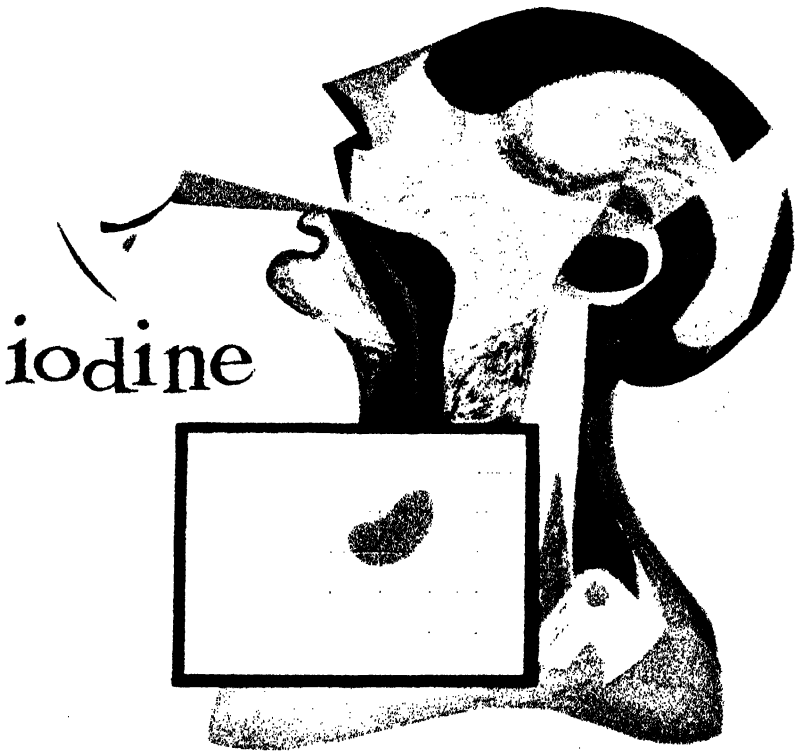
So, in the production of food for hungry mankind, the radio-isotopes are potentially a great help. It is very important to know what parts of fertilizers, soils, and soil nutrients are actually taken up by the roots of various plants; the addition of small amounts of radio-isotopes will tell the story. When the plant grows, a Geiger counter will tell how much fertilizer material has actually been used by the plant in building its body. The radio-isotopes can further be traced through the body of an animal that eats the





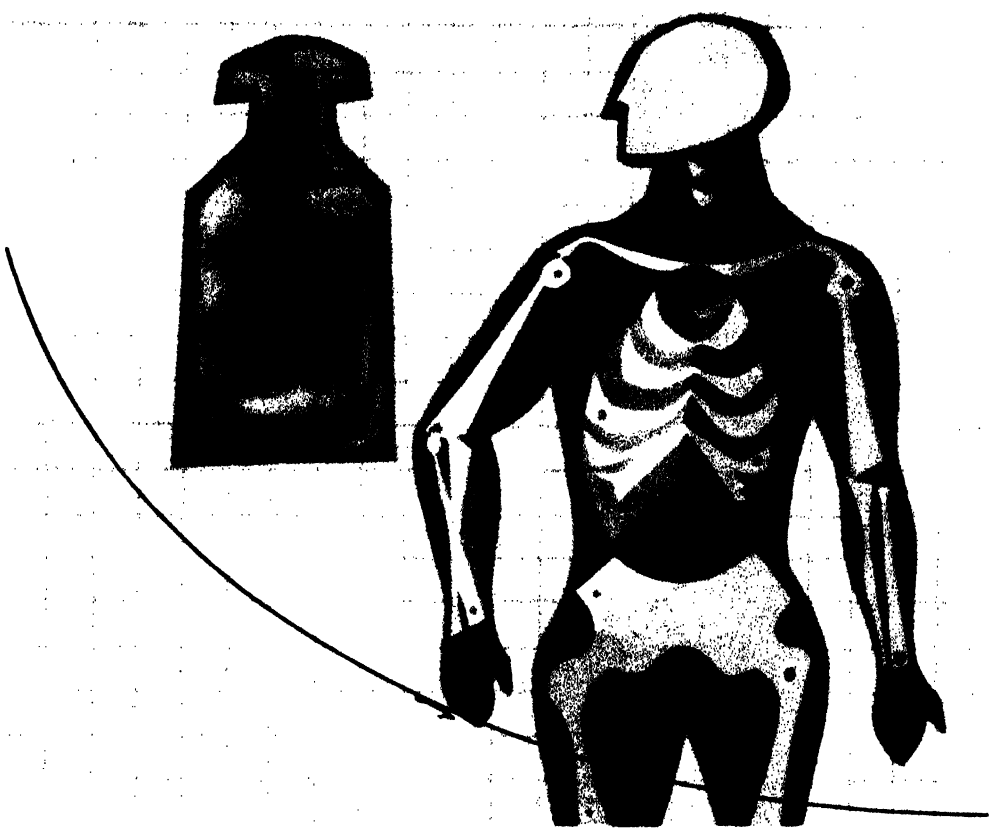
plant. Radio-isotopes, in brief, tell us what the living bodies of plants and animals are doing. Future research with tracer atoms will lead to better crops and will increase the efficiency of our farms. Radio-isotopes will help us produce sufficient food for the increasing population of the world.

