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NIELS BOHR

NIELS Bohr, who was born in Copenhagen on 7 October, 1885, was one of the foremost scientists of the twentieth century. Before the First World War, he took the new quantum theory and used it to construct the first successful, detailed picture of how atoms work; in the 1920s, he first extended this understanding to explain the periodic table of the elements. Then revolutionary new developments transformed quantum theory into the foundation stone of modern physics, and Bohr was instrumental in providing the interpretation of quantum physics, the Copenhagen Interpretation, which is still today the basis for translating quantum ideas into everyday terms. He worked on the Manhattan Project, the construction of the first atomic bomb, but in the 1950s he campaigned to achieve control of nuclear weapons, and his efforts to promote the peaceful use of atomic energy led to his receiving the first US Atoms for Peace award, in 1957.

Bohr came from an intellectual family. His father, Christian Bohr, was professor of physiology at the University of Copenhagen; his younger brother, and lifelong friend, Harald, was an eminent mathematician; and his son, Aage, followed Niels both in the directorship of the Institute of Theoretical Physics in Copenhagen and as a winner of the Nobel Prize in physics.

In his early academic career Niels Bohr displayed thoroughness rather than brilliance, carrying out a painstaking measurement of the surface tension of water in 1906, then moving on to analyse the behaviour of electrons in metals, a project for which he received a PhD in 1911. It was only after he completed this work, and moved first to Cambridge and then, in March 1912, to the University of Manchester, that Bohr displayed what became his characteristic approach to scientific problems.

His particular genius, which was just the thing required to make progress in atomic physics in those days, was his willingness to patch together different ideas, from different sources, to make an imaginary "model" of the atom (a set of equations, and a physical picture) that worked at least in rough agreement with the way observations suggested that real atoms worked. Once he had a rough idea what was going on, Bohr could tinker with the theories to make the bits fit together even better, and so work towards a complete picture. This was just about the only approach that could have worked in the second decade of the twentieth century, for what physicists knew about atoms was decidedly fragmentary and incomplete.

The electron itself, which we now know to be a component of the atom, had only been discovered in 1887, and it was only in 1911 that New Zealand physicist Ernest Rutherford (1871-1937), on the basis of experiments carried out in Manchester, suggested that there must be a small central nucleus to every atom, containing all of its positive charge and most of its mass, while the electrons formed a cloud of negatively charged particles around the nucleus.

Niels Bohr (right) with Einstein in Brussels, in 1930. Einstein believed that there were laws governing the behaviour of everything in the universe from electrons to planets and to the end of his life he was unwilling to accept a central notion of quantum theory that the precise movement of a single electron could not be predicted. "God", he once said, "is subtle but he is not malicious." And on another occasion "God does not play at dice." To which Bohr is said have retorted "Stop telling God what to do."

Photo © Niels Bohr Institute, Copenhagen

Later experiments showed he was correct—the nucleus is only one hundred thousandth of the size of the atom. Typically, a nucleus about 10^{-13} cm across is embedded in an electron cloud 10^{-8} cm across. To put these figures in perspective, imagine a pinhead, perhaps a millimetre across, in the centre of the dome of St Paul's Cathedral (35 metres in diameter), surrounded by a cloud of microscopic dust motes far out in the dome. The pinhead represents the nucleus, and the dust motes represent electrons. Atoms are mostly empty space.

But at the beginning of 1912, Rutherford's picture of the atom was still controversial. In particular, since opposite electric charges attract one another, physicists could not explain why all the electrons in every atom did not immediately fall in to their nuclei, releasing a burst of energy (radiation) in the process. This is where Bohr came in, naturally gravitating to Manchester to work with Rutherford's group as his interest in the atomic puzzle grew.

The simplest image of the atom that emerged from Rutherford's work was something like the Solar System, with a nucleus at its heart, in place of the Sun, and electrons orbiting around it, in place of the planets. The picture is oversimplistic, but it was the first step on the road to understanding the atom. Everything physicists knew about charged particles in orbit said that they should radiate electromagnetic energy (light, X-rays or radio waves) and spiral inwards. So there was an obvious flaw with the model. Bohr resolved the dilemma by

a pragmatic genius

by John Gribbin

plucking a totally different idea out of current developments in physics, and sticking it on to Rutherford's atomic model.

