THREE PUBLIC LECTURES ON MODERN PHYSICS[1]

I

WHAT THINGS ARE MADE OF

TWENTY-FIVE HUNDRED years ago, when ancient Greece was beginning to carve out the brilliant civilization that was to be her destiny, Thales, the sage of Asia Minor, proposed a search for the answer to the great question which man must always ask, "Of what and how is the world made?" Only by finding a right answer to this question, he contended, is it possible for man to adjust his life and thoughts to his surroundings. It is not surprising that he himself never found a satisfactory solution. For twenty-five centuries we have been continuing his quest, and we are yet far from the complete answer to his problem. Nevertheless progress has been made. The main outlines of our great universe are now spread out before us. The time is ripe for science to report what has been learned and what remains to be found out "concerning the nature of things."

Earth, water, air, and fire were the elements out of which Thales would build his world. His successors however carried the analysis deeper. Democritus and his fellow atomists recognized that things are made of minute particles, which they called atoms, and in terms of these atoms

[1]Delivered at the Rice Institute in March, 1932, by Professor Arthur H. Compton of the University of Chicago.

they accounted for everything from a gorgeous sunset to the love of a man for a maid. This was mostly lost in the dark days of the Middle Ages, and has been rediscovered only during the last few centuries. In that relatively brief era of world history between Copernicus and Einstein we have learned much more reliably and precisely than the Greeks ever knew about man's surroundings.

Let us take a brief preview of the microworld as we now know it. Stars, mountains, people—what are the parts of which they are made, and how are these parts put together? Light, radio rays, X-rays—what are these radiations?

When we take apart this infinitely complex mechanism that we call dirt, or perhaps a diamond, or it may be a flower, we find it made up of a myriad of tiny molecules. Each molecule is itself complex, but is more perfectly formed than the wheels of a Swiss watch. Moreover, these molecules are in continual motion, having continued to run for years without winding and without wear. We find that the molecules which make up matter in its endless variety of forms are themselves built up of a few hundred kinds of atoms. Some of these atoms differ from each other by their chemical properties, others only by their weights.

Our few hundred atoms are themselves made of yet more tiny particles, which become evident through their electric charges. There are found to be two kinds of them, carrying positive and negative electric charges respectively. As nearly as we can tell, all those of any one kind are exactly alike. The positively charged particles, called *protons,* have most of the weight of the atom, while the negatively charged particles, or *electrons,* are the lively little bodies responsible for chemical combinations, electrical conductivity, and the like. By grouping themselves in various ways, these little particles form the various atoms.

Rocks and trees and people do not, however, make up the whole of the universe. How about the sunlight that gives us warmth and makes the trees grow? These rays, though having all the characteristics of waves, are found to consist of minute corpuscles, which are known as *photons.*

Protons, electrons, and photons—these are the elements with which the modern physicist replaces the earth, water, air, and fire of Thales. We sometimes think of standardization as being the distinctive keynote of modern industry. Yet even the most standardized motor car has hundreds of different parts. What then shall we say of the Maker of our universe, who, using but three kinds of pieces, protons, electrons and photons, has made our world with its infinite variety of beauty and life.

MOLECULAR MOTIONS

Let me lead you into this microworld through the lenses of a powerful microscope, as Brown was led into it a century ago while examining some tiny objects suspended in water. "They're alive," he exclaimed. But to make sure he turned his glass on some wax particles suspended in the same way, and found that they also moved. Everything that is small enough moves, he found, unless it is held fast to something solid. These are the *Brownian movements.*

What is the cause of this motion? For many years physicists had explained the pressure of a gas on the walls of a vessel which holds it by supposing that the gas is made of little particles, the "molecules," which dart about in the gas at high speed. They could calculate how fast these molecules must go to account for the observed pressure, and found that if the energy of their motion was proportional to the temperature they could accurately account for the increase of pressure with temperature. The calculation showed too that the energy of motion of the little molecules should be the same as that of the big molecules, which would mean that the little molecules must move the faster.

