

2. The discovery of nuclei

How a new world was revealed by radioactivity

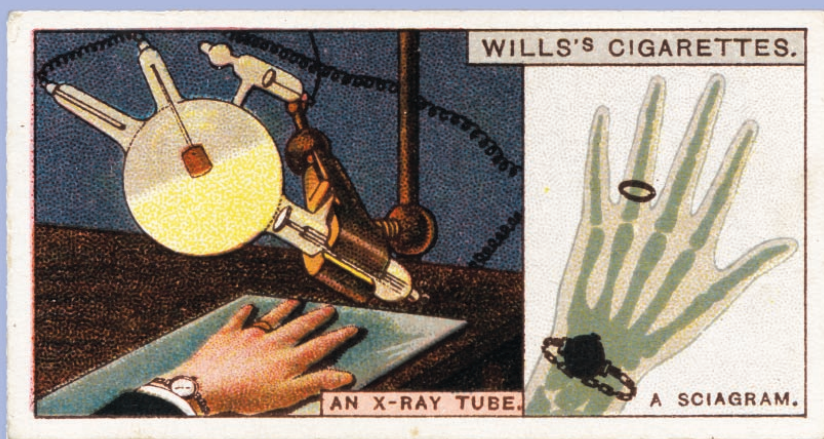
As the nineteenth century drew to a close, many scientists felt that all the important questions in science had been answered. This was wishful thinking. Scientists could not even agree that matter was made of atoms let alone explain something as basic as why copper is red! The majority just thought that it was because it had 'redness'. Today, such a statement would not be acceptable; the colour of copper can be explained with far more convincing arguments, but only because the structure of atoms is understood more thoroughly.

Gaining the means to investigate the structure of something as small as an atom began in 1895 when Wilhelm Röntgen astonished the world with the discovery of X-rays. He had been investigating the source that had fogged some photographic plates which had been kept carefully wrapped in his laboratory. Röntgen eventually tracked the source to a gas-discharge tube. The discovery of X-rays sent shock waves around the world. Here were mysterious new rays that could pass through solid materials to cloud photographic film. Very soon, people all over the world were marvelling at photographs showing the bones in their hands.

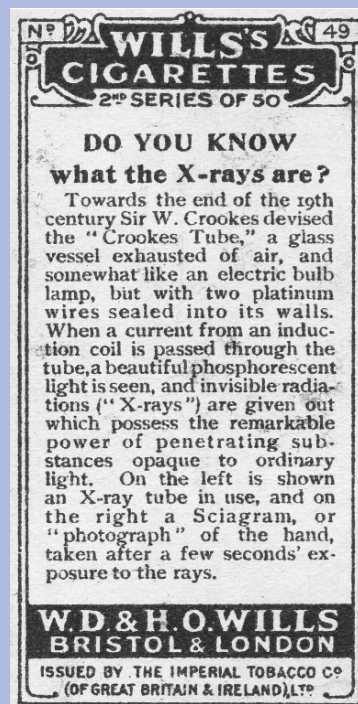
The mysterious X-rays seemed to be streaming out of a part of the tube that glowed in the dark; it was fluorescent. This property was investigated by Henri Becquerel, who studied a uranium compound he knew emitted this eerie glow. Like X-rays, he found the radiation from uranium could pass through the black paper protecting photographic film from light, and leave its traces on the undeveloped film. Unlike X-rays, which disappeared when the X-ray tube was switched off, the radiation from the uranium was emitted continuously. Becquerel soon found that any compound of uranium, even pure uranium metal, worked just as well.



Wilhelm Röntgen, 1845–1923, whose accidental discovery of X-rays in 1895 opened a new window on the world. (Copyright the Nobel Foundation.)

