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Chapter 14

INSIDE THE ATOM

In the late 1800's, a series of discoveries led to a new understanding of the atom, which was found to have a complex internal structure.

RADIOACTIVITY

Becquerel

In 1896, the French physicist Henri Becquerel discovered that crystals of a uranium compound emitted a mysterious form of penetrating radiation. Later, he traced this radiation to the uranium atoms in the crystals. Later still, this ability to emit radiation spontaneously was called "radioactivity".

The Curies

Becquerel's discovery inspired a young physicist, Marie Sklodowska Curie (1867-1934), to devote her life to the study of radioactivity. Born in Poland, at 24 she moved to Paris. There, she studied mathematics and physics, and married another physicist, Pierre Curie. Together, they began investigating the radioactivity of certain chemical elements. In 1898, the Curies discovered two strongly radioactive elements, polonium (which Marie named in honor of her native country) and, a few months later, radium.

Overcoming enormous difficulties in relatively primitive laboratory conditions, Marie and Pierre succeeded in isolating radium in pure form, an undertaking that would have required industrial resources. In 1903, they shared with Becquerel the Nobel Prize for physics.

In 1906, Pierre died at 46, killed by a horse-drawn wagon while crossing a street in bad weather. Marie was unanimously chosen to succeed him in his professorship, the first time a woman had ever been elected to teach at the prestigious Sorbonne, the University of Paris.

In 1911, she received the Nobel Prize for chemistry, becoming the first person to be awarded two Nobel Prizes. (In 1930, her daughter Irene would also receive a Nobel Prize for her work in radioactivity.) Marie Curie died in 1934 at the age of 67, from leukemia caused by excessive exposure to radiation.

Rutherford

The connection between radioactivity and the very structure of matter was revealed by the work of Ernest Rutherford (1871-1937), one of the greatest experimental physicists of all times. He was born in New Zealand, in a family of modest means. In 1895, after graduating from college, he left New Zealand with a 2-year scholarship to study at Cambridge, England. Here, he began to work as a research assistant to J.J. Thomson, who would later discover the electron.

Rutherford showed that the Becquerel rays consisted of two distinct types of radiation: the "alpha" rays, and the much more penetrating "beta" rays. Later, he showed that the alpha rays are positively charged helium atoms stripped of their electrons, whereas the beta rays are electrons.

(A third type of radiation, the gamma rays, was discovered in 1900. Unlike the alpha and beta rays, which are particles, the gamma rays are electromagnetic waves. It is because of the more penetrating beta and gamma rays that radiation has acquired its frightful reputation. Even a sheet of cardboard, on the other hand, is sufficient to stop a beam of alpha particles.)

In its early years, radioactivity was a most mysterious phenomenon. It seemed to defy the principle of energy conservation. The radiation from radioactive substances carried enormous energy, which exceeded by far that produced in any chemical reaction.

In 1898, Rutherford left Cambridge to accept a professorship at McGill University in Canada. Here he collaborated with Frederick Soddy, a talented young chemist. In 1902, they concluded that, as the result of radioactivity, atoms of one element spontaneously disintegrate into atoms of an entirely different element.

This "transformation" theory was opposed by many chemists, who strongly believed in the immutability of matter. To them, the idea that atoms of one element could break down into atoms of another element was a throwback to the medieval alchemists, who tried to transform lead into gold.

In 1908, Rutherford moved back to England to teach at Manchester University. Here, in 1911 he made his greatest contribution to science with his nuclear theory of the atom, as discussed in a later section. In 1919, he succeeded his former mentor, J.J. Thomson, as director of the prestigious Cavendish Laboratory.

Rutherford received many honors in recognition of his accomplishments. In 1908, for his work in radioactivity, he was awarded the Nobel Prize for chemistry (a choice he found disappointing, since he considered himself a physicist). He was knighted in 1914, and made Baron Rutherford of Nelson in 1931. When he died in 1937, he was buried in Westminster Abbey.

THE ELECTRON

For 25 centuries, atoms had been conceived as the ultimate indivisible building blocks of matter. By 1900, however, there was strong evidence to the contrary.