Radio-isotopes as used in the human body are bringing about a new era of medicine. They can be used in so many ways that thousands of papers have already been published about them in the medical journals. They are of greatest value in the diagnosis of human disorders, helping in many cases where X-rays fall short. Sodium, for example, can be made radioactive and processed to ordinary salt. In the form of a salt solution the sodium radio-isotope is injected in the arm of the patient; there it is picked up by the bloodstream and transported to the heart. A Geiger counter placed near the heart of the patient will start to click at exactly the moment when the tagged batch of blood arrives at the heart. In this way the blood flow from arm to heart can be timed exactly, offering a valuable clue in the recognition of certain heart diseases.



A patient may have a disorder of the thyroid gland, located in the lower front of the neck. Such a patient is given an "atomic cocktail" containing a small amount of radioactive iodine. Since thyroid tissue has a strong preference for the chemical element iodine, after a few hours most of the iodine radio-isotope has been collected by the thyroid, and there the isotope gives off its tell-tale rays. The patient is then put under a special counter that sweeps slowly across his neck. Measuring the radiation from all directions, a surgeon can map the exact size and location of the thyroid and measure the accumulation of iodine in this gland. Thus although an X-ray of the neck would show nothing, the radio-isotope of iodine may reveal enough for an exact diagnosis of the thyroid condition.

Radio-isotopes can heal, too. Tiny sources of healing radiation can be planted in different parts of the body—to help where radium and X-rays are impractical. Radio-isotopes of gold, for example, are used to cure disorders of the lymph system. Other elements go directly to those parts of the body where they are needed. Phosphorus, for example, is one of the chemical elements of which bones are built, and radio-isotopes of phosphorus therefore collect in the bones. There, its mild radiation works close to the bone marrow, where the body manufactures blood cells. Certain types of blood disease can thus be cured. The radio-isotope phosphorus-32 has a half-life of only 14½ days; so the radiation dwindles and virtually stops after a few months. A patient, then, can carry his own radiation source with him; it does its work all the time, day and night; and after the right dose has been received the radiation dies out by itself.



And there is the radio-isotope of cobalt. We saw that the cobalt-60 isotope has a half-life of more than five years. This is quite long and makes it worth our while to encase a chunk of cobalt in a heavy lead shield and ship it to a hospital. This is the famous "cobalt bomb" which is already in use in many hospitals all over the country. A normal-size cobalt bomb gives off radiation equivalent to three full pounds of radium, but it is much cheaper. It is a bomb built for health—not for death. Carefully controlled amounts of radiation concentrated on a cancer may slow the growth or eliminate it entirely.

Food and health . . . through our second wish we have received the tools to achieve both!

THE THIRD WISH: PEACE

There is left to us the third and last wish. It is an important one that demands wisdom. If the last wish is unwise, then—as some of the old legends tell—all the wishes granted before may be lost.

THE ATOMIC Genie holds in his hands the powers of both creation and destruction. The world has reason to fear those powers of destruction. They could yet destroy civilization and much of humankind.

So our last wish should simply be for the atomic Genie to remain forever our friend!