Now a careful study of these Brownian movements reveals the fact that the energy of the particles under the microscope is just what the kinetic theory says a molecule should have. And the speed of their motions increases at higher temperatures, just as the molecular theory predicted. At one instant more molecules strike a globule on one side, and the next instant more strike on another. In fact, in a very real sense, one may correctly consider the motions of these little particles as true molecular motions. We must remember, however, that these globule "molecules" which are seen under the microscope consist of perhaps a million or more atoms each, whereas a gaseous molecule usually has only one atom or two or three.

We have here a glimpse of Nature's continual activity. How far from the truth is our idea of "dead matter"! Our little friends, the atoms and molecules, to whom we have just introduced you, are indeed very lively little fellows. If they were not, whence would our own life come?

ATOMS

> "According to convention there is a hot and a cold, a sweet and a bitter, and according to convention there is color; in truth there are atoms and a void."
>
> —Democritus.

A few years ago we were camped beside a mountain lake in the foothills of the Himalayas. The warm air from the plains of India was blowing over a nearby mountain range, and was coming down again into the beautiful Vale of Kashmir. Clouds were continually forming as the air, cooled by expansion on coming up the mountain side, became supersaturated with moisture. But after passing the crest of the range, the air was warmed again by compression as it sank to lower levels, and the clouds evaporated into the thin air.

It was while watching a similar occurrence in his native hills of Scotland that C. T. R. Wilson conceived his beautiful laboratory experiments on clouds. Though he could not bring the mountains into his laboratory, he could expand his moist air in a cylinder of glass and see what was

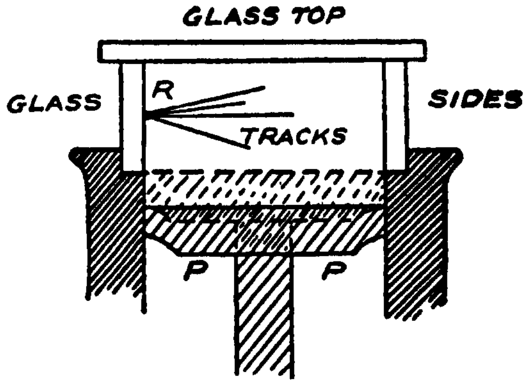

Fig. 1

going on. Figure 1 shows an instrument similar to Wilson's original expansion chamber. Note its glass walls and top and the movable piston at the bottom. Some water is also kept in the chamber, so the air will be moist. After the air is compressed, it is allowed to stand for a moment until it is saturated with moisture, and is then allowed to expand. The resultant cooling causes a cloud to form in the glass chamber just as it did on the mountain top.

Did it ever occur to you that when a cloud forms each little drop of moisture in the cloud must condense on something? Usually it condenses on a speck of dust floating in the air, so that after a rainstorm these dust particles are carried to the ground and the air is beautifully clear. But when the dust has been removed, on what can the moisture condense? There are always in the air some broken bits of atoms and molecules which we call *ions*. These ions may be produced by rays from radioactive substances in the ground, and other sources. So Mr. Wilson tried the experiment of placing a speck of radium in his expansion chamber, to see what kind of clouds would be formed.

Instead of a diffuse cloud, little white lines of fog appeared, like rays shooting out from the speck of radium. These linear clouds are easily visible, and may be photographed, as in figure 2, which is one of Wilson's earliest cloud pictures. We see the glass walls of the expansion chamber, and the rod on the tip of which the radium is placed. The white lines radiating from this point are clouds of water droplets. Some of the more diffuse lines show their foggy character more clearly.

Why do the clouds form along these radiating lines? It is apparent that the lines mark the paths of some particles shot out from the radium. A photograph taken so as to show the lines more sharply is shown in figure 3.

ATOMS OF HELIUM

What are these particles shot out from the radium? Let us call them alpha particles, in order not to imply anything about what they are, and investigate their properties.