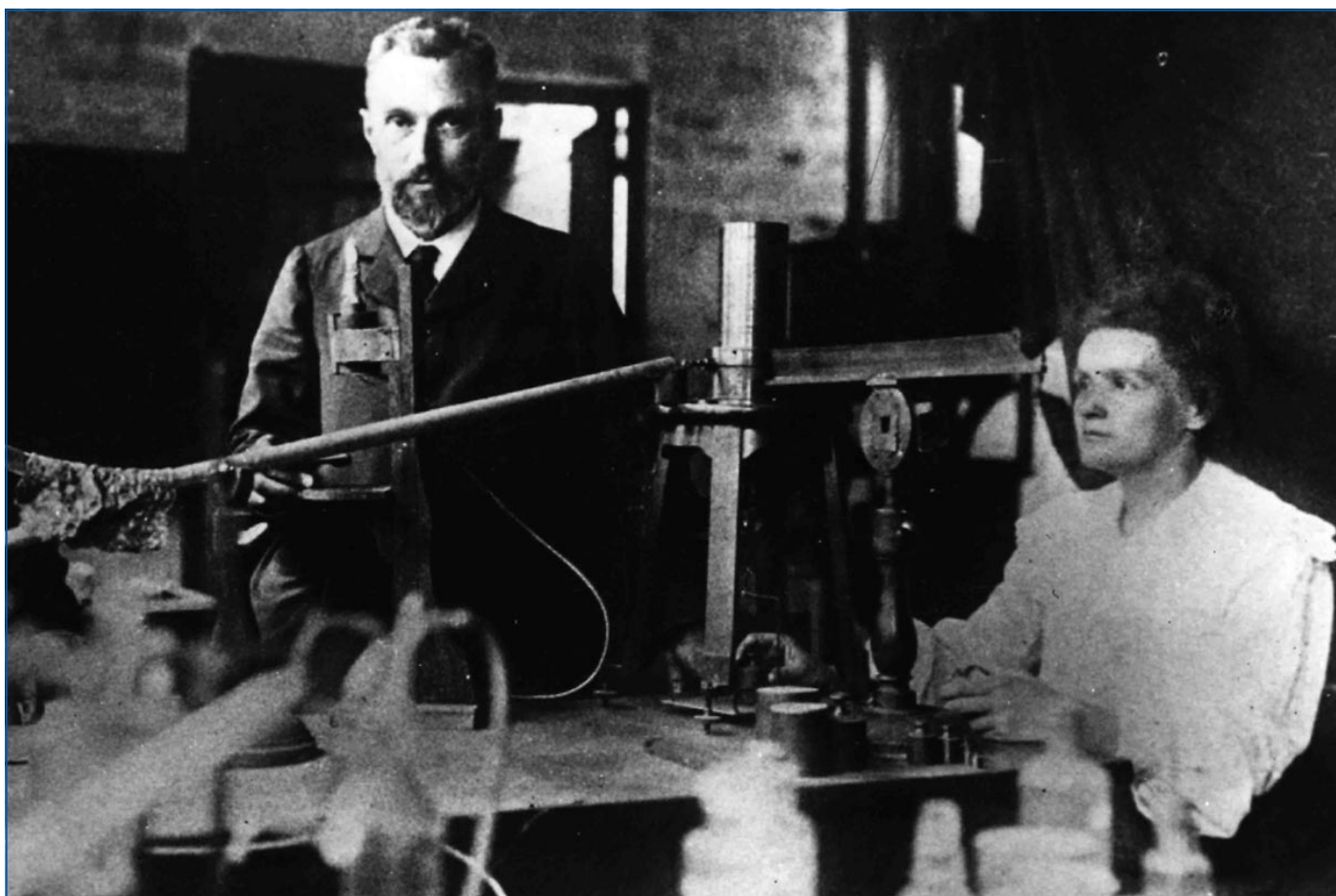


X-rays stimulated scientists around the world into action. They also aroused a great deal of public interest which had not abated decades later, as the cigarette card shows.





X-rays came into their own during the first world war. This image of a hand with a shell splinter is taken from Marie Curie's book "Radiology in War", published in 1921. (ACJC-Archives Curie and Joliot-Curie.)



Pierre, 1859–1906, and Marie Curie, 1867–1934, in their laboratory in 1898. (ACJC-Archives Curie and Joliot-Curie.)

For a while, only uranium and its compounds were known to emit these new rays. Further studies by Marie Curie in Paris, however, revealed that another element, thorium, had the same property. Again, the chemical form of thorium did not matter, all forms – thorium metal, thorium oxide etc. – emitted exactly the same rays, which, just as for uranium, poured out steadily without any external source of energy being applied.

Until the 1890s, thorium was just an element whose oxide was used to make gas lighting mantles bright, while uranium had been used since Roman times as a yellow pigment in glass. These rather boring elements were about to leap to the centre of the scientific stage and offer unique clues about the structure of matter.

The hunt for radioactive elements

Marie Curie was one of the few scientists of the time who was inspired to continue Becquerel's work. She was the one who first used the word 'radioactivity' to describe the radiation emitted by uranium and thorium. Becquerel's work took some time to gain significance, perhaps because of the recent discovery of X-rays which had very obvious applications in medicine and industry. X-rays had gripped both the public and scientific imaginations; popular cartoons made jokes about how the new rays would penetrate the many layers of Victorian petticoats. However, Marie Curie had the instinct of a great scientist to spot a wholly new window into nature.

Lord Rutherford is celebrated on the New Zealand 100 dollar bill.



Born Marie Sklodowska, she had recently arrived in Paris from Poland and married Pierre Curie, who had himself already made some important discoveries in physics. The story of how Marie Curie discovered polonium, a new radioactive element lurking in trace amounts in uranium ore, followed by radium, an element far more radioactive than uranium and very much rarer, is an inspiring one.

Unlike uranium, pure radium glows in the dark. It also gives out heat. Even the tiny amounts that Marie Curie was able to extract radiated a measurable supply of heat. Radium soon became highly prized as a source of powerful radiation for further experiments. From the earliest days, it was also studied as a possible cure for cancer. This was the beginning of radiotherapy.

Joseph John Thomson, 1856 – 1940, discoverer of the electron, the first fundamental particle of Nature to be identified.
(Copyright the Nobel Foundation.)

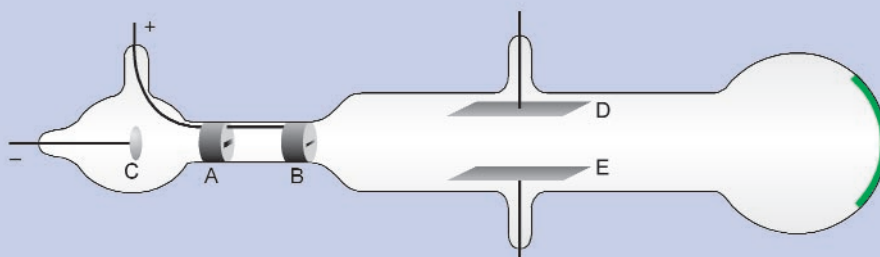


Rutherford joins the quest

Meanwhile, a young New Zealander called Ernest Rutherford had arrived in Britain to work in Cambridge with J.J. Thomson, the greatest experimental physicist of the day. 'J.J.' was interested in how X-rays made air conduct electricity. If you rub a plastic ruler on a woollen sweater, it will pick up small pieces of paper. This is because it acquires an electric charge on its surface. Near an X-ray machine, such a ruler quickly loses its charge because the air becomes conducting and the charge drains away. The reason for this is that the X-rays ionize the air by freeing some electric charge (electrons) from their atoms.

Thomson and Rutherford initially set out to explore this ionization by X-rays. It was known that Becquerel's new kind of radiation also ionized air and exploring this new phenomenon of radioactivity soon became Rutherford's passion.

J.J. discovered the electron with this apparatus, a forerunner of the cathode ray tube found in computer monitors and TV sets. Rays emitted from the 'cathode', C, strike the fluorescent screen at the far end of the tube, leaving a spot of light. Thomson's genius was to interpret the paths of the rays in terms of charged corpuscles, later called electrons. Electrodes A and B were at a positive voltage, drawing off the electrons through the slits. These were then bent by electric and magnetic fields. Electrodes D and E supplied the electric fields, external coils provided the magnetic fields.



At about this time, temporarily leaving his work on X-rays, Thomson made the momentous discovery that electric charge exists in packets or particles of electricity, now called electrons. For this, he won the Nobel Prize. It is now known that electric currents in wires are just the flow of these electrons; and electrons are a key component of every atom.

Shaking the foundations of science

While Thomson worked on the nature of electric charge, Rutherford had made his first big breakthrough. He had found that there were two distinct kinds of radioactivity. This was not a trivial discovery in the days before modern instruments; it had the hallmarks of insight and ingenuity that were to make Rutherford famous.