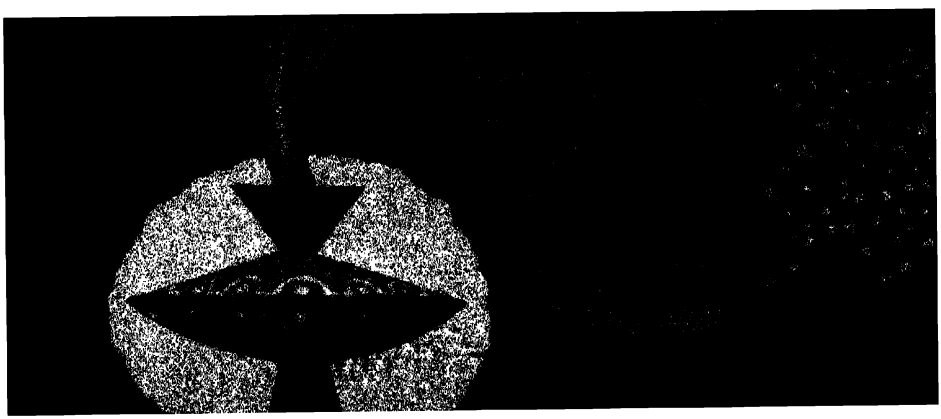
It lies in our own hands to make wise use of the atomic treasures given to us. The magic power of atomic energy will soon begin to work for mankind throughout the world. It will grant the gifts of modern technology to even the most remote areas. It will give more food, better health—the many benefits of science—to everyone.

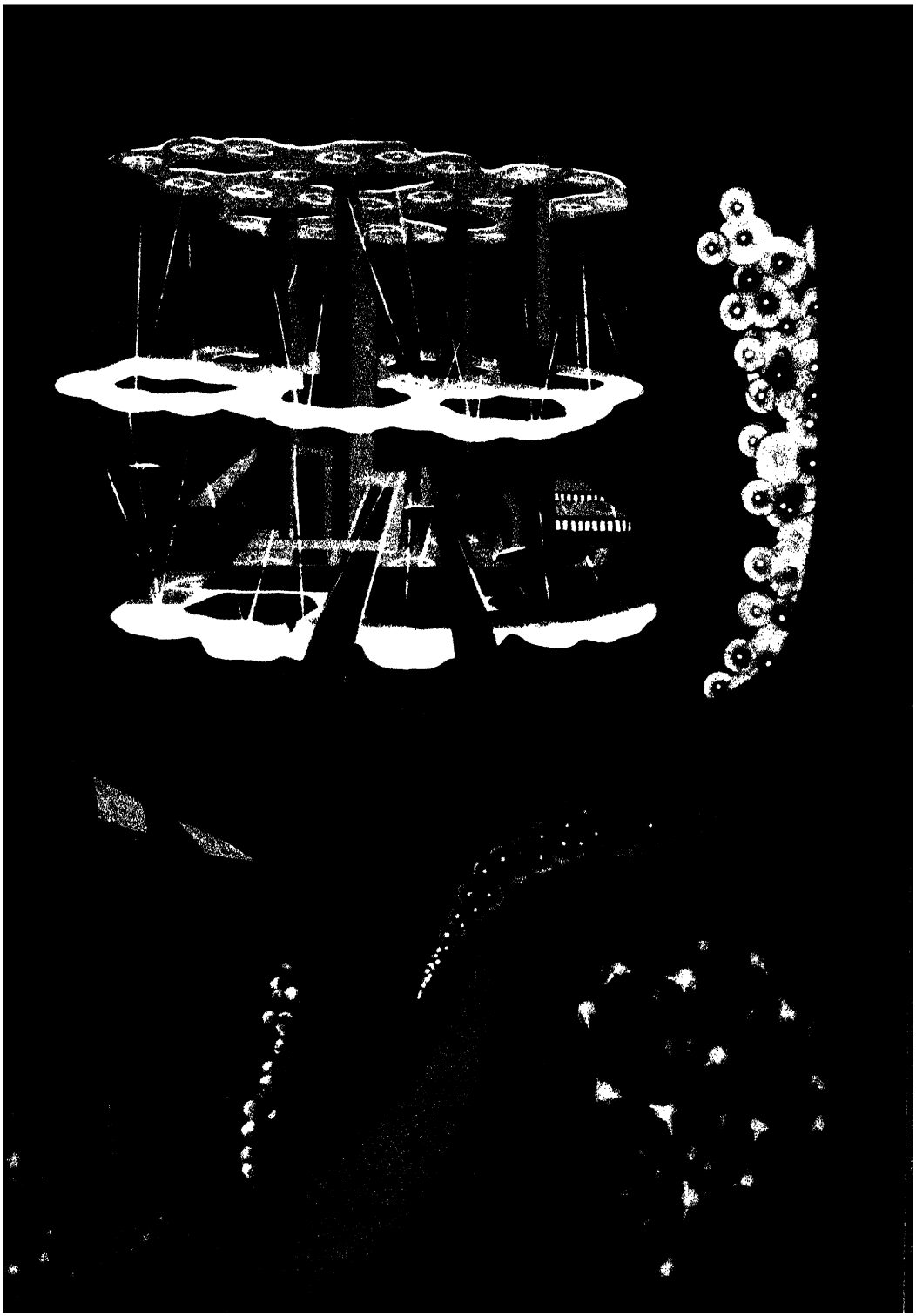
We still have much to learn. But the key to a peaceful atomic future lies in the spirit of the great thinkers of the past. From them we have inherited a great wealth of knowledge. Whatever benefits the atom brings us will come from that heritage: the ideas of Democritus, Galileo, Gassendi, and Boyle . . . the work of Lavoisier, Dalton, and Avogadro . . . of Roentgen, Becquerel, and the Curies . . . Einstein, Rutherford, Bohr, Hahn, and many others.