Lord Rutherford once caught a large number of these particles in the effort to learn what they make when there are enough of them to handle. He compressed a highly radioactive gas into a fine glass tube with walls so thin that the alpha particles could pass through. After a few days he noticed gas collecting in the space surrounding the tube. When an electric discharge was passed through the collected

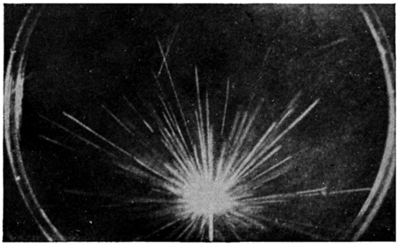

Fig. 2

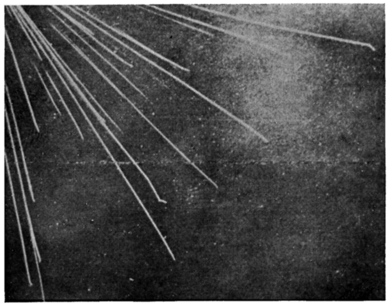

Fig. 3

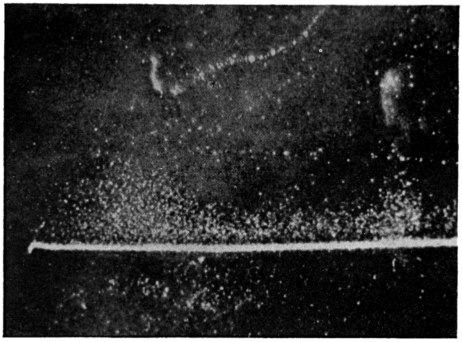

Fig. 4

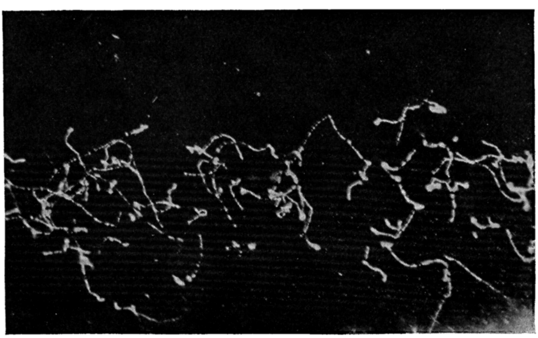

Fig. 5

gas, the light viewed through a spectroscope showed the brilliant spectrum of the gas helium.

Let us recall the romance of helium. Observed many years ago by Lockyer in the spectrum of the sun, it remained unknown on earth for a generation until Raleigh and Ramsay, making a precise measurement of the density of nitrogen in the air, found it different from the nitrogen prepared in the laboratory. Search for the cause of this discrepancy revealed a whole series of new gases—argon, with which our incandescent lamps are filled; neon, with which we advertise our wares in blazing red; helium, with which we now fill our dirigibles; and two others, krypton and xenon, which have become of great value in certain laboratory experiments. Thus was helium found; and in these cloud photographs we see it being formed—the birth of helium atoms. For these alpha particles are none other than atoms of helium gas.

It is possible to count the atoms one by one as they come from a preparation of radium. This might be done with the help of a cloud expansion chamber, counting the tracks as they appear. We should thus have, however, only an intermittent count. A better method is to allow the atoms to enter an electrical counting chamber. They can thus be made to make an audible sound as each particle enters the chamber, or still better, each particle can be made to trip an electrical counter. Rutherford's glass tube, through whose walls the alpha particles came which made up the helium gas, was immensely more radioactive than the radium samples used in such counting experiments. Nevertheless, by comparing the radioactivity of the two samples we can estimate the number of atoms that must have come out of the glass tube. Suppose that we have thus counted all the atoms that have come through the tube and made the gas observed in Rutherford's spectroscope. How many atoms would we have? In a small thimble filled with helium at atmospheric pressure, the number of atoms is about 1 with nineteen ciphers after it. For helium, each atom is a molecule. In the case of air each molecule of nitrogen or oxygen has two atoms. As Avogadro showed many years ago, however, the number of molecules of air or helium or any other gas required to fill a cubic centimeter at atmospheric pressure is the same for all, and is found to be 1.9×10^{19}. This is known as "Avogadro's number."

