Collaborative Learning Activity – How is it we have come to understand the inner workings of the atom?

You will be split between several Groups, dependent on class size. In each group you will be responsible for a specific volume of the material. As "**experts**" you must be able to teach your part of the information regarding the historical development of the present-day model of the atom to others in each group. You will create a timeline of historical figures and brief sketches of each model of the atom as it evolved into what science now understands regarding the atom. The biographical information presented is important, but your main focus should be on the scientific contributions and experimentation that have guided physicists to present day understanding of the nature of the atom.

Home Groups 1-6

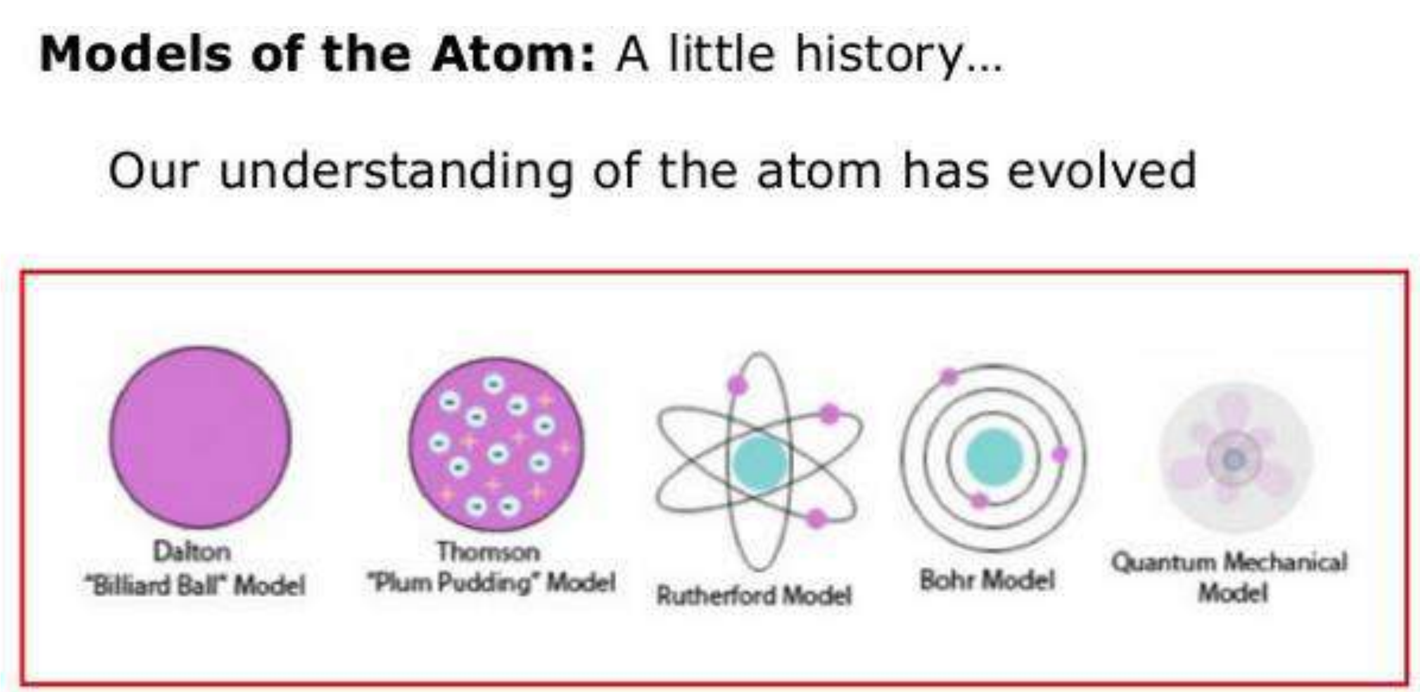
Select Experts A - F rotate between Home Groups, Experts stay put.

Activity: **Step one day one.** As a group, identify and illustrate the historical developments relevant to the structure of the atom as it came to be known during the period assigned to your group. Devise a plan to present to various Home Groups the following day. We will explore and highlight key developments from the ancient Greeks till now.

Step two – <u>Preparation</u>: Finalize any of your research and Expert Graphic Organizer for presenting to Home Groups.

