LECTURES ON SUBJECTS IN PHYSICS, CHEMISTRY AND BIOLOGY

I

THE ULTIMATE PARTICLES: ELECTRONS, PROTONS, PHOTONS, AND NEUTRONS

THE idea that matter consists of minute indivisible particles or atoms is as old as philosophy, but it did not lead to anything of importance until Dalton developed his chemical atomic theory early in the nineteenth century. According to Dalton's theory each chemical element was supposed to consist of exactly equal atoms which were thought of as minute hard indivisible particles.

The relative weights of the atoms of different elements were calculated from the percentage composition of compounds. For example, sulphur dioxide contains fifty per cent by weight of sulphur and fifty per cent of oxygen, so that since it is found to contain two atoms of oxygen to one of sulphur it follows that the weight of an atom of sulphur is just twice that of an atom of oxygen. In the same way water contains 11.18 per cent of hydrogen and two hydrogen atoms to one of oxygen, so that an oxygen atom must be 88.85/5.59 or 15.88 times as heavy as an atom of hydrogen. Taking the atomic weight of oxygen to be 16, the atomic weights of sulphur and hydrogen are therefore 32.00 and 1.0077.

In this way chemists determined the relative weights of the atoms of all the known elements. It was found that some of the atomic weights, taking that of oxygen to be 16, were whole numbers, for example, carbon 12.00, nitrogen 14.00, sodium 23.00. Also many atomic weights were not whole numbers, for example, chlorine 35.46 and silver 107.88. Until nearly the end of the nineteenth century Dalton's chemical atoms were supposed to be the ultimate particles of matter. All the atoms of any one element were thought of as minute exactly equal hard indivisible particles. It was supposed that these atoms excited fields of force in the space around them so that they could attract or repel each other when very near together. The differences between the properties of the different elements were attributed to differences between the fields of force excited by their atoms.

In solid bodies it was supposed that the atoms were rather tightly packed so that nearly all the space occupied by a solid was filled up with hard indivisible particles.

Electricity was thought of as an immaterial fluid with which atoms could be charged. An electric current in a copper wire was thought of as a flow of this fluid from one atom to another in the copper. The electric fluid was not regarded as an essential constituent of the atoms.

These nineteenth century ideas about matter and electricity have turned out to be erroneous. We do not now regard atoms as indivisible particles and it is found that the atoms of any element are not all equal. The atomic weights as found by chemists have turned out to be merely average values not equal to the true relative weights of the atoms. Electricity is no longer thought of as an immaterial fluid but is found to consist of material atoms out of which the atoms of the chemical elements are constructed. Matter in fact is just electricity and nothing else.

In this lecture I am going to try to outline briefly the experimental results and the arguments based on them which have led to such revolutionary conclusions.

The collapse of the old ideas began about 1897 when J. J. Thomson at the Cavendish Laboratory in England showed that particles more than a thousand times lighter than hydrogen atoms could be obtained from any kind of matter. These particles were called electrons. Electrons escape from any substance at a high enough temperature. They come off hot bodies just like vapor from a hot liquid. Electrons are just particles of negative electricity, so a very hot body in a good vacuum loses negative but not positive electricity. This evaporation of electrons from a hot body in a vacuum may be shown experimentally with an apparatus consisting of a large glass bulb containing a tungsten wire like the filament of an electric light bulb. The wire is inside a metal cylinder in the large bulb and when the wire is made white hot by passing a current through it the electrons escape from the wire so that a current of negative electricity can be passed through the vacuum from the hot wire to the surrounding cylinder. But no current will flow in the opposite direction because no positive electricity escapes from the hot wire. Electrons are attracted by positive electricity and repelled by negative, as we should expect. They are deflected sideways in a magnetic field just as an electric current in a wire is deflected.

J. J. Thomson studied the motion of electrons in electric and magnetic fields and showed that they behave like particles of negative electricity. He found that the amount of electricity carried by a unit weight of electrons was very large, about two thousand times greater than the amount carried by unit weight of charged hydrogen atoms.

Now Faraday had shown that electrically charged atoms carry charges which are always small multiples of the charge carried by a hydrogen atom. For example, he found that an oxygen atom carries just twice as much electricity as a hydrogen atom and an iron atom just three times as much. These results of Faraday suggested that electricity is made up of equal atoms and that a charged hydrogen atom carries one such atomic unit of electricity, an oxygen atom two, and an iron atom three.