Perhaps such a number means but little. Let us then put it this way: Two thousand years ago Julius Cæsar gave a dying gasp, "*Et tu, Brute?*" In the intervening milleniums the molecules of air that he breathed out with that cry have been blown around the world in ocean storms, washed with rains, warmed by the sunshine, and dispersed to the ends of the earth. Of course only a very small fraction of those molecules are now in this room; but at your next breath each of you will inhale several of the molecules of Caesar's last breath.

Molecules and atoms are very tiny things; but there are so many of them that they make up the whole world in which we live.

PARTS OF ATOMS

The story is told of Lord Kelvin, famous Scotch physicist of the last century, that after he had given a lecture on atoms and molecules, one of his students came to him with the question, "Professor, what is your idea of the *structure* of the atom?" "What!" exclaimed Kelvin, "The structure of the atom! Don't you know that the very word 'atom' means the thing that can't be cut? How then can it have a structure?"

"That," remarked the facetious young man, "shows the disadvantage of knowing Greek."

To the ancient atomists the "atom" was the smallest unit into which matter could be divided. The physicist of the present day gives the name of "atom" to a particular type of minute unit of matter which is found to occur in nature. For many years no method was known of dividing these units into smaller components, and they were therefore frequently identified with the "atoms" of the ancients. There are, however, several hundred different kinds of atoms recognized, one for each of the chemical elements, and many of the elements are composed of several different types of atoms which differ from each other in weight. May there not be some more fundamental substance of which these atoms in turn may be built?

THE ELECTRON

In figure 4 is shown a photograph of the trail of helium atom on a larger scale than those shown in figures 2 and 3. Below the trail left by the helium atom we notice a much fainter trail, which is very crooked. This appears to be due to something much smaller than the particle which made the broad bright trail above. If we called the upper one an *alpha* particle, let us call the lower one a *beta* particle, and try to find out what kind of thing it is.

Similar beta particles knocked out of air by the action of X-rays are shown in figure 5. The air in the chamber might be replaced with argon, and beta particles would still appear. If thin sheets of aluminum or gold are placed in the chamber, beta particles are seen to come out of the metal. It is found that they can be ejected from anything. Beta particles are, that is, a common component of all different forms of matter of whatever nature.

The photograph shown in figure 6 was taken with a strong magnetic field applied to the expansion chamber when the cloud was formed. It will be seen that the trails of the beta particles are curved in circles. Such a bending of paths is just what we should expect if the moving particles are electrically charged. For a magnetic field produces a force on a moving electric charge just as it does on a wire carrying an electric current. From the direction of the curvature one can show that the particle is negatively electrified.

Many years ago, Michael Faraday, the centennial of whose great discovery of electromagnetic induction was celebrated last year, showed that when an electric current passes through a liquid, it is carried by electrically charged atoms, or ions, each of which carries one or two or three unit electric charges. Thus the hydrogen ion always carries one unit charge and the oxygen atom two units of charge. So when an electric current is passed through water, it requires twice as many hydrogen atoms to carry the current to the cathode as oxygen atoms to the anode, and hydrogen is produced twice as rapidly as oxygen. Similarly the silver ion carries one unit of charge, whereas the copper ion carries two units. Thus if the same electric current passes through solutions of silver and copper, twice as many silver atoms are liberated as copper atoms. Since we have found how to count the molecules in a unit volume of gas, if we measure the quantity of electricity required to produce a unit volume of hydrogen by electrolysis, we can indeed calculate the charge carried by the hydrogen ion. It is merely $e = Q/2N$, where Q is the total amount of electricity required, N is Avogadro's number of molecules per unit volume, and 2 is the number of hydrogen atoms in a hydrogen molecule. This quantity e is about 0.000,000,000,5 of an electrostatic unit, and is known as the *electronic unit of charge.*