He discovered that one kind of radiation was highly ionizing and very easily absorbed, even by thin sheets of paper. He called this 'alpha' radiation. The other type was far more penetrating and was named 'beta' radiation. Soon afterwards, Rutherford established one of the most puzzling and characteristic features of radioactivity: no matter how much radioactive material is present initially, half of it will disappear after a time interval known as the 'half-life'. After two half-lives, only a quarter of the original material remains, and so on. This property, known as exponential decay, is tied up with the quantum mechanical nature of atoms described in the next chapter. Rutherford followed these findings with another important discovery that earned him, somewhat to his amusement, the Nobel Prize in chemistry.

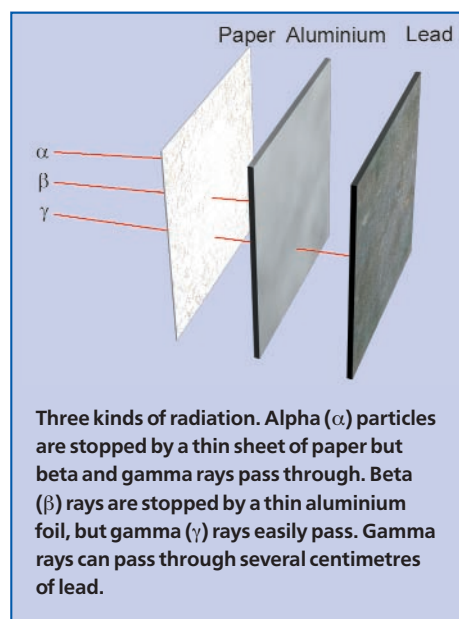
The end of chemistry's most cherished belief

Elements are the foundation stones of chemistry. The vast variety of substances around us are made from combining elements – such as carbon, oxygen, hydrogen and nitrogen – in different ways. At the turn of the twentieth century, a firmly held belief was that atoms never change. Carbon atoms remain carbon atoms; iron stays iron; gold cannot be made from lead; and once uranium, always uranium. Rutherford and his colleague Frederick Soddy, who was at that time working with him at McGill University in Montreal, Canada, overturned this idea. They found radioactivity was a process that could transform one element into another. Somehow, one type of atom emitted a particle and became another type of atom. No doubt mindful of the ill-repute arising from thousands of years of futile attempts to make gold from lead, Rutherford is reported to have said to his friend: "Don't call it transmutation, Soddy, or they'll have our heads as alchemists!"

The idea of atoms transmuting from one type to another met with initial resistance, even from the Curies. Within a few years, however, such overwhelming evidence was presented by Rutherford, Soddy and many others, that transmutation became widely accepted. A great number of people were soon involved in unravelling the complicated story of which element transmuted into what. This task was made much easier by knowing the nature of alpha and beta radiation, as well as by the discovery of a third type of radioactivity called gamma rays.

The nature of radiation

Following the discovery of alpha and beta radiation, physicists were keen to investigate their nature. Beta particles were relatively easy to identify. Their paths are deflected easily by strong magnets which shows they are electrically charged and are thousands of times lighter than atoms. Beta particles were soon identified



as electrons – the particles recently discovered by Thomson to be the smallest carriers of charge.

The nature of alpha particles was harder to establish. They are certainly electrically charged, but are harder to deflect by magnets, which means that they have to be much heavier than electrons. Rutherford discovered that alpha particles are helium ions: helium atoms that have been stripped of their electrons, leaving them positively charged.

Age of the Earth mystery

The idea of transmutation, together with an understanding of what alpha and beta rays are, opened up the possibility of using radioactivity for a variety of measurements. By 1905, Rutherford could claim to know the age of the rocks he was carrying in his pocket simply because he knew that alpha particles were helium ions.

Rocks naturally contain a small amount of radioactive uranium that transforms into another type of element, spitting out helium ions in the process. These ions soon pick up their missing electrons and become neutral helium atoms which are trapped in the rocks. These minerals are studied in a laboratory to see how much helium they hold.

Knowing the amount of helium locked away in the rocks, Rutherford could determine how much time had passed since the rocks were formed. He had to take into account the amount of uranium in the rock along with other elements, such as lead, which are the end products of a whole chain of transmutations starting with uranium. Today, analyses like this are crucial to geology, and dating rocks by studying the decay of radioactive minerals is a highly developed application of nuclear techniques.