When these scientists created their theories and made their discoveries, they perhaps hardly foresaw that there would ever be widespread application of their work. They simply marveled at the world around them and deeply desired to know about Nature and her ways. That the results of their noble efforts could or even would ever be applied for destruction—this was farthest from their minds and hearts.

They gave us knowledge of the atom, and our last and most important wish will come true if we use the power of this knowledge in their spirit.

Then the atom will become truly our friend.





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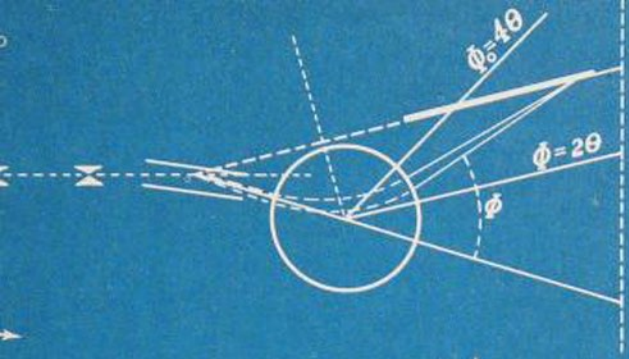
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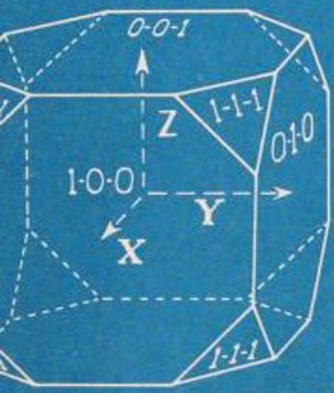
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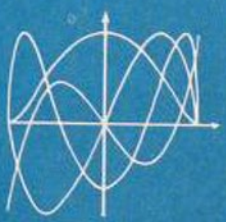
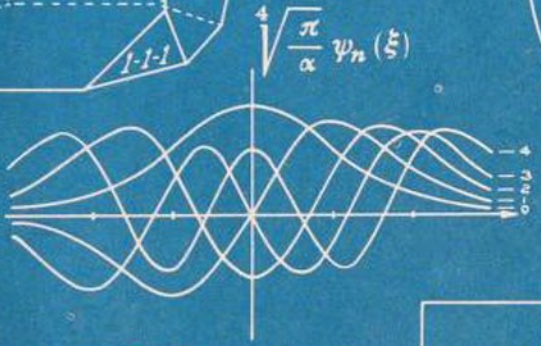
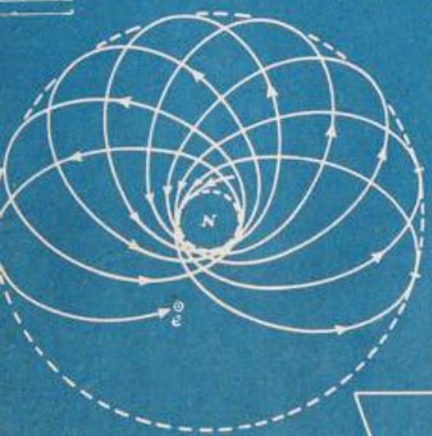
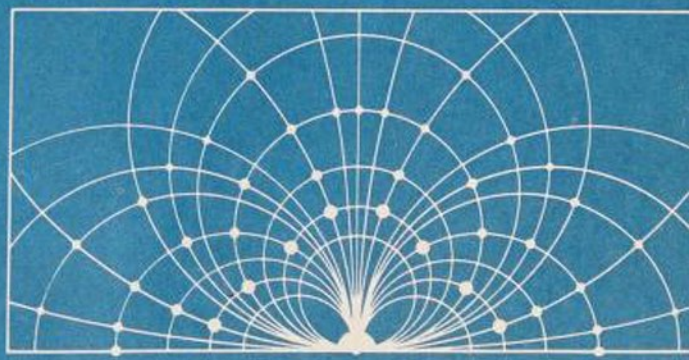
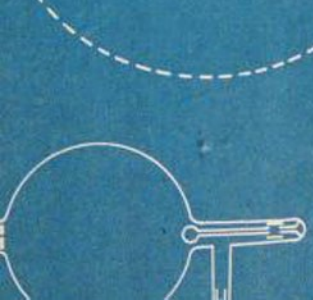
X
1-1-1