J. J. Thomson adopted this idea and supposed that his electrons were the atoms of negative electricity. Since he found the charge per unit weight of the electrons to be two thousand times greater than for charged hydrogen, it followed, if the electrons and the hydrogen atoms carried equal charges, that the weight of an electron was two thousand times smaller than that of a hydrogen atom. This assumption has since been proved to be correct. Thus it appears that all substances contain electrons which are very much lighter particles than the chemical atoms. Also it is found that all atoms contain electrons. Thus for example when X-rays are passed through a gas they knock electrons out of the gas atoms.

J. J. Thomson's results, which have been confirmed and extended by many other physicists, showed clearly that atoms are not hard indivisible particles but are complicated structures containing electrons.

Electrons are just particles of negative electricity, so that it is clear that an electrically neutral atom must contain positive electricity as well as electrons. The total amount of positive charge in an electrically neutral atom must be exactly equal to the total negative charge. The negative charge in the atom is always an exact multiple of that of one electron so that the positive electricity in the atom must also be made up of atomic units equal to the electronic charge. We should therefore expect to find particles of positive electricity in atoms equal to the electrons. It is found that atoms do contain particles of positive electricity having charges equal though of opposite sign to the negative charges of electrons, but the positive particles are about two thousand times heavier than the negative particles or electrons. The positive particles are called protons. It is not possible to make protons escape from hot bodies like electrons, and the arguments for the existence of protons in atoms are less direct, though not less convincing, than those for the existence of electrons.

When an electric current is passed through a gas at a low pressure it is found that the current is carried by electrons moving in one direction and positively charged atoms moving in the opposite direction. The stream of positively charged atoms can be allowed to pass through a hole in the negative electrode and so may be separated from the stream of electrons. Such a stream of positively charged atoms is called a beam of positive rays and the properties of these positive rays have been very carefully investigated mainly by J. J. Thomson and Aston in the Cavendish Laboratory.

Aston devised a method of studying these rays in which they are deflected by electric and magnetic fields and then allowed to fall on a photographic plate. The fields are so designed that the position at which the rays strike the plate is determined by the weight per unit charge of the rays. Thus the positive rays are separated into groups, all those in any one group having the same weight per unit charge. Each group makes a line on the photographic plate and the position of the line is determined by the weight per unit charge of the rays in the group.

The charge on a positively charged atom is always a multiple of the positive charge equal to the negative charge of an electron. For if we start with an electrically neutral atom and then remove one electron from it, we get an atom with a positive charge equal to the negative charge on one electron. If we then imagine that the atom loses another electron, its positive charge is doubled, and so on. The weight per unit charge for the atom is equal to its atomic weight divided by the number of electrons which it has lost. For example, an oxygen atom of atomic weight 16, which has lost two electrons and so has two units of positive charge, has weight per unit charge equal to 8. In the same way a mercury atom of atomic weight 200 which has lost four electrons has weight per unit charge 200/4 or 50.

With his positive ray apparatus Aston was able to measure the weight per unit charge for the rays obtained from any element with great accuracy and so was able to determine the relative weights of the atoms in the rays.

Now the relative weights of the atoms have been determined by the chemists, and so we should have expected Aston's results to agree with the chemical atomic weights. However this has not proved to be the case. In the first place, Aston finds that the atomic weights, taking that of oxygen to be 16, are all very nearly whole numbers. For example, he finds the atomic weight of chlorine to be 35.00, whereas according to the chemists it is 35.45. In the same way he finds 200 for the atomic weight of quicksilver, while the chemical atomic weight is 200.6. The chemical determinations of atomic weights really only give the average atomic weight of an enormous number of atoms which are assumed to all have equal weights. Aston's method gives the actual weight of the atoms which fall on his photographic plate at a given place because any atoms with a different weight would go to a different place.

It is clear therefore that Aston's results are correct, so that it appears that the true atomic weights of the elements are equal to whole numbers or integers when that of oxygen is taken to be 16. The only plausible explanation of this result, which has been suggested, is that the atoms are built up out of units of atomic weight one. Also since, as we have seen, atoms must contain units of positive electricity equal to the negative charge on electrons, it is natural to suppose that the units of atomic weight one have also equal positive charges equal but of opposite sign to the electronic charge. We are thus led to regard the atoms of all the different chemical elements as built up out of only two different sorts of particles, namely, electrons and positively charged particles of atomic weight one, which are called protons. The atomic weight of hydrogen is nearly one, so an electrically neutral hydrogen atom should consist of one proton and one electron. It should be observed here that since any neutral atom contains as many electrons as protons, the atomic weight unity is really the sum of the atomic weights of an electron and a proton, but that of the electron is so small, only about 0.0005, that it is negligible.