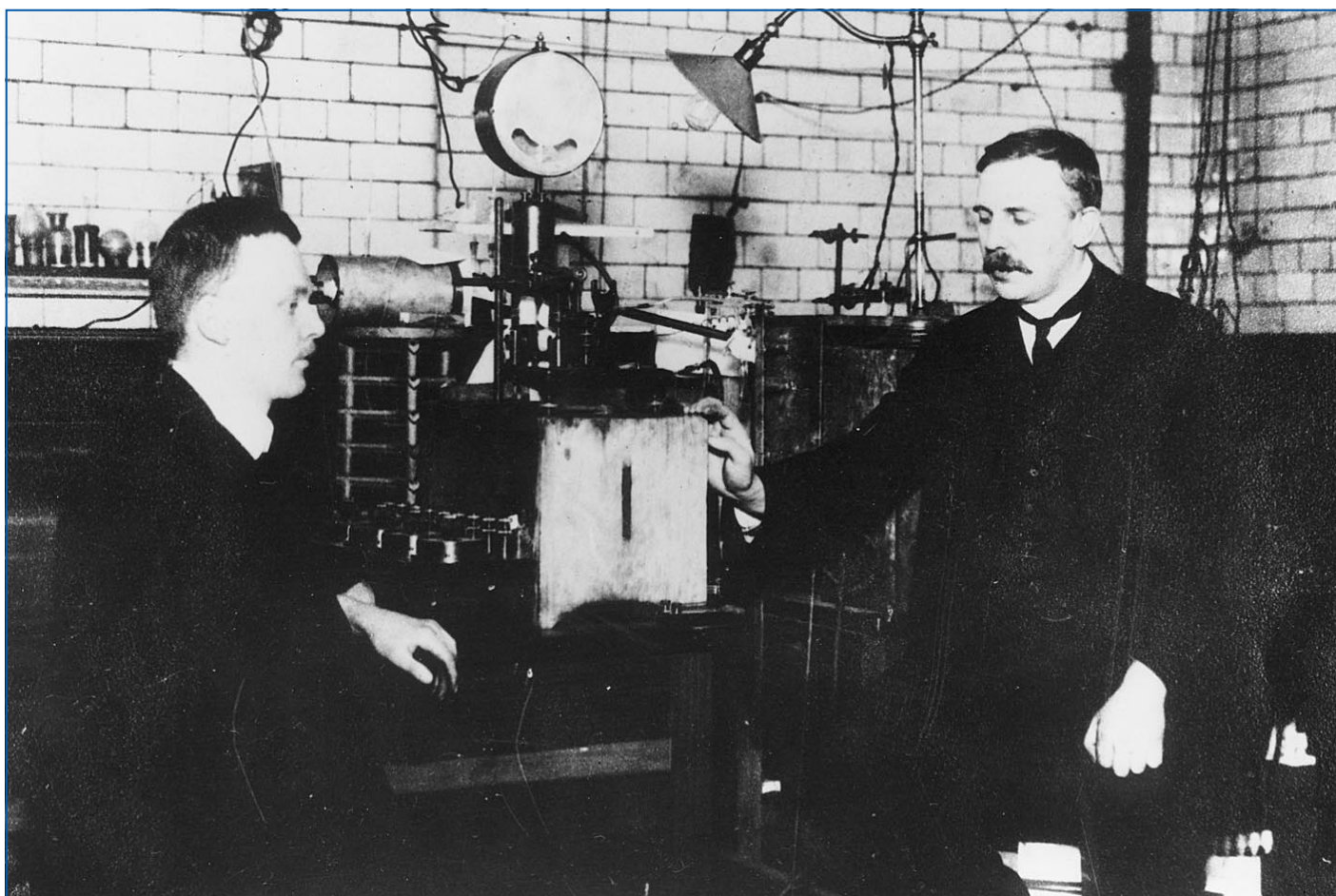
Having demolished one of chemistry's most cherished beliefs – namely that the elements cannot change from one type to another – radioactivity was also beginning to threaten a cornerstone of physics. This was the law proclaiming that energy is always conserved. Although it can be transformed from one form to another, the total amount of energy of a system always remains the same. How could radioactive materials seemingly pour out energy from nowhere? This was a real dilemma. Later it was found that the total mass of nuclear particles becomes less following radioactive decay. It was Albert Einstein who first showed that a loss of mass means a release of energy.

But in 1904, before Einstein's theory of relativity, nuclear energy solved another vexing problem. The great physicist Lord Kelvin had estimated that the Earth could not be more than 100 million years old, otherwise its interior would have had time to cool down. Geologists argued that it was much older; and biologists knew that life would have needed much more time to evolve. Rutherford pointed out that the radioactivity of minerals in the ground was an additional source of heat, which made a much older Earth possible. In fact, the rocks in his pocket were themselves much older than Kelvin's estimate of the age of the Earth.

The next application of radioactivity was momentous: studying the inner structure of matter itself. The result was the discovery of the atomic nucleus. The physicist in the vanguard of this research was a New Zealander working at Manchester University in the North of England – Ernest Rutherford.



Our blue planet is approximately 4.5 billion years old. If it were not for the nuclear decay processes at the core, the Earth would have cooled down to a solid ball long ago, without plate tectonics, earthquakes or volcanoes. (Courtesy of M. Jentoft-Nilsen, F. Hasler, D. Chesters NASA/Goddard and T. Nielsen University of Hawaii.)



Hans Geiger, 1882–1947, left, with Ernest Rutherford, 1871–1937, in Rutherford's laboratory in Manchester. This picture was taken at about the time of the discovery of the nucleus. (Science Museum/Science and Society Picture Library.)

Signatures of the invisible

In spite of the unimaginably small size of each alpha particle – a million, million times smaller than a flea – individual alpha particles can be detected. This remarkable fact made it possible to use radioactivity to explore the fundamental structure of all matter.

A single alpha particle striking a screen made of zinc sulphide creates a tiny flash of light (a scintillation). The ability to see these flashes attests to the extreme sensitivity of human eyes to tiny amounts of light – sensitivity, that is, only for those prepared to spend hours in a pitch-dark room allowing their eyes to adapt. This was a price the early explorers of radioactivity were happy to pay. Even the fact that the flashes occurred at all was significant, since it was one of the clinching arguments for the very existence of atoms.

By the first decade of the twentieth century, there were various 'informed' guesses as to the structure of atoms. The most widely known of these was Thomson's 'plum pudding' model. According to Thomson, the negatively charged electrons were dotted like plums in a pudding made of positively charged matter. Although he did not know how many 'plums' the pudding contained, there had to be enough electrons to make the positive and negative charges balance as, overall, atoms are neutral.

A key point of Thomson's model was that the positive charge was spread throughout the atom, rather than concentrated at a particular point. Thomson and his contemporaries never expected that such a model could ever be tested – atoms were then far beyond the power of any imaginable microscope – and as for seeing their internal structure, that was just a dream.

Discovery of the nucleus

Rutherford moved to Manchester in 1907 where he carried out experiments with alpha particles in meticulous detail. One feature struck him as very puzzling: as they passed through air or thin sheets of mica the paths of the alpha particles seemed to deviate very slightly from straight lines. Whereas lesser mortals might have shrugged it off, Rutherford spotted a real problem as alpha particles passing through an atom like Thomson's plum pudding model would hardly be deflected at all. Rutherford enlisted the help of Ernest Marsden, an undergraduate student who was being trained by Hans Geiger. In Rutherford's words: "One day Geiger came to me and said, 'Don't you think that young Marsden, whom I am training in radioactive methods, ought to begin a small research?' Now I had thought so too, so I said, 'Why not let him see if any alpha particles can be scattered through a large angle?'"

As this research occurred before the development of the Geiger counter, Geiger and Marsden had to physically count the individual scintillations, viewed under a microscope as the alpha particles hit a zinc sulphide screen. Using this technique, they measured the fraction of alpha particles that were deflected by the atoms in a thin sheet of gold placed between the radioactive source and the screen.