It is now a basic assumption of physics that the properties of matter depend on the properties and interactions of sub-atomic fundamental particles. Of these, the first to be discovered was the electron in 1897.

In the late 18th and early 19th century, it was popular to think of an (electrically) charged object as if it contained some sort of a fluid that could easily flow through a metal, but not through an insulator. Charge was considered to be continuous, that is, it could be increased or decreased by infinitesimal amounts.

A different theory of electrical charge began to evolve toward the middle of the 19th century, in order to explain consistently how current is conducted in metals, liquids and gases. According to this theory, charge is quantized, that is, it can be increased or decreased only in multiples of a single indivisible quantity. This fundamental unit of charge was called the "electron"; it is traditionally represented by the letter e.

In the 1890's, many physicists were experimenting with the flow of electric current through various types of sealed glass tubes, from which air had been evacuated as much as the technology of the day permitted. Sealed inside such a vacuum tube were a heated filament (the "cathode") and another terminal (the "anode"), with an appropriate voltage applied across the two.

The small amount of gas still in the tube could be seen to glow, revealing the paths of negative charges flowing from the heated cathode to the positive anode. At the end of the 19th century, there was intense speculation about the mysterious nature of these paths, which were called "cathode rays".

In 1897, J.J. Thomson (1856-1940) showed experimentally that these cathode rays marked the paths of material "corpuscles" (tiny bodies), each carrying a negative charge. In a specially designed vacuum tube, the cathode rays could be sharpened into a narrow beam, which, upon striking a specially coated screen, caused a phosphorescent spot. (We have here the basic idea for the present-day cathode ray tubes, or CRT's, used in TV sets and computer monitors.)

Thomson showed that the narrow beam behaved just as one would expect for a stream of negatively charged particles under the influence of electric and magnetic fields. Although he could not determine either the mass or the charge of a corpuscle, he was able to compute their ratio.

In 1897, Thomson announced the discovery of a new form of matter, the cathode-ray corpuscles, which were called the "atoms of electricity". Later, they were called electrons after the fundamental unit of negative charge, of which they are the carriers.

Between 1909 and 1911, the American physicist Robert A. Millikan performed a series of experiments which proved directly that charge is quantized, and yielded the actual value of the fundamental unit of charge. Although elementary particles of various types differ significantly in mass, only three values have ever been observed for their charge: +e, -e, and 0 (for neutral particles).

From Millikan's fundamental charge and Thomson's mass-to-charge ratio, it became possible to compute the incredibly small mass of an electron. The combined mass of a billion billion billion electrons is only one gram!

Thomson's electron was immediately seen as a building block in the structure of atoms. Since matter is electrically neutral, the individual atoms that make up matter would have to be neutral themselves. As indicated by a variety of experiments, the heavier the atom, the larger the number of electrons contained in it. Their combined negative charge would have to be neutralized by an equal but positive charge in the rest of the atom.

The simplest atom, that of hydrogen, would contain a single electron carrying one unit of negative charge, and an equal but positive charge, with which would be associated a mass about 1800 times the mass of the electron. Thus, practically the entire mass of the hydrogen atom would be associated with its positive charge.

There was no direct evidence, however, on how the electrical material might be arranged inside an atom. In 1902, Lord Kelvin proposed an atomic model in which the positive charge was distributed throughout a very small region, possibly a sphere, within which the electrons were embedded like raisins in a cake.

In recognition of his work, Thomson was awarded the Nobel Prize for Physics in 1906, and was knighted in 1908. An outstanding teacher, his contributions to physics rest almost as much on the work he inspired in others, as on his own. Seven Nobel prizes were awarded to physicists who worked under him.

THE NUCLEUS

Rutherford's work in radioactivity had convinced him that the structure of the atom could be studied by shooting a narrow beam of alpha particles at a very thin foil of metal. Careful measurements of how the alpha particles were scattered (deflected) might give a clue about the structure of the atoms bombarded by the particles.