Step three day two. Selected experts will rotate around the room and present their findings. Complete Timeline and sketches of the various models.

Step four - <u>Preparation</u>: Complete / finalize any notes you miss.



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Group 1 - Group 1 - Group 1 - Group 1 - Group 1 - Group 1

Do atoms exist? One of the most remarkable features of atomic theory is that even today, after hundreds of years of research, no one has yet “seen” a single atom. Some of the very best microscopes have produced images of groups of atoms, but no actual picture of an atom yet exists. How, then, can scientists be so completely certain of the existence of atoms and of the models they have created for them? The answer in part is that models of the atom, like other scientific models, can be tested by experimentation. The results are then interpreted, validated by other scientists, which then allows them to infer through indirect observation the nature of the atom. Models of the atom that pass the test of experimentation survive, while those that do not are shelved. The model of the atom that scientists use today has been rebuilt and redesigned through trial and error by untold thousands upon thousands of hours of experimentation. It will continue to adapt and be subjected to more and more technologically advanced testing in the future as we peer deeper and deeper into the unseen world of the very, very, small.

The first person to suggest the idea of atoms is credited to a Greek philosopher named Democritus. More than 2400 years age, Democritus asked whether it is possible to divide a sample of matter forever into smaller and smaller pieces. After much thought, he concluded that it was not. At some point, a smallest piece would be reached. In fact, the word “atom” comes from the Greek word *atomos*, meaning “cannot be divided.” Democritus and his students did not know what scientists today know about atoms. However, they hypothesized that atoms were small, hard particles that were all made out of the same material. They also believed them to be infinite in number and that they were always moving and could be joined together. Democritus first suggested the existence of the atom but it took almost two millennia before the atom was placed on a solid foothold as a fundamental chemical unit by John Dalton (1766-1844). Although two centuries old, much of Dalton's atomic theory remains valid in modern chemical thought.


John Dalton

John Dalton was an English chemist with a Quaker background. His religious beliefs, and perhaps his modesty, prevented him from accepting much of his deserved fame and recognition. Today Dalton is known primarily for his atomic theory, although his inquisitive nature and diligent research led him to make many important discoveries in fields outside of just chemistry. He made a careful study of colorblindness, a condition from which he himself suffered. Dalton was also a pioneer meteorologist, keeping daily records of the weather for nearly 57 years. His fascination with weather and the atmosphere led to his research into the nature of gases, which in turn became the foundation on which he built his atomic theory. Experiments with gases that first became possible at the turn of the nineteenth century led Dalton in 1803 to propose a modern theory of the atom based on the following assumptions.

1) All matter is made of atoms. Atoms are indivisible and cannot be destroyed
2) All atoms of a given element are identical in mass and properties
3) Compounds are formed by a combination of two or more different kinds of atoms.
4) A chemical reaction is a ***rearrangement*** of atoms.
5. Atoms cannot be created or destroyed. When a compound decomposes, the atoms are recovered unchanged.

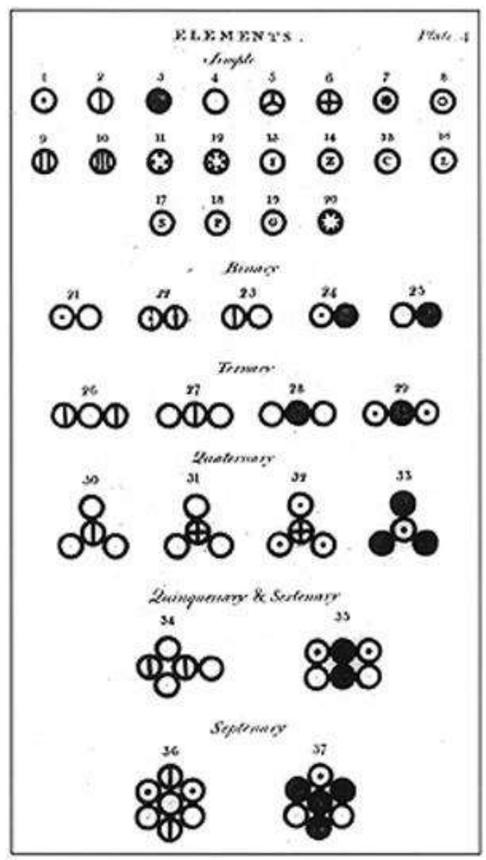
Modern atomic theory is, of course, a little more involved than Dalton's theory but the essence of Dalton's theory remains valid. Today we know that atoms can be destroyed via nuclear reactions but not by chemical reactions. Also, there are different kinds of atoms (differing by their masses) within an element that are known as "isotopes", but isotopes of an element have the same chemical properties.