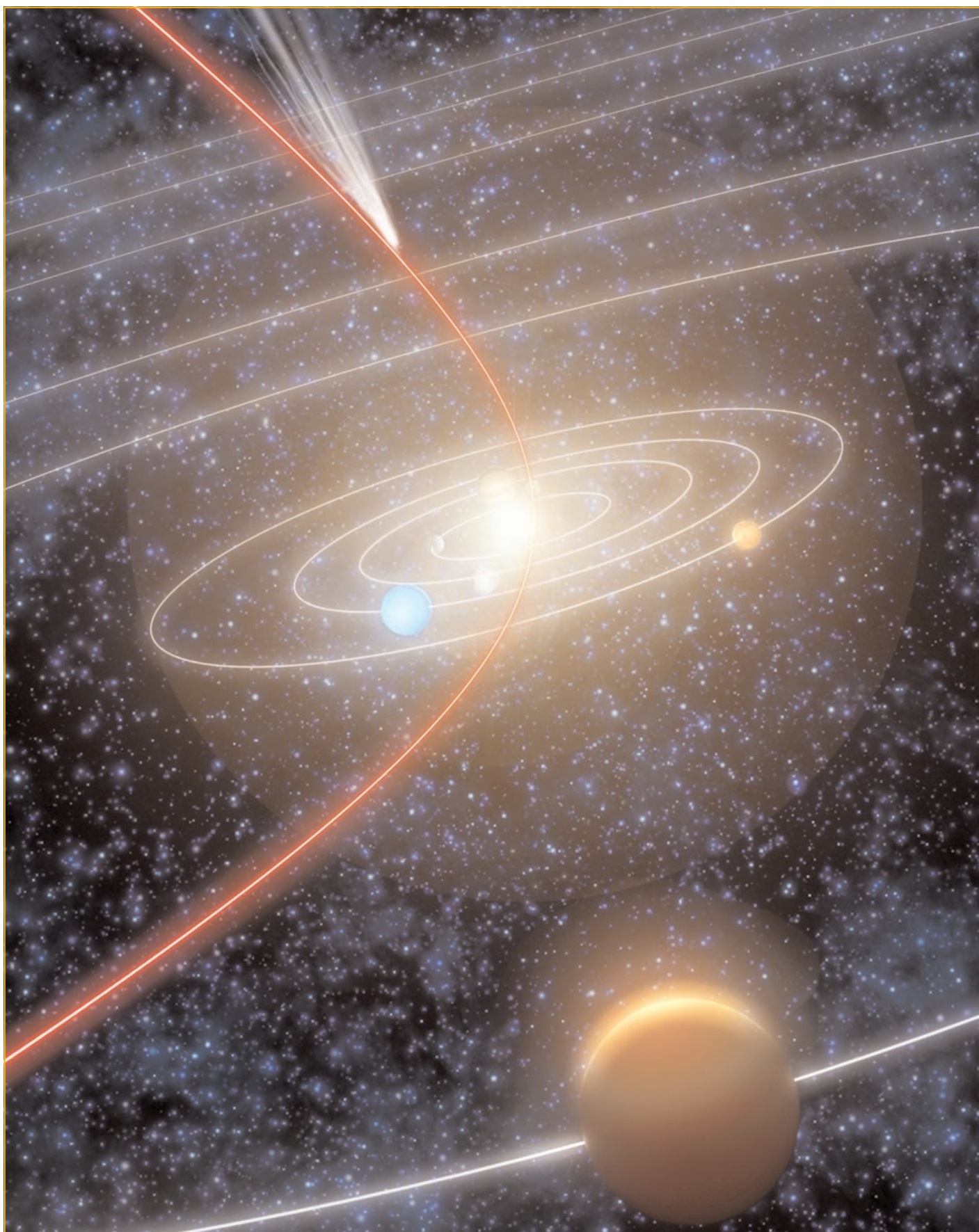
Most of the radiation went straight through, deflected only slightly by the gold foil, while a small but significant number of alpha particles were scattered at large angles. This prompted Rutherford to exclaim: "It was as though you had fired a fifteen inch shell at a piece of tissue paper and it had bounced back and hit you."

Rutherford knew that the positive electrical charge was just too spread out in the plum-pudding model to provide the huge force needed to turn the alpha particles round in their tracks. After all, the alpha particles were moving at a good fraction of the speed of light. The only way to muster sufficient force would be if most of each atom's mass and electric charge was concentrated in a tiny volume. Certainly, the alpha particles could not bounce back from the electrons, which are 8000 times less massive – that would be like a grain of rice deflecting a bowling ball.

Rutherford deduced that the alpha particles must be scattered by a very small, dense, charged nucleus at the centre of the atom. If the positive charge was spread evenly throughout the volume of each atom, all the alpha particles would have gone through the target virtually undeflected.

Scattering unlocks the secrets

Geiger and Marsden's simple first experiment with gold atoms was a slender foundation for a revolutionary new picture of matter. From his nuclear model of the atom, Rutherford then calculated how many particles should be scattered at what angles for different types of material. To do this he made use of the latest ideas from chemistry, which predicted how much electric charge the nuclei of atoms of aluminium, silver and gold might have.



A Solar System analogy for the strong deflection of alpha particles passing through an atom. A comet's path is very curved close to the Sun. This is because the Sun's gravitational force is large near the Sun and much smaller further away. If the mass of the Sun were spread through the huge volume of the Solar System, a body coming from outside the Solar System would only be weakly deflected. In the same way, an alpha particle would be weakly deflected if the positive charge were not concentrated in a tiny volume, the nucleus. (Julian Baum)

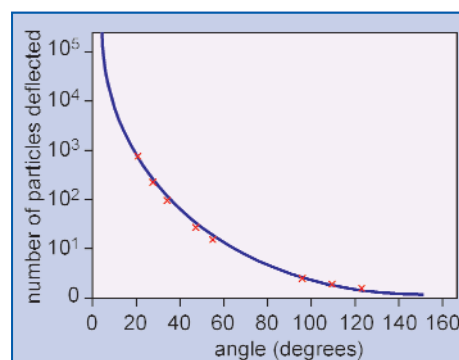
Geiger and Marsden bombarded a whole range of substances with alpha particles. Counting individual zinc sulphide scintillations in the dark using a microscope, they then painstakingly measured what proportion of the particles went straight through various thin metal foils, what proportion were bounced back and the numbers scattered at all the intermediate angles. Extreme patience was needed to get a reasonable number of counts for the large angles to make the results meaningful. Rutherford freely admitted that he did not have the patience for the job.