This was the basic idea behind a series of experiments that were performed in 1909 at Manchester University by one of Rutherford's collaborators, Hans Geiger, who invented the first detector of individual alpha particles (the Geiger counter). He found that alpha particles going through thin foils of metal were deflected by an angle that was usually small, in the order of one degree.

Rutherford suggested investigating whether any alpha particle could be scattered by a large angle. He did not expect that it could: after all, an alpha particle was a (relatively) massive particle traveling at about 10,000 miles per second. The probability of a particle being scattered backward could be computed to be very small. Anyway, it seemed to be a good project to further the training of Geiger's young assistant, Ernest Marsden.

A special apparatus was built for the experiment. In it, inside a vacuum chamber, a radioactive source emitted alpha particles, which were channeled into a narrow beam aimed at a very thin gold foil suspended at 90 degrees. There were detectors to count alpha particles that might be deflected at various angles.

A few days later, with great excitement, Geiger reported to Rutherford that some of the alpha particles had been deflected backwards by substantial angles. Rutherford was astonished. Later, he wrote "It was quite the most incredible thing that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch [artillery] shell at a piece of tissue paper and it came back and hit you."

The results of the Geiger-Marsden experiment were not consistent with the raisin-in-the-cake model of the atom. From his calculations, Rutherford concluded that the atom had to have the great bulk of its mass and all of its positive charge concentrated in a sphere much smaller in radius than the whole atom. The atom was mostly empty space! Objects that appear to be solid are actually made of these empty spaces, and are held together by forces acting on electric charges.

If we enlarged the atom to a sphere 520 feet in diameter, the nucleus sitting at the center would be a sphere with a diameter of only one sixteenth of an inch (100,000 times smaller): the electrons would be mere dust specks somewhere between the two spheres.

In 1911, instead of the raisins-in-the-cake model, Rutherford proposed a new model, which has become the foundation of our present understanding of atomic structure. In this model, an atom consists of a highly concentrated positive charge (the nucleus) and a number of electrons spread out somehow over a much larger region.

The results of the Geiger-Marsden experiment could now be explained as follows. Since an atom is mostly empty space, the alpha particles rarely came near a nucleus. Little or no deflection was experienced by the great majority of particles. The closer an alpha particle flew by a nucleus, the larger the angle of deflection due to the repulsive force between their positive charges. The few very large deflections observed were due to near misses.

INSIDE THE NUCLEUS

Later, it was discovered that the nucleus itself has an internal structure. At first, it was believed that nuclei consisted only of one or more "protons", each with a positive charge equal and opposite to the charge of an electron, and a mass about 1800 times that of an electron. In 1932, the English physicist James

Chadwick discovered another particle very similar to the proton; since it has no electric charge, it was called the "neutron".

Except for the simplest form of hydrogen with one proton and one electron, all stable nuclei contain at least as many neutrons as protons. All atoms contain equal numbers of protons and electrons, and are therefore neutral. It is the number of electrons in an atom that determines the chemical element of the atom (i.e., whether it is gold or lead) and its chemical properties. It is called the "atomic number". In the periodic table (see end of Chapter 5), the elements are arranged in increasing order of atomic numbers. As we move from one element to the next, we find one more electron and one more proton in the atom.

Elements can come in varieties, called "isotopes", which differ in the number of neutrons in the nucleus. For instance, carbon with 6 protons has two isotopes: one with 6 neutrons, and one with 7. The number of "nucleons" (protons + neutrons) is called the "mass number". One isotope of Uranium, for instance, with 92 protons and 143 neutrons, has a mass number of 235; it is accordingly designated as Uranium-235.

The largest number of protons in any naturally occurring nucleus is 92, in uranium. Physicists have been able to manufacture nuclei with up to 106 protons, but they are unstable. A complex nucleus may be compared to a wobbly drop of water that hangs from a faucet with a tendency to split into smaller droplets. Radioactivity occurs when an unstable complex nucleus spontaneously "transmutes" (decays) into a simpler and more stable configuration. This decay results in the emission of particles and electromagnetic energy.

The "half-life" of a radioactive element is defined as the time required for half of any given amount of the element to decay. Half-lives range from more than a billion years for some nuclei to less than one billionth of a second.