Many unexplained chemical phenomena were quickly explained by Dalton with his theory. Dalton's theory quickly became the theoretical foundation in chemistry.

Despite the uncertainty at the heart of Dalton's atomic theory, the principles of the theory survived. Dalton was correct by many accounts, but as so often is the case in science, there are always exceptions. It is true that atoms cannot be subdivided, created, or destroyed into smaller particles when they are combined, separated, or rearranged in chemical reactions, however during nuclear fusion or fission this very thing can and does happen but then these are not chemical reactions. In addition, the idea that all atoms of a given element are identical in their physical and chemical properties is not precisely true, as we now know today that different isotopes of an element have slightly varying atomic masses (numbers of neutrons). However, Dalton had created a theory of immense power and importance.

Dalton then proceeded to publish his findings in print; the first published table of relative atomic weights. Six elements appear in this table, namely hydrogen, oxygen, nitrogen, carbon, sulfur, and phosphorus, with the atom of hydrogen conventionally assumed to weigh 1. Dalton provided no indication in this first paper how he had arrived at these numbers, so not the best science book keeping, but we will cut him some slack. However, in his laboratory notebook under the date 6 September 1803 there appears a list in which he sets out the relative weights of the atoms of a number of elements, derived from analysis of water, ammonia, carbon dioxide, etc. by chemists of the time. It appears, then, that confronted with the problem of calculating the relative diameter of the atoms of which, he was convinced, all gases were made, he used the results of chemical analysis to determine much of his findings.

Even in his day scientific method was becoming the golden rule of good scientific investigation. Assisted by the assumption that combinations always takes place in the simplest possible way, he thus arrived at the idea that chemical combination takes place between particles of different weights. Basically, the idea that not all things are pure atoms or elements. Rather, many things are in fact or combinations of atoms or compounds in particular ratios. This is what distinguished his theory from the historic theories of the Greeks, such as Democritus.



Various atoms and molecules as depicted in John Dalton's *A New System of Chemical Philosophy* (1808).

Group 2 - Group 2 - Group 2 – Thomson

J. J. Thomson (left) and Ernest Rutherford (right)

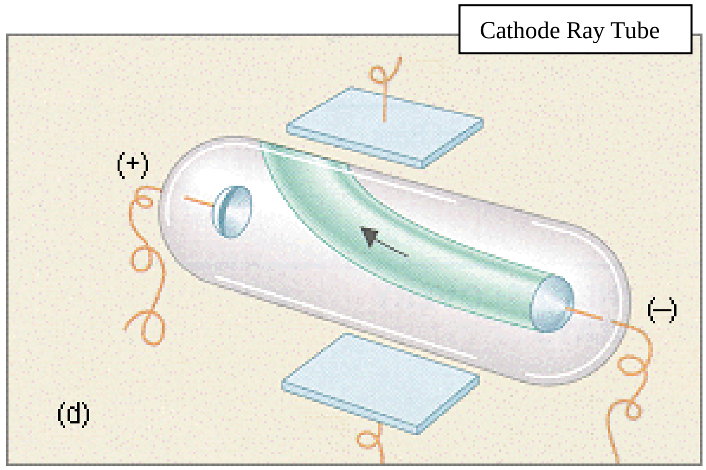
Late nineteenth- and early twentieth-century atomic models

As each part of Dalton's theory was tested, new ideas about atoms were discovered. The first scientist to suggest that atoms contain smaller particles was English physicist J.J. Thomson (1856–1940) of England. In 1897, using something called a cathode ray tube, he passed an electric current through a gas. Thomson found that the cathode rays can be deflected by an electric field. He found that atoms are divisible and **not indivisible as Dalton once suggested.** What he released was that these cathode rays were in fact particles being emitted from the gas atoms inside his cathode tube.