The atomic weight of hydrogen however is an exception to Aston's rule that the atomic weights are whole numbers. It is 1.0077 according to Aston and also as determined by the chemists. The atomic weight of helium is 4.000 so a neutral helium atom should consist of four protons and four electrons and so if a hydrogen atom is one proton and one electron, either the atomic weight of hydrogen should be 1.000 or else that of helium should be 4×1.0077 or 4.0308 which is certainly not the case. It appears that if helium could be prepared from hydrogen there would be a loss of weight so that 4.0308 pounds of hydrogen would only give 4.000 pounds of helium.

It is believed that this anomaly can be explained by supposing that in order to convert hydrogen into helium it would be necessary to remove a large amount of energy from the hydrogen and that the loss of weight is just the weight of the energy which would have to be removed.

Aston also obtained another result of fundamental importance. He found that atoms of several different weights but all of the same chemical element exist. Thus, for example, he found chlorine to be a mixture of atoms having atomic weights 35 and 37. These two sorts of atoms are present in ordinary chlorine in such proportions that the average atomic weight is 35.45 which is the value found by chemical methods.

We are thus led to conclude that the atoms of all the chemical elements are not indivisible particles but are formed out of just two sorts of ultimate particles, namely, electrons and protons. Electrons and protons, moreover, are just electricity and nothing else. The ninety-two different chemical elements are therefore not really elements at all, in the old sense of the word, but are all compounds of electrons and protons. They are nevertheless still called elements because they cannot be split up into electrons and protons by ordinary chemical processes.

Besides electrons and protons there is another sort of ultimate particle the existence of which has been demonstrated in recent years. These particles are called photons and they are quite different from electrons and protons. Photons are found in light, in fact we may say that light is just a stream of photons. Now light is emitted by very hot bodies, for example, the ordinary electric light bulb is just a glass bulb containing a loop of fine wire which is made very hot by passing a current of electricity through it. Such a hot wire as we have seen emits electrons but it also emits light which consists of photons. The emission of electrons is supposed to show that the wire contains electrons, so we might suppose that the wire must also contain photons, since it emits them when hot. However a photon is a much less material sort of particle than an electron, and it is customary to believe that photons are generated in the wire out of nothing but energy before they are emitted.

Light is believed to consist of photons because the effects produced by light are such as might be expected to be produced by a stream of particles. Consider, for example, the action of light on a photographic plate. Such a plate is coated with a thin layer of gelatine containing minute grains of silver bromide. When the plate is developed, after being exposed to weak light for a short time, it is found that a few of the grains have been changed by the light but that the majority of them are quite unaffected. This can be explained by supposing the light to consist of particles or photons for then only those grains of silver bromide should be affected which happen to be hit by a photon. If light consisted of waves as was formerly supposed we should expect all the grains to be equally affected, which is not the case.

The particle nature of light can be most clearly demonstrated by using X-rays which are of the same nature as light but have photons of much greater energy.

X-rays are obtained by allowing a stream of electrons of high energy to fall on a metal plate. The electrons collide with the metal atoms in the plate and excite them so that they emit X-rays.

When X-rays are passed through a gas like air they cause a few of the gas atoms to emit electrons. This effect can be demonstrated very clearly by the beautiful method developed by C. T. R. Wilson of the Cavendish Laboratory.

The X-rays are passed through air supersaturated with water vapor and the electrons emitted by the air atoms then produce visible tracks consisting of minute drops of water which can be photographed in a bright light. In this way a permanent record of the electron tracks is obtained. The length of these electron tracks depends on the energy of the electrons and it is found that the energy of these electrons is just equal to that of the energy of the electrons used to produce the X-rays.

Thus an electron having kinetic energy hits a metal atom which emits an X-ray. The X-ray travels a long distance, perhaps 100 feet, and then hits a gas atom and causes the gas atom to emit an electron with the same kinetic energy as that of the first electron which hit the metal atom 100 feet away. It is clear that the energy of the first electron must have travelled from the metal atom to the gas atom. This can only be explained by supposing that the X-ray is a particle which carries the energy from the metal atom to the gas atom. The energy could not be transmitted in this way by waves because waves diverge in all directions and so could only carry a minute fraction of the energy of the first electron from the metal atom to the gas atom.