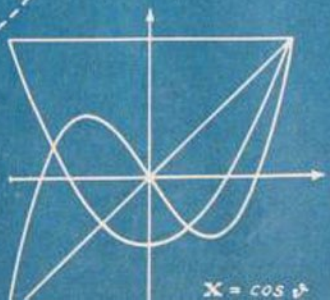


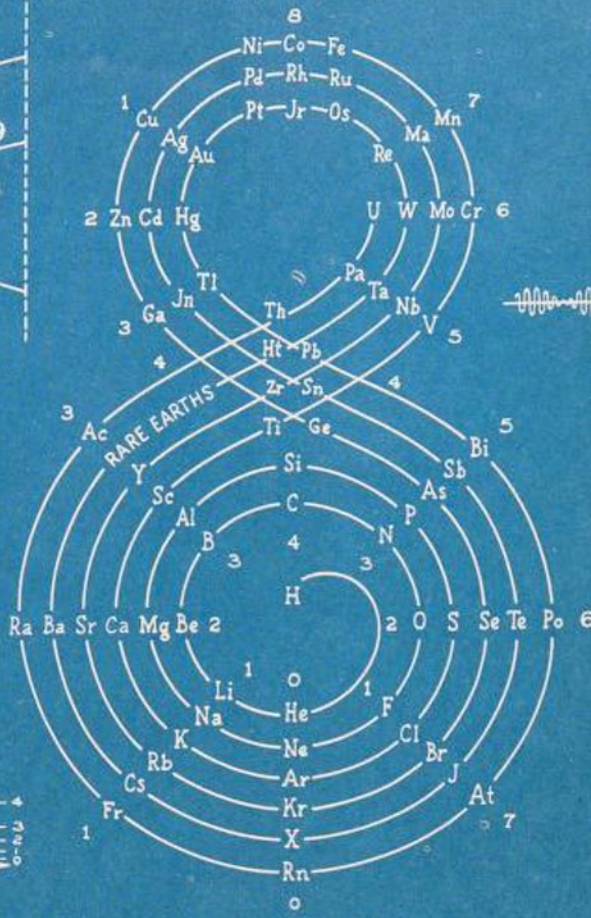

$\sqrt[4]{\frac{\pi}{\alpha}}\,\psi_n(\xi)$
4
3
2
0


N






$X = \cos^2$


8
Ni Co Fe
Pd Rh Ru
Pt Jr Os
1 Cu Ag Au Mn 7
Re Ma
2 Zn Cd Hg U W Mo Cr 6
Pa Ta Nb V 5
Tl Jn Ga 3
Th
Ht Pb 4
Zr Sn 4
3 Ac RARE EARTHS Ti Ge Bi 5
Y Si Sb
Sc Al C As
B 3 4 N P 3
H