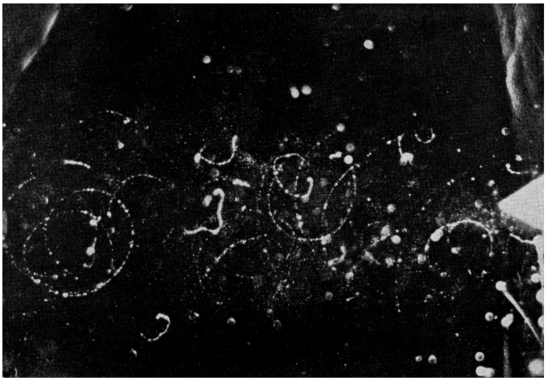

Fig. 6

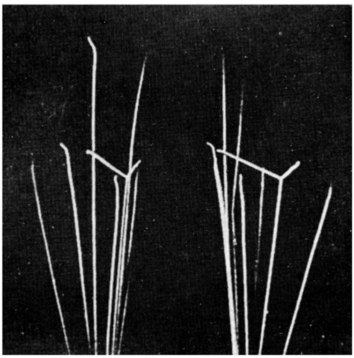

Fig. 7

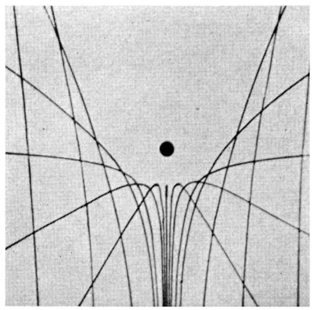

Fig. 8

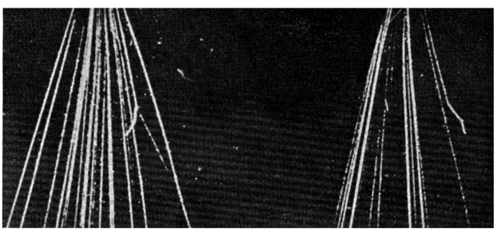

Fig. 9

Millikan has devised an electroscope which is so sensitive that it is capable of measuring even the minute charge carried by a beta particle. In place of the ordinary gold leaf, he caught a tiny drop of oil or mercury between a pair of electrified plates, and threw a beam of ultraviolet light or X-rays on the droplet. The effect of the light was to eject a beta ray. This left the droplet with a positive charge equal to the negative charge carried away by the beta particle, and the electric field due to the plates could be so adjusted that the force on the droplet's charge would just balance its weight. Knowing the weight of the droplet, it was thus possible to determine its charge. It was found that each beta ray which left the droplet carried with it the same negative charge, a charge equal in magnitude to that carried by the hydrogen ion in electrolysis.

The electronic unit of charge is thus of very fundamental significance. It measures not only the charge on the various atomic ions in electrolysis, but also the charge of these beta particles which seem to be sub-atomic in size.

When once we know the charge carried by these particles, we can estimate how heavy they are by measuring how sharply they are bent by a magnetic field. A massive particle will be bent only slightly from its course, whereas a lighter one will be deviated more easily. Magnetic deflection experiments, such as those shown in figure 6, show that a beta particle is much more readily deflected than is a hydrogen ion that carries the same charge. In fact the mass of the beta particle is only 1/1845 that of a hydrogen atom. We were thus right in our guess that these beta particles are things much smaller than the smallest known atom.

Since we find that such particles can be removed from every kind of matter, it follows that they must be one of the components of which the atoms themselves are built. We shall now give to these beta particles the name of *electrons*.

THE HEART OF THE ATOM

It is not possible to suppose that atoms are constituted solely of electrons, for electrons have negative charges, and atoms are electrically neutral. The atoms must therefore have some positive electric charge as an essential part of their structure. An examination of the trails of alpha particles such as those shown in figure 7 give an important clue to the distribution of the positive charge within the atom. It is really a most remarkable thing that most of the alpha ray tracks are so straight, since a simple calculation shows that in the portion of the tracks shown in this figure each alpha particle has passed through some 20,000 atoms of air. But we have seen that the alpha particle is itself a helium atom with a positive charge. This photograph therefore means that while the helium atom is passing through the oxygen and nitrogen atoms of air, we have repeated 20,000 times the most unusual phenomenon of two bodies occupying the same space at the same time.