It appears therefore that light and X-rays consist of particles which are called photons. Photons always move along with the velocity of light, 186,000 miles a second. The color of light depends on the energy of the photons. The photons in violet light have about twice as much energy as those in red light and X-ray photons have about ten thousand times as much energy as those of violet light.

Photons do not have an electric charge like electrons and protons; they have nothing but kinetic energy, so if a photon loses its kinetic energy it disappears. A photon cannot be stopped without being destroyed because to stop it is to take away its kinetic energy. Electrons and protons can be stopped and still exist because they are particles of electricity. When they are moving they have kinetic energy like photons but they do not disappear when stopped because of their charges.

The rays from an X-ray tube diverge in all directions, so that the greater the distance from the tube the weaker the rays. It is found that the very weak rays at a great distance from an X-ray tube knock electrons out of atoms with exactly the same energy as the intense rays close to the tube. Near the tube more electrons are knocked out than farther away, but the energy of each electron is the same at any distance. This result cannot be explained on the wave theory of X-rays, but it is easily explained on the particle theory. The rays emitted by radioactive elements like radium are of three kinds: photons, electrons, and alpha-rays. No protons are emitted which is perhaps rather surprising. The alpha-rays are found to be helium atoms which have lost two electrons. A neutral helium atom consists of four protons and four electrons, so an alpha-ray is four protons and two electrons which are closely combined together into a very small particle. Thus an alpha-ray is positively charged; it has twice the charge and four times the weight of a proton.

Alpha-rays make visible tracks in air supersaturated with moisture just as electrons do, but the alpha-ray tracks are very different from electron tracks. The alpha-ray tracks are straight and much thicker than the electron tracks, which are not straight but irregularly curved. The alpha-rays are nearly 4000 times as heavy as electrons and so are not so easily deflected by collisions. A particle like an electron or an alpha-ray moving rapidly through a gas like air collides with many thousands of atoms while it moves one inch. The electrons are deflected by these collisions but the alpha-rays are not. Now when a rapidly moving body collides with another body we should expect it to be deflected unless it is very much heavier than the body with which it collides. For example, a motor car weighing 4000 pounds is not appreciably deflected by a collision with a stone weighing one pound, but is seriously affected by a collision with another car. We are forced therefore to conclude that electrons and alpha-rays moving rapidly through a gas only collide with the electrons in the gas atoms. An electron is deflected by a collision with another electron but an alpha-ray which is 4000 times as heavy as an electron is not appreciably deflected by a collision with one. But, as we have seen, atoms contain as many protons as electrons, so we might have expected as many collisions with protons as with electrons. An alpha-ray is only four times as heavy as a proton and so should be appreciably deflected by a collision with one. It appears therefore that, although atoms contain as many protons as electrons, yet the protons must only occupy a very small fraction of the space in an atom, so that an alpha-ray moving through the atoms in a gas hardly ever hits a proton although it hits electrons in every atom it passes through.

When a large number of alpha-ray tracks is examined it is found that a few are sharply bent through appreciable angles. These rare deflections are supposed to be caused by collisions with the protons. A study of such deflections of alpha-rays led Lord Rutherford to propose his nucleus theory of the atom according to which the protons and about half the electrons in an atom are closely packed into a very small nucleus, while the rest of the electrons are outside the nucleus moving about round it. For example, an oxygen atom has a nucleus containing 16 protons and 8 electrons, and there are 8 electrons outside the nucleus. The chemical properties of the atoms are determined by the number of electrons outside the nucleus. Thus, for example, chlorine atoms all have 17 outside electrons, although some chlorine atoms contain 35 protons and some 37. All the atoms of any one element are alike as regards their outside electrons, although they may not all have the same number of protons in their nuclei.

Up to early in the year 1932 matter and radiation were supposed to be made of electrons, protons, and photons and nothing else. In that year, however, the existence of a fourth type of ultimate particle was discovered. These new particles are called neutrons.

Bothe and Becker, in Germany, in 1930 found that solid elements of small atomic weight, like lithium, boron, and beryllium, when exposed to alpha-rays emit a very penetrating radiation which they supposed probably consisted of photons. This radiation was studied by I. Curie and Joliot in France, and by Chadwick in England.