This was the idea, stemming from the work of German physicist Max Planck (1858-1947) at the turn of the century, that electromagnetic radiation (light, or the other forms) could only be emitted or absorbed by an atom in discrete units, called quanta. The automatic bank-note distributor at my bank in London operates much the same way. It will only issue me with money in units of £5. I can get £20, or £45, but I cannot get £1, or £37, out of it. Bohr said that the electrons "in orbit" around the nucleus of an atom could not spiral gently inward because that would involve radiating energy continuously. Quantum theory said that they could only release certain fixed amounts of energy, and to do so an electron would have to "jump", instantaneously, from one "orbit" to another—rather as if Mars suddenly jumped into the Earth's orbit. There were stable orbits, said Bohr, corresponding to fixed amounts of energy, rather like the rungs on a ladder. But there were no in between orbits, and an electron could not spiral into the nucleus because that would involve releasing fractional amounts of energy.

What Bohr did had no right to work. The whole idea of an orbit depends on classical physics, Newton's laws; the idea of electron states corresponding to fixed amounts of energy (energy levels, as they came to be called) came from quantum theory. Making a model which patched together bits of each theory gave no insight into what made atoms tick, but it provided just enough of a starting point for Bohr to make progress throughout the next ten years.

Niels Bohr used to begin his lectures by saying to his students "Every sentence that I utter should be regarded by you not as an assertion but as a question." He is seen here, in 1936, at the Niels Bohr Institute, Copenhagen, in conversation with two other Nobel Prizewinning physicists, Werner Heisenberg (centre) and Wolfang Pauli (right).

That progress continued in Copenhagen, where the authorities created a new Institute to entice Bohr back. He became director of the Niels Bohr Institute in 1920, developing it into one of the great scientific centres, where theoretical physicists came from all over the world to bounce ideas off one another and to probe the mysteries of quanta and the atom. And in the early 1920s Bohr produced his greatest single achievement, a theory of the atom which explained, at least in broad outline, the whole science of chemistry.

The Siberian Dmitri Mendeleyev (1834-1907) had come up with his classification of the elements in the 1860s. He showed that these fundamental substances could be ranked in a table in order of increasing atomic weight, in such a way that elements with similar properties appeared beneath each other in the columns of the table. But there was no explanation of why elements with very different atomic masses should just happen to have similar chemical properties, until Bohr improved his theory of the atom in the years following the First World War. It was clear to Bohr, and his contemporaries, that the chemical properties of atoms depend almost exclusively on the number of electrons they contain. These are related to the number of protons (positively charged particles) in the nucleus, and therefore to the atomic mass. But the electrons themselves are the visible face an atom shows to the world, the "handles" by which it interacts with other atoms. So why should an atom of lithium, which has three electrons, be very similar chemically to an atom of sodium, which has eleven electrons, and potassium with nineteen? Once again, Bohr produced an imaginary model of the atom to explain the observations, without waiting for the fundamental physics to be worked out.

Imagine the electron "orbits" around the atom as more like onion skins, nestling one inside the other, than like the orbits of the planets around the Sun. What Bohr said, in effect, was that the innermost orbit, or "shell", only has room for two electrons. He didn't worry why this should be so; he just chose the restriction to match the observed patterns of chemical properties of the elements. The next shell out from the nucleus, however, has room for eight electrons. So an atom which has, say, six protons in its nucleus, and therefore "needs" six electrons to ensure its electrical neutrality, will slot two into the innermost shell, and four into the second shell. But an atom with eleven protons (sodium) has two in the innermost shell, eight in the second, full, shell, and the last has to go into a new shell, out on its own. This is very similar to the pattern for lithium, which has two electrons in its innermost shell, and, once again, just one out on its own. And potassium fits the picture if we imagine it to have three filled shells (two, eight and eight electrons each), with a lone electron in the fourth shell.

What matters for chemistry is primarily the number of electrons in the outermost shell that contains any electrons at all. Working outward through the shells for heavier and heavier atoms, with more and more electrons, Bohr was able to explain the relationship between the elements in Mendeleyev's periodic table in terms of atomic structure, and although he had no idea why a shell containing eight electrons should be "closed" to further additions, he could use the fact that it was to explain how atoms combine with one another.

Bohr proved nothing mathematically—he just knew that things had to be this ▶

Niels Bohr (left) sitting back-to-back with Ernest Rutherford during a river-side picnic in 1923, at Cambridge, where he had gone to receive an honorary Doctor of Science degree. In 1911, Rutherford had made the greatest of his many contributions to science—his nuclear theory of the atom (see article). It was while working with Rutherford at Manchester University that Niels Bohr developed the theoretical implications of the nuclear model of the atom, combining it with the quantum theory developed by the German physicist Max Planck.