When excited by means of an electrical current, atoms break down into two parts. One of those parts is a tiny particle carrying a negative electrical charge, the electron. To explain what he had discovered, Thomson suggested a new model of the atom, a model widely known as the plum-pudding atom. The name comes from a comparison of the atom with a traditional English plum pudding, in which plums are embedded in pudding, as shown in the accompanying figure of the evolution of atomic theory. In Thomson's atomic model, the "plums" are negatively charged electrons, and the "pudding" is a mass of positive charge.

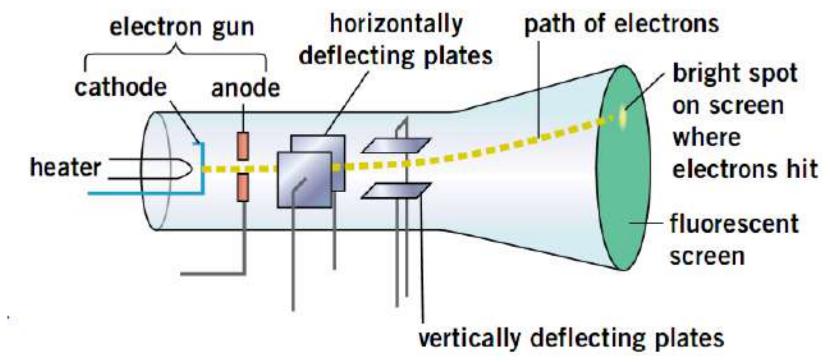
By balancing the effect of a magnetic field on a cathode-ray beam with an electric field, Thomson was able to show that cathode rays are actually composed of particles. This experiment also provided an estimate of the ratio of the charge to the mass of these particles. If you have the ratio and you know the charge, you can find the mass, or if you know the mass can find the charge (*just how negative (-) or positive + a particle can be.)*

Cathode Ray Tube



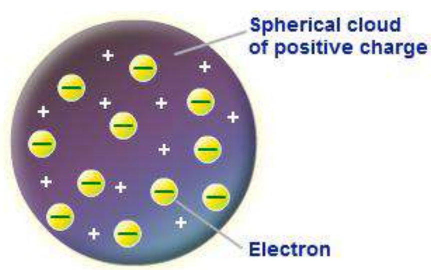
He found that the gas gave off rays made of negatively charged particles. Today these particles are known as electrons and in that way can be said to credited with their discovery. Because the electrons were negative and atoms were known to be neutral, Thomson reasoned that there must also be some positive charge holding the atom together. Thomson hypothesized that an atom is made up of mostly positively charged material with electrons scattered evenly throughout.

Thomson found the same charge-to-mass ratio regardless of the metal used to make the cathode and the anode. He also found the same charge-to-mass ratio regardless of the gas used to fill the tube. He therefore concluded that the particles given off by the cathode in this experiment are a universal component of matter. Although Thomson called these particles *corpuscles*, the name electron, which had been proposed by **George Stoney** several years earlier for the fundamental unit of negative electricity, was soon accepted. The cathode rays also can be deflected by an electric field in a direction which suggests they are negatively charged.



The Raisin Pudding Model of the Atom (J. J. Thomson)

Thomson soon recognized one of the consequences of the discovery of the electron. We know matter to be electrically neutral, so there must be a positively charged particle that balances the negative charge of electrons being emitted from the cathode experiment. He hypothesized there must be a positive charge to balance out the negative electrons somewhere. Thomson was able to calculate the mass of the electron proportionally to the rest of the atom. If electrons are much lighter than atoms, then the remaining positively charged portion, *soon assumed to also be particles* must carry the majority of the mass of the atom. Thomson therefore suggested that atoms are spheres of positive charge in which light, negatively charged electrons are embedded, much as raisins might be embedded in the surface of a pudding. At the time Thomson proposed this model, evidence for the existence of positively charged particles was also soon available from other cathode-ray tube experiments.