Chadwick showed that this penetrating radiation did not have the properties of photons, but that its properties were such as could be explained by assuming it to consist of particles of atomic weight one not having any electric charge. He proposed to call these particles neutrons.

When photons are passed through air supersaturated with moisture they do not produce any visible track themselves but they knock electrons out of the air atoms and these electrons produce thin irregularly curved tracks.

Protons and alpha-rays produce straight thick tracks very rarely bent appreciably by collisions with atomic nuclei. Neutrons, or the penetrating radiations from beryllium bombarded by alpha-rays, behave like photons in not producing any tracks themselves but do not knock electrons out of the air atoms and so produce no electron tracks. They do, however, produce a very few short thick tracks such as might be due to air atoms moving with a high velocity.

Now protons and alpha-rays, when they hit the nucleus of an atom and are so appreciably deflected, impart enough energy to the atom to cause it to produce a short thick track. In such cases the short thick track appears as a branch track branching from the alpha-ray track at the point where it is deflected.

Thus neutrons resemble photons in not producing tracks themselves and resemble protons and alpha-rays in colliding with atomic nuclei and causing these nuclei to make short thick tracks.

Also it is found that neutrons when passed through paraffin wax, which contains hydrogen, knock protons but no electrons out of the wax, while photons do not knock protons out of such wax but only electrons.

It is clear therefore that neutrons are quite different from photons, electrons, protons, or alpha-rays.

Charged particles like electrons, protons, and alpha-rays produce visible tracks while photons which are not charged do not. Since neutrons produce no visible tracks themselves we conclude that they are not electrically charged and so resemble photons in this respect.

Neutrons, protons, and alpha-rays collide with the nuclei of atoms and cause the atoms to produce short thick tracks. We conclude that neutrons are relatively heavy particles like protons and alpha-rays. Feather, working in the Cavendish Laboratory with Chadwick, has shown that neutrons passing through nitrogen sometimes produce V-shaped tracks which are believed to be due to the neutron knocking an alpha-ray out of a nitrogen atom. The alpha-ray recoils in one direction and the rest of the nitrogen atom in another, so making the V.

The atomic weight of nitrogen is 14 and that of an alpha-ray is 4, so that if an alpha-ray is knocked out of a nitrogen atom a particle of atomic weight 10 remains. But there is no known substance of atomic weight 10, so it seems probable that the atomic weight of the neutron is one and that the neutron is captured by the nitrogen atom so giving a particle of atomic weight 11, which is boron. When boron is bombarded by alpha-rays, neutrons are emitted. A boron atom of weight 11 and an alpha-ray of weight 4 give a nitrogen atom of weight 14 and a neutron of weight one. The lengths and directions of the short thick tracks observed when neutrons are passed through air supersaturated with moisture are found to be such as might be expected to be produced by a collision of a particle of atomic weight one with an air atom.

There are therefore good reasons for believing neutrons to be uncharged particles of atomic weight one.

Very recent observations by Anderson at the California Institute of Technology suggest the existence of particles like electrons but positively instead of negatively charged. These observations have already been confirmed in Cambridge.

We have then at present as ultimate particles: photons, negative electrons, positive electrons, protons, and neutrons. Perhaps it may turn out that a proton is a combination of a neutron and a positive electron, or that a neutron is a combination of a proton and a negative electron. The discovery of neutrons and positive electrons makes the constitution of atoms uncertain. With only electrons and protons it was clear that atoms contained equal numbers of these two sorts of particles. But with neutrons and positive electrons as well we cannot tell how many electrons there are in an atom. For example, the nucleus of a chlorine atom of atomic weight 35 with 17 outside negative electrons might contain

35 neutrons and 17 positive electrons, or say 18 neutrons and 17 protons, or any other combination which would give a nucleus of weight 35 and positive charge 17.

The discovery of positive electrons is of fundamental importance and raises all sorts of interesting questions. For example, why is it so easy to get negative electrons out of matter but so difficult to get positive electrons out that they have escaped detection until now? Do metals like copper contain free positive electrons as well as free negative electrons? If both sorts of free electrons are present then a current in a copper wire is a stream of positive electrons going one way and negative electrons going the other way and not merely negative electrons going one way as has been supposed for many years.

Much experimental and theoretical investigation will be required before such questions can be answered.

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