▶ way. In his Autobiographical Notes, published in 1949, Einstein said of Bohr's work and the early quantum theory "that this insecure and contradictory foundation was sufficient to enable a man of Bohr's unique instinct and talent to discover the major laws of spectral lines and of the electron-shells of the atoms together with their significance for chemistry appeared to me like a miracle—and appears to me as a miracle even today".

In 1922, Bohr received the Nobel Prize for physics for this work; in the same year, a previously unknown element, whose existence had been predicted by his atomic theory, was discovered, and named hafnium. But it was only in 1926 and 1927 that physicists at last began to put the quantum theory on a secure footing, discovering the relationships and laws which explained why electrons had to behave in this peculiar manner, why the numbers allowed in each shell were limited. That full version of the quantum theory brought in concepts that still seem bizarre. No longer could the electron be thought of as a tiny particle, but rather as an entity which could be both wave and particle at the same time. Any experiment designed to find a particle would indeed show the electron behaving as a particle—but set up an experiment to measure wave properties, and it would show electrons behaving like waves. What was "really" going on?

By the late 1920s, physicists had a complete theory, a set of self-consistent equations, to describe the behaviour of atoms, electrons and radiation. The only trouble was it didn't make sense. Once again,

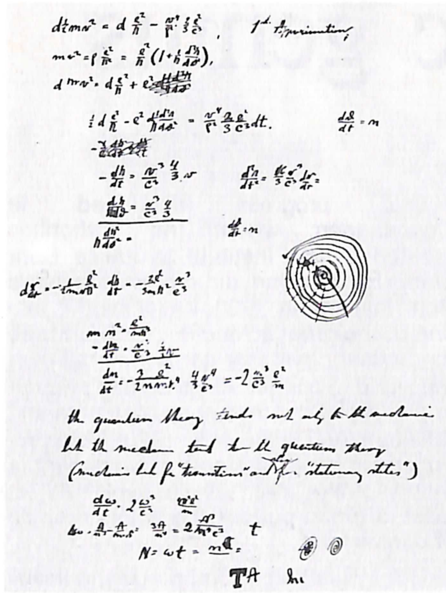

Photo © Niels Bohr Institute, Copenhagen

This document, in Niels Bohr's handwriting, is a calculation of the rate of change of radius and frequency of an electron moving in a circle.

Bohr came to the rescue. It didn't have to make sense, he said. The only thing we have direct knowledge of is the outcome of an experiment, and as long as we can predict how experiments will turn out, there is no need to worry about what the particles (or waves) do when we are not looking at them. This is a slight oversimplification of the philosophy that became known as the "Copenhagen Interpretation" of quantum mechanics, but only a slight simplification.

For more than half a century, following Bohr's teaching, physicists have used the quantum theory to explain the behaviour of molecules, including biological molecules such as DNA, to design nuclear power stations (and bombs), to build solid state computers, digital watches, and lasers. To this day, nobody "knows" what the particles of the quantum world are really like, what they are "doing" when they are not being monitored by our experiments. But every experiment carried out in the past half century has produced results in agreement with the predictions of the quantum theory.

Bohr's greatest triumph was undoubtedly his explanation of the periodic table of the elements; and his pragmatic approach to the contradictions of quantum theory, that as long as it works it is not of overriding importance to know why it works, influenced a generation of researchers and still influences many scientists today. But even after the 1920s he made major contributions, especially to the understanding of nuclear fission, and as one of the prime movers in the establishment of the European Centre for Nuclear Research (CERN) in 1952. He died peacefully in Copenhagen on 18 November, 1962, a few weeks after his seventy-seventh birthday. ■

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Nuclear Nirvana

For some reason, an atom seeks out a state in which its outermost shell is closed, or full. For an atom like sodium, the easiest way to achieve this is to discard its outermost electron, leaving bare the closed shell of eight electrons beneath; for an atom like chlorine, which happens to have seven electrons in its outermost shell, the easiest way to achieve chemical nirvana is to find a spare electron to add to its collection. So sodium and chlorine eagerly react together. Each sodium atom loses an electron and is left with a net positive charge; each chlorine atom gains an electron, and has a net negative charge. And the charged atoms (ions) then arrange themselves in a crystal lattice, held together by electric forces. The crystals are those of common salt, that we sprinkle on our food.

The same end can be achieved in another way. A pair of electrons can be shared between two atoms, to form a chemical bond. This happens, for example, when hydrogen and carbon combine to form methane. Each carbon atom "wants" another four electrons to complete its outer shell; each hydrogen atom needs just one electron to fill its only shell, the innermost one, which only holds two electrons. So four hydrogen atoms surround a carbon atom in such a way that eight electrons are shared between them, and each atom has the illusion of existing in the desired state, with a closed shell of electrons around it. ■