Thomson's Plum pudding model

Like the Dalton model before it, Thomson's plum pudding atom was soon put to the test. It did not survive very long. In the period between 1906 and 1908, English chemist and physicist Ernest Rutherford (1871–1937) studied the effects of bombarding thin gold foil with alpha particles. Alpha particles are helium atoms that have lost their electrons and therefore, are positively charged. Rutherford reasoned that the way alpha particles traveled through the gold foil would give him information about the structure of gold atoms in the foil.

Group 3 - Group 3 - Group 3 - Group 3 - Group 3 – Rutherford

Thomson (left) and Rutherford (right)

Like the Dalton model before it, Thomson's plum pudding atom was soon put to the test. It did not survive very long. Everyone at that time imagined the atom as a "plum pudding." That is, it was roughly the same consistency throughout, with negatively-charged electrons scattered about in it like raisins in a pudding. In the period between 1906 and 1908, English chemist and physicist Ernest Rutherford (1871–1937) studied the effects of bombarding thin gold foil with alpha particles. As part of an experiment Rutherford was shooting a beam of alpha particles (or alpha rays, emitted by the radioactive element radium) at a sheet of gold foil only 1/3000 of an inch thick, and tracing the particles' paths. Alpha particles are helium atoms that have lost their electrons and therefore, are positively charged. Rutherford reasoned that the way alpha particles traveled through the gold foil would give him information about the structure of gold atoms in the foil itself. He would not be disappointed.

Most of the particles went right through the foil, which would not be expected if the atoms in the gold were like a plum pudding. But every now and then, a particle bounced back as though it had hit something solid. After tracing many particles and examining the patterns, Rutherford inferred that the atom must have nearly all its mass in a tiny central nucleus about 10,000 times smaller than the atom itself. He also reasoned that this tiny central mass had to be where all of the positive charge was and not as *raisins* scattered throughout. All of the negative charge was held in the electrons, which must orbit the dense nucleus like planets around the sun was the next logical step in the evolution of the model of the atom.

Rutherford's experiments provided him with two important pieces of information. First, most of the alpha particles traveled right through the foil without being deflected at all. This result tells us, Rutherford concluded, that atoms consist mostly of empty space. Second, a few of the alpha particles were deflected at very sharp angles. In fact, some reflected completely backwards and were detected next to the gun from which they were first produced. Rutherford was enormously surprised. The result, he said, was something like shooting a cannon ball at a piece of tissue paper and having the cannon ball bounce back at you! This was because sometime the alpha actually struck the nucleus.

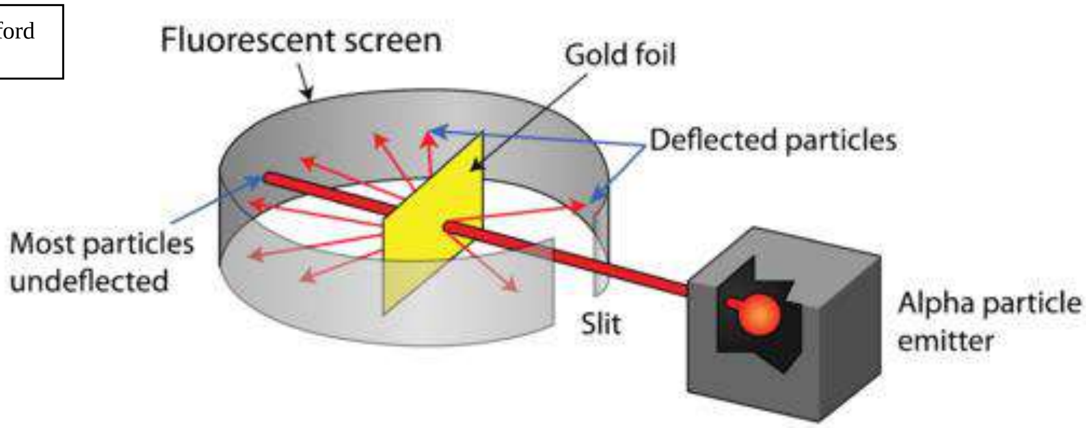
According to Rutherford, the conclusion to be drawn from this result was that the positive charge in an atom must all be packed together in one small region of the atom. He called this region the **nucleus** of the atom and credited till this day with its discovery.