2 Ra Ba Sr Ca Mg Be 2 2 O S Se Te Po 6
1 0 1
Li He F
Na Ne Cl
K Ar Br
Rb Kr J
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Fr Rn
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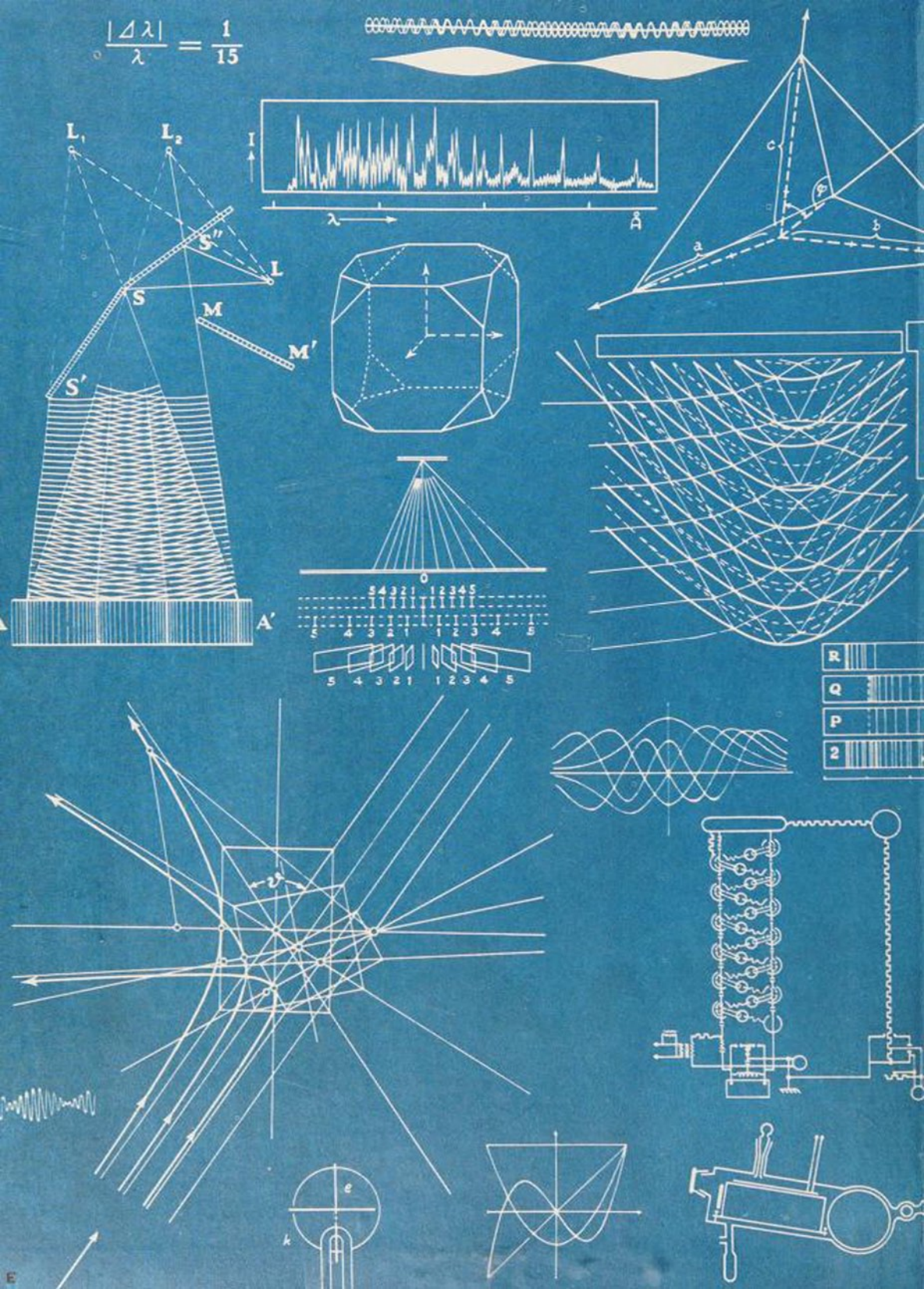
$\frac{|\Delta\lambda|}{\lambda} = \frac{1}{15}$
L1
L2
S''
L
S
M
M'
S'
A'
I
λ
Å
a
b
c
α
β
0
5 4 3 2 1 1 2 3 4 5
R
Q
P
2
e
k