Geiger and Marsden's measurements matched Rutherford's predictions perfectly. These pioneers with their acute eyes and patience were rewarded with a momentous discovery: atoms have nuclei. Their discovery revolutionized not just physics, but also astronomy, chemistry, biology and our everyday view of the world.

The experiments even made it possible to say that the hydrogen and helium nuclei must be less than four femtometres in diameter (a femtometre being 10^{-15} of a metre) and that the gold nucleus must be no more than ten times this size. To put these numbers into perspective, one femtometre is to one micron what a micron is to a kilometre. Or to put it another way, the size of a typical nucleus relative to one metre is about the same as the size of a pinhead relative to the distance between the Earth and the Sun.

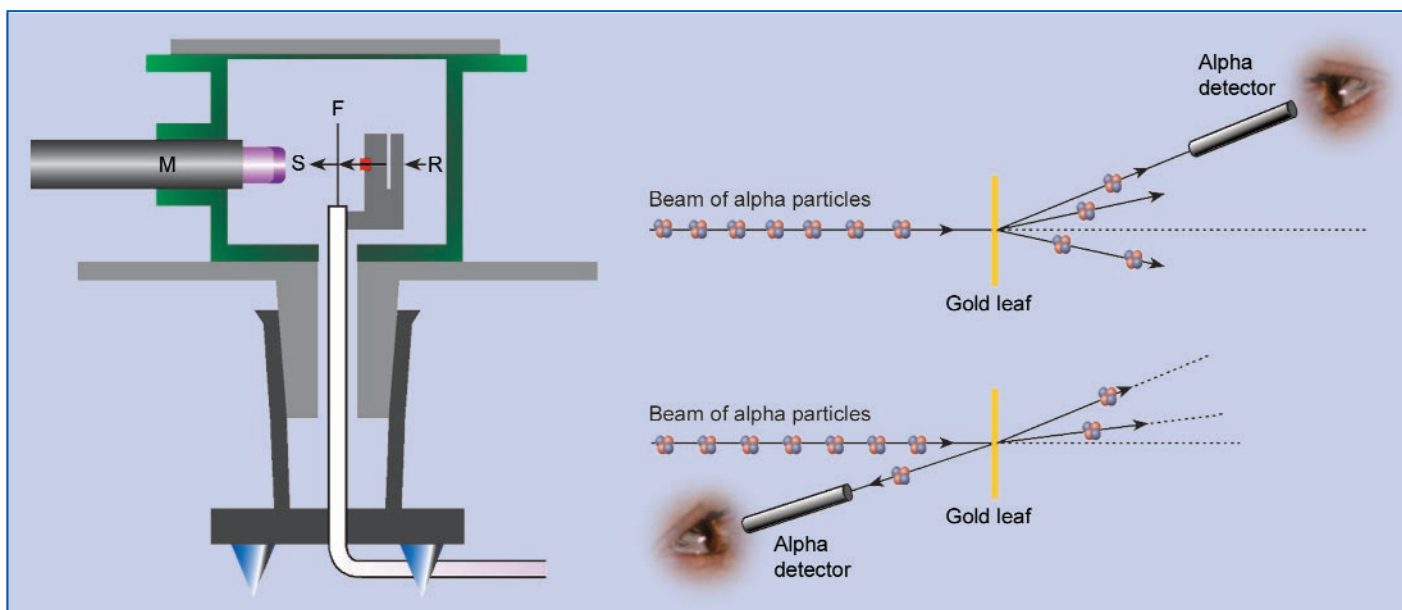
These experiments did much more than prove the existence of atomic nuclei. They inaugurated a whole new method of studying nature: the scattering experiment. Even today, the most important way to study atoms and their nuclei is to fire a beam of particles at a target and watch how they are scattered.

It is certainly not at all obvious that we can learn anything about atoms that are 10^{-10} metres across, or nuclei that are between 10,000 to 100,000 times smaller still, but, nearly a hundred years later, we have learnt a huge amount, mostly from scattering experiments. Today, such experiments are vastly more complex than Geiger and Marsden's, but they are based on the same principle. Particle accelerators can provide particles at far higher energies and intensities than radioactive sources, and scientists no longer sit in darkened rooms counting flashes of light with their eyes. Instead they use complex electronic detectors and an array of computers to sort and store many gigabytes of data from the experiments.



The solid line shows Rutherford's prediction that many alpha particles would be scattered through small angles, but much fewer at large angles. The dots show the measurements of Geiger and Marsden agreeing very well. According to pre-nuclear models, all alpha particles would hardly be deflected at all.

The apparatus used by Geiger and Marsden to verify Rutherford's prediction of alpha particle scattering. R is the alpha emitter, F is the foil, S is the fluorescent screen and M is the viewing microscope. Screen and microscope could be moved around so that the number of alpha particles scattered at different angles could be counted.