Occasionally, however, the alpha particle strikes something so hard and immovable that it must change its course. From the fact that there is only one such collision for thousands of atoms traversed, it is clear the object struck is much smaller than the atom itself. Further, the manner in which the impinging helium atom glances off shows that the object is heavier than an atom of helium. It is not, however, a collision with a stone wall. There is a fork in the track, showing that the particle struck by the alpha particle itself rebounded and left a short track.

From the relative length of the tracks of the deflected alpha particle and the thing which recoiled from the impact, it seems probable that the object has a mass several times that of a helium atom, or about the mass of an oxygen atom. Collisions of this character indicate that there must be something within the atom hard and impermeable, very much smaller in size than the atom itself, yet possessing practically the whole mass or weight of the atom. This something has been named the atomic *nucleus*.

It has been shown by Lord Rutherford that an atomic nucleus deflects an alpha particle as if the force between them were one of repulsion between two electric charges. On this view the paths of alpha particles passing a nucleus should be as shown diagrammatically in figure 8. All the particles are bent slightly, but only those coming close to the nucleus are bent through a large angle. It is obvious that if the charge on the nucleus is large its effect will extend to a greater distance. That is, the nucleus will act as a larger obstacle and the number of collisions will be greater. So by counting the number of collisions occurring when a group of alpha particles passes through a known number of atoms we can determine the charge on the nucleus. Measurements of this kind have shown that the nucleus of the hydrogen atom has a positive charge equal to one electronic unit, helium that of two, lithium three, and so on down the list of chemical elements to uranium with a charge equal to 92 electrons on its nucleus. This is expressed by saying that the nuclear charge is equal to the *atomic number* of the element.

PROTONS, OF WHICH NUCLEI ARE BUILT

This discovery suggests that the nucleus may be built of units carrying a positive charge equal to the negative charge of the electron. Such a unit we find in the nucleus of the hydrogen atom. It is perhaps surprising that the positive unit of electric charge should have almost two thousand times the mass that is associated with the negative unit. Rutherford has, however, performed a series of experiments which gives good reason to suppose that our guess is correct. These experiments consist in shooting alpha rays from radium through various substances. It is found that particles having the same charge and mass as the hydrogen nucleus can be knocked out of some of the lighter elements. An event of this kind is shown in figure 9, a remarkable photograph taken by Mr. Blackett. We see here the impact of an alpha particle with the nucleus of a nitrogen atom. There is a thin trail left by the hydrogen nucleus escaping from the nitrogen nucleus.

Similar results are obtained when alpha particles traverse boron, aluminum, phosphorus, and certain other light elements. It would seem that the only reason that hydrogen cannot be liberated from other elements by such methods is that our hammer, the alpha particle, does not strike a sufficiently powerful blow. It would thus appear that the nuclei of the various atoms are indeed built of an aggregate of hydrogen nuclei cemented together with electrons. These hydrogen nuclei we shall now call *protons*, i.e., the fundamental things.

It is the nucleus of an oxygen atom which appears associated with the deflected alpha particle in figure 7. For an oxygen atom of atomic weight 16, this nucleus presumably consists of 16 protons and 8 electrons, leaving a positive charge equal to its atomic number of 8. There are, however, a very few oxygen atoms which have weights of 17 and 18 respectively. Their nuclei must thus consist of 17 or 18 protons and 9 or 10 electrons, respectively, in order that both their masses and their resultant charges shall be correct. For it is the resultant charge of the nucleus, 8 electronic units, which distinguishes oxygen from any other chemical element.

We have thus found the parts of which atoms are built. There is an electron atmosphere, which is responsible for the ordinary physical and chemical properties of the atom, and inside this atmosphere a tiny massive core, compactly built of protons and a few electrons. It is a remarkable thing that this wonderful world of ours can be composed of only a few hundred kinds of atoms. Now we find that all of these atoms are made of two more fundamental units, protons and electrons. We seem to be approaching the ultimate in simplicity.