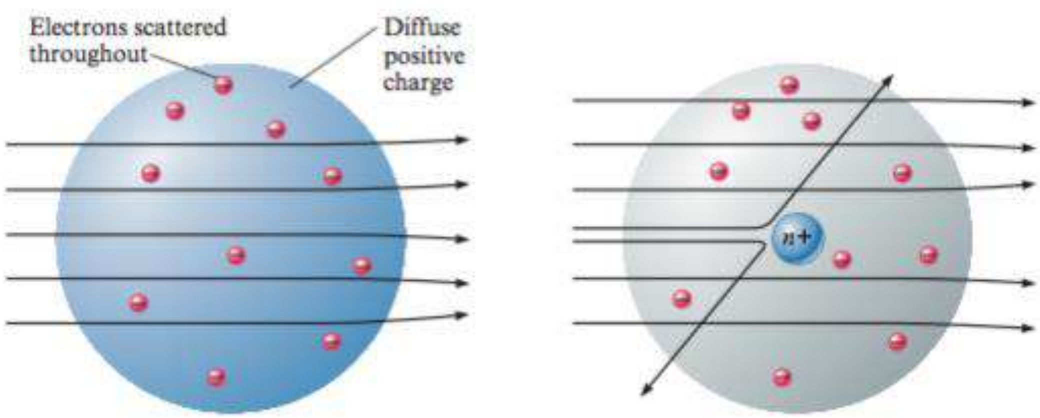
The planetary atom. One part of Rutherford's model (the nucleus) has turned out to be correct. However, his placement of electrons created some problems, which he himself recognized. The difficulty is that electrons cannot remain stationary in an atom, as they appear to be in the figure. If they were stationary, they would be attracted to the nucleus and become part of it. (Remember that electrons are negatively charged and the nucleus is positively charged; opposite charges attract.)

But the electrons could not be spinning around the nucleus either. According to a well-known law of physics, charged particles (like electrons) that travel through space give off energy. Moving electrons would eventually lose energy, lose speed, and fall into the nucleus. Electrons in Rutherford's atom could neither be at rest nor in motion.

The solution to this dilemma was proposed in a new and brilliant atomic theory in 1913, by a Danish physicist named Niels Bohr.

The Rutherford Experiment



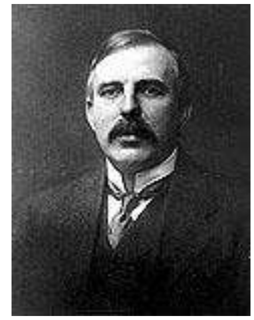


Thomson Model 1897 Rutherford Model 1908

PEOPLE AND DISCOVERIES

A SCIENCE ODYSSEY

Ernest Rutherford
1871 - 1937



Ernest Rutherford's family emigrated from England to New Zealand before he was born. They ran a successful farm near Nelson, where Ernest was born. One of 12 children, he liked the hard work and open air of farming, but was a good student and won a university scholarship. After college, he won another scholarship to study at Cambridge University in England -- a turning point in his life. There he met J.J. Thomson (who would soon discover the electron), and Thomson encouraged him to study recently-discovered x-rays.

This was the start of a long, productive, and influential career in atomic physics. Rutherford eventually coined the terms for some of the most basic principles in the field: alpha, beta, and gamma rays, the proton, the neutron, half-life, and daughter atoms. Several of the century's giants in physics studied under him, including Niels Bohr, James Chadwick, and Robert Oppenheimer.

Early on he found that all known radioactive elements emit two kinds of radiation: positively and negatively charged, or alpha and beta. He showed that every radioactive element decreases in radioactivity over a unique and regular time, or half-life, ultimately becoming stable. In 1901 and 1902 he worked with Frederick Soddy to prove that atoms of one radioactive element would spontaneously turn into another, by expelling a piece of the atom at high velocity. Many scientists of the day scorned the idea as alchemy. They stuck with the age-old belief that the atom is indivisible and unchangeable. But by 1904 Rutherford's publications and achievements gained recognition. He was an extremely energetic researcher: in the span of seven years, he published 80 papers.