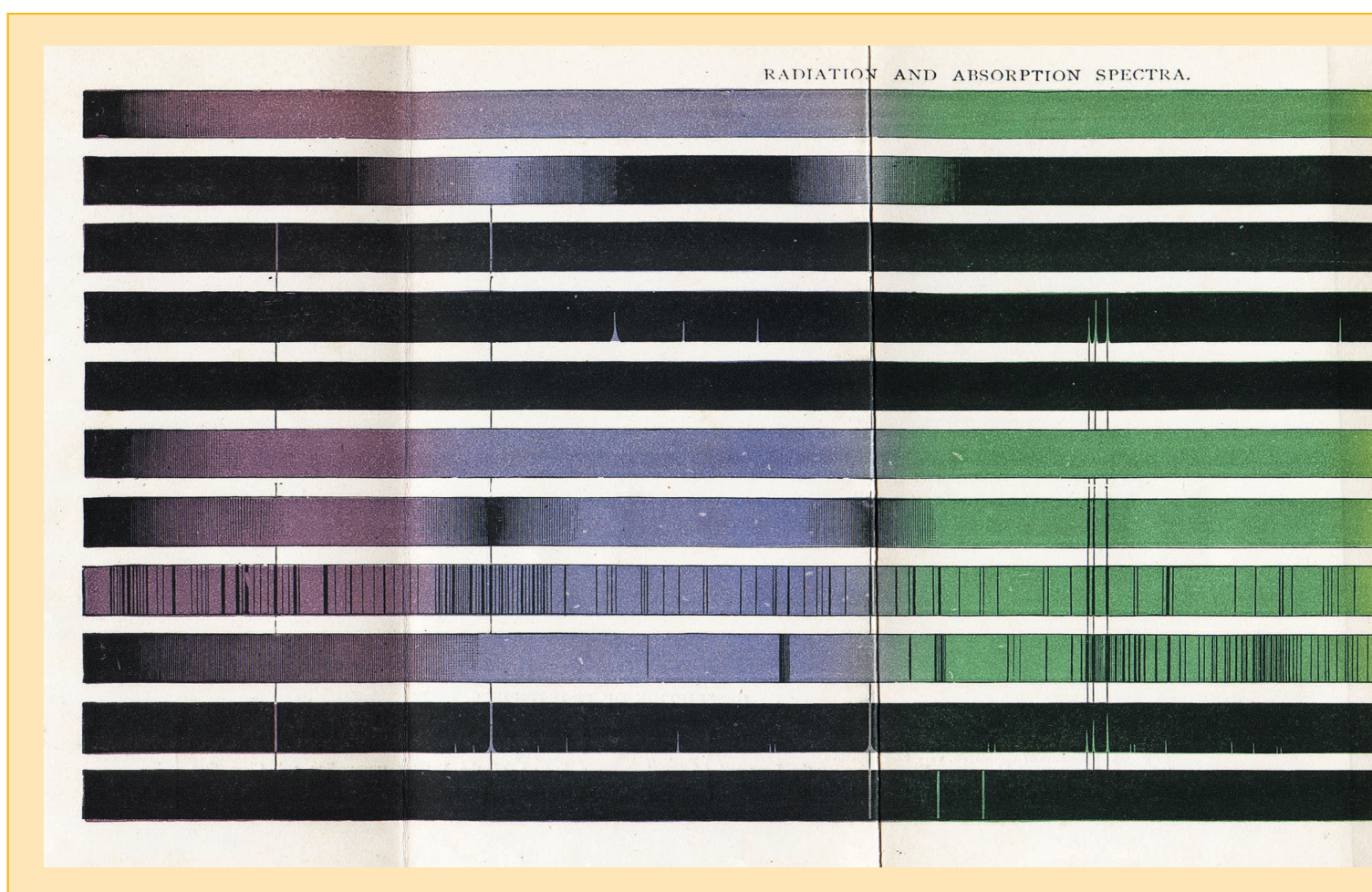
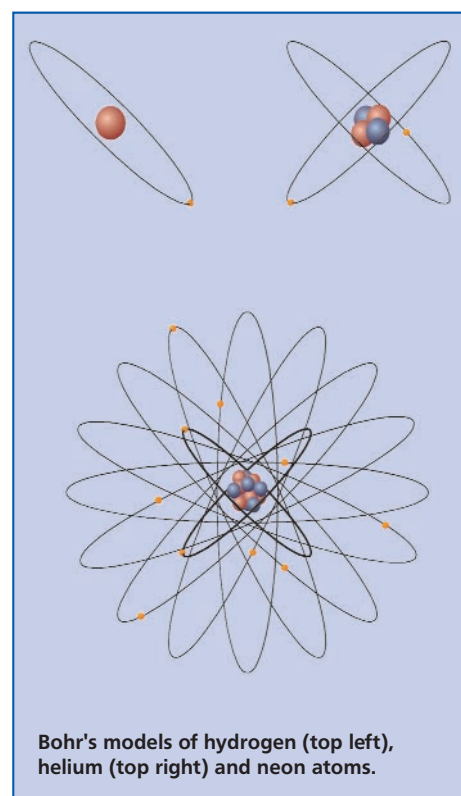


Rutherford knew that his nuclear model left many unresolved problems. For example, if all the positive charge was in the tiny central nucleus while the negatively charged electrons orbited around like planets around the Sun, why did these electrons, which are attracted to the positive charge, simply not fall into the nucleus and neutralize it? There is an important difference between an atom and the Solar System. The Earth and other planets are all in stable orbits around the Sun, whereas the orbiting electrons should be losing energy as they go round the nucleus. This is because electric charges emit radiation when accelerated; a particle moving in circular motion is accelerating, even if its angular velocity is constant. This loss of energy means that the electrons should rapidly spiral in towards the nucleus. The resolution of this puzzle would require a stroke of genius from a young newcomer.

Electrons in orbit

A young Dane called Niels Bohr was on an extended visit to Rutherford in Manchester. Bohr's answer to Rutherford's problem also explained a puzzling property of the light given out when an electric current is passed through hydrogen gas. A Swiss schoolteacher, Johann Balmer, had earlier discovered a remarkable mathematical pattern when analysing the colour of this light. Scientists believed that a strikingly regular pattern like the so-called 'Balmer' series should have a clear-cut explanation. Bohr solved the mystery.

The basic idea of his model was that the electrons do not fall into the nucleus because they revolve around it in fixed orbits without radiating any energy.