In 1907 he went to the University of Manchester and with Hans Geiger (of the Geiger counter) set up a center to study radiation. In 1909 he began experiments that were to change the face of physics. He discovered the atomic nucleus and developed a model of the atom that was similar to the solar system. Like planets, electrons orbited a central, sun-like nucleus. Acceptance of this model grew after it was modified with quantum theory by Niels Bohr. For his work with radiation and the atomic nucleus, Rutherford received the 1908 Nobel Prize in chemistry. He was slightly put out, since he was a physicist and felt a bit superior to chemistry! In 1914 Rutherford was knighted.

During World War I, he left his research to help the British Admiralty with problems of submarine detection, but was soon back in the lab. He managed to produce the disintegration of a non-radioactive atom, dislodging a single particle. The particle had a positive charge, so it must have come from nucleus: he called this new particle a proton. With this experiment, he was the first human to create a "nuclear reaction," though a weak one. In 1919 he took over as director of the Cavendish Laboratory. His warm, outgoing personality made him an outstanding mentor to researchers attracted there by his scientific achievements.

He took on more supervision and less direct research as years went by. In 1931 he was made the first Baron Rutherford of Nelson, allowing him to join the House of Lords. He was fiercely anti-Nazi, and in 1933 he served as president of the Academic Assistance Council, established to help German refugees. He would not personally help chemist Fritz Haber, however, who had been instrumental in creating chemical weapons in World War I. Rutherford died two years before the discovery of atomic fission.

"All science is either physics or stamp collecting."

Group 4 - Group 4 - Group 4 - Group 4 - Group 4 - Group 4


Niels Bohr (1885–1962)

One part of Rutherford's model (the nucleus) turned out to be correct. However, his placement of electrons created some problems, which he himself recognized. The difficulty is that electrons cannot remain stationary in an atom, as they appear to be in the figure. If they were stationary, they would be attracted to the nucleus and become part of it. (Remember that electrons are negatively charged and the nucleus is positively charged; opposite charges attract.)

The solution to this dilemma was proposed in a new and brilliant atomic theory in 1913 by a Danish physicist Niels Bohr (1885–1962). He suggested that places exist in the atom where electrons can travel without losing energy. Let's call those places "permitted orbits," something like the orbits that planets travel in their journey around the Sun. If we can accept that idea, Bohr said, the problem with electrons in Rutherford's atom would be solved.

Scientists were stunned. Bohr was saying that the way to explain the structure of an atom was to ignore an accepted principle of physics, or at least for certain small parts of the atom. The Bohr model sounded almost like cheating: inventing a model just because it might look right.

The test, of course, was to see if the Bohr model could survive experiments designed specifically to test it. And it did. Within a very short time, other scientists were able to report that the Bohr model met all the tests they were able to devise for it. By 1930, then, the accepted model of the atom consisted of two parts, a nucleus whose positive charge was known to be due to tiny particles called protons, and one or more electrons arranged in distinct orbits outside the nucleus. Due to this fact, it fair to say that Bohr ought to be credited with the discovery of the proton.

Imagine that you are taking a walking along a beach. As you walk along, you see a sand-castle that someone has built. As you get closer to the sand castle, you discover that you can only stand three meters, two meters, or one meter from the sand castle and no distance in between. You cannot stand at one and a half meters, nor can you stand at two and three quarters of a meter from the sand castle. No matter how hard you try, some mysterious force keeps you at one of those three distances. In everyday life such a situation is absurdly impossible. However, bizarre or unusual it might seem in the physics of the very small, it is a necessity.

This description in which electrons can only occupy certain orbits is called the *shell model* of the atom, because Bohr described the possible orbits of the electrons as *orbitals* or *shells*. When an atom of a gas *released* energy, an electron would move *down* to a lower orbit (requiring less energy), and when an atom *acquired* energy, an electron would move *up* to a higher energy levels. But these orbits or shells were *discrete*, like the distances from the sand castle. The orbits were not a smooth, continuous series of possibilities as one finds in the everyday world, but rather a set of *distinct states* separated from each other, much like the separation of the quanta of electromagnetic radiation that Planck had discovered. This caused the *distinct lines* in the spectrum. For the first time, quantum physics had been applied to matter.