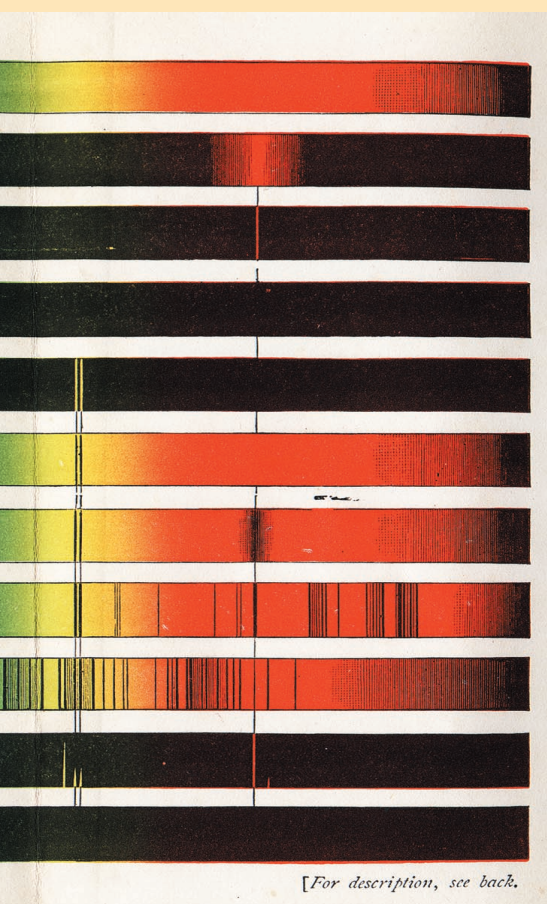
In addition, Bohr's model only allowed certain distinct orbits, almost as if there were a number of invisible rail-tracks around the nucleus on which the electrons had to run. These paths were determined by the standard theories of physics of Bohr's day, with the crucial addition of a certain new ingredient: the quantum theory proposed by Max Planck and Albert Einstein.

Planck and Einstein had used the revolutionary idea that energy comes in packets called 'quanta' to explain a number of puzzling properties of radiation and heat. In 1913, Bohr applied these ideas to atoms and gave a first explanation of why electrons in atoms did not fall into the nuclei. His model convinced many people of Rutherford's nuclear picture of the atom, and was a key step towards the quantum theory that was to become the basic theory of all phenomena at the atomic scale.

That was far from the end of the story however. While most people were convinced that there must be something to Bohr's model, it failed to account for many of the properties of atoms other than hydrogen. It was not until the development of quantum mechanics in the 1920s that the full picture of atomic structure emerged.

Ingredients to make an element

Despite its limitations, the broad concept of Bohr's atomic model remains applicable today. It furnishes a framework for understanding the chemical elements and also provides the language used to describe atoms and nuclei.



Each element has a unique light 'fingerprint' or spectrum. The different colours emitted when the element is heated can be separated by passing the light through a prism or other kind of 'spectroscope'. The resulting pattern is called an emission spectrum. If white light, composed of all colours, passes through a vapour containing atoms of a particular element, then those atoms all absorb light of the same colours. The result is called an absorption spectrum and can be seen as a series of black lines shown here. This picture, showing a range of different spectra, was the frontispiece of Norman Lockyer's "Elementary Lessons in Astronomy" 1874. Lockyer became famous for discovering helium on the Sun before it was known on Earth – and it is also for this reason that the element was named after the Greek word for the Sun, 'Helios'.

The total charge on a neutral atom is zero because the negative charge on all the electrons balances the positive charge on the nucleus; the number of electrons in an atom equals the number of positively charged particles in the nucleus. This quantity is called the atomic number and is denoted by the letter Z . The Z of a particular atom tells us which chemical element it is. For example, the simplest element, hydrogen, has $Z = 1$, while the next simplest element, helium, has $Z = 2$. Helium therefore has two electrons in orbit about a compact nucleus containing two positive charges.

Hydrogen and helium are the most abundant elements in the Universe. About three-quarters of the matter in the Universe is hydrogen and the rest is mostly helium. The other 90 or so elements make up the remaining 2%. Of course, there are certain places where some of these elements, like carbon, oxygen and iron, are more common. The Earth is one such place. The rarer elements are mostly made when massive stars explode as supernovae – events which will be investigated later.

Protons, neutrons and isotopes

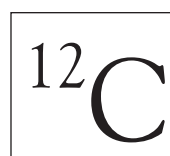
Rutherford gave the hydrogen nucleus a name of its own: the proton. The charge of the proton is equal and opposite to that of the electron and it weighs about 2000 times more, consistent with Rutherford's model of the atom having most of its mass in the central nucleus.

The helium nucleus is four times heavier than the hydrogen nucleus, not twice as massive as might be expected. This is because it contains two uncharged particles called neutrons, as well as the two protons. Protons and neutrons have about the same mass.

Some important Isotopes

Symbol	Nucleus
^1H	ordinary hydrogen
^2H	deuterium (heavy hydrogen)
^3H	tritium (radioactive hydrogen)
^4He	helium (alpha particle)
^{12}C	carbon, commonest isotope
^{14}C	rare radioactive isotope, used for dating
^{16}O	oxygen, common isotope
^{56}Fe	iron, common isotope
^{235}U	uranium, rare isotope
^{238}U	uranium, most common isotope

Nuclear notation



A nucleus is denoted by the chemical symbol of its element along with a number denoting the sum of the number of protons and neutrons it contains. Thus ^{12}C (you read it as carbon-twelve) is a nucleus with 6 protons (the signature of carbon) and 6 neutrons whereas the isotope ^{14}C , which also contains 6 protons, has two extra neutrons. Atomic and nuclear masses are often given in atomic mass units (amu), where one amu (or 1.66×10^{-27} kg) is defined as one twelfth of the mass of the neutral ^{12}C atom. The total number of nucleons is known as the atomic mass number, or just mass number.

In fact, not all hydrogen nuclei consist of just a lone proton, some also contain one or two neutrons. Similarly, not all helium nuclei are made of two protons and two neutrons, a few have two protons but only one neutron. Nuclei with a particular number of protons can have different numbers of neutrons. However, it is the number of protons that identifies a particular element, not the number of neutrons. Atoms with different numbers of neutrons but the same number of protons (and electrons) are different isotopes of the same element.

Each element has a number of different isotopes. In fact, nuclei are usually identified by a third number, called the atomic mass number, which refers to the total number of protons and neutrons. For example, most of the carbon atoms in the world have 6 protons and 6 neutrons, giving them an atomic mass number of 12. These are the atoms of the isotope carbon-12. Henceforth, we will use the nuclear physics convention of writing this as ^{12}C , where the letter denotes the chemical symbol of the element. An isotope of carbon with 8 neutrons also exists in small quantities. These rarer ^{14}C atoms are radioactive and are used to date ancient remains, a technique known as ‘carbon dating’.

We can now say exactly what an alpha particle is. It is the nucleus, ^4He , of a helium atom. Why some larger nuclei choose to emit such objects is part of the unfolding drama, as we continue our journey into the heart of matter.