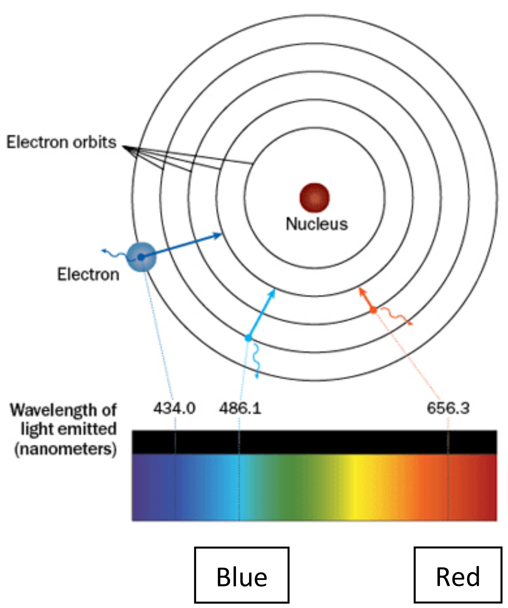
The neutron. One final problem remained. In the Bohr model, there must be an equal number of protons and electrons. This balance is the only way to be sure that an atom is electrically neutral, which we know to be the case for all atoms. But, if one adds up the mass (total amount of matter) of all the protons and electrons in an atom, the total comes no where near the actual mass of an atom.

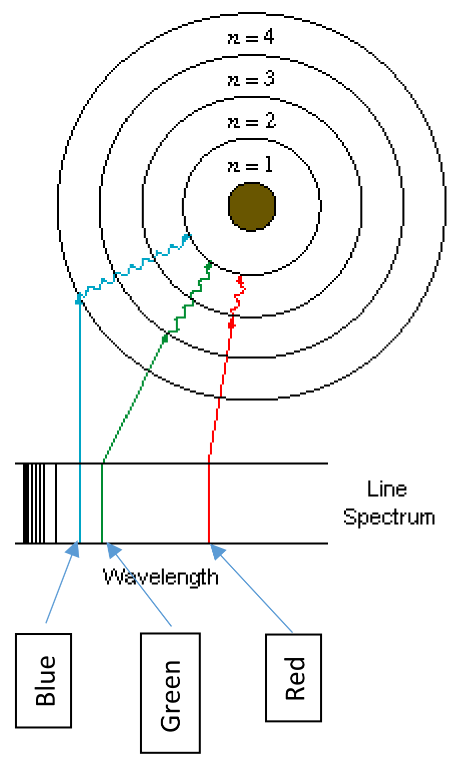
The solution to this problem was suggested by English physicist named James Chadwick (1891–1974) in 1932.

In 1911, Niels Bohr earned his PhD in Denmark with a dissertation on the electron theory of metals. Right afterwards, he went to England to study with J.J. Thomson, who had discovered the electron in 1897. Most physicists in the early years of the twentieth century were engrossed by the electron, such a new and fascinating discovery. Few concerned themselves much with the work of Max Planck or Albert Einstein. Thomson wasn't that interested in these new ideas, but Bohr had an open mind. Bohr soon went to visit Ernest Rutherford (a former student of Thomson's) in another part of England, where Rutherford had made a brand-new discovery about the atom and ultimately used Planck's formulas to explain his model of the atom.

In 1912 Bohr joined Rutherford. He realized that Rutherford's model wasn't quite right. By all rules of classical physics, it should be very unstable. For one thing, the orbiting electrons should give off energy and eventually spiral down into the nucleus, making the atom collapse. Or the electrons could be knocked out of position if a charged particle passed by. Bohr turned to Planck's quantum theory to explain the stability of most atoms. He found that the ratio of energy in electrons and the frequency of their orbits around the nucleus was equal to Planck's constant the proportion of light's energy to its wave frequency. Bohr suggested the revolutionary idea that electrons "jump" between energy levels (orbits) in a quantum fashion that is, without ever existing in an in-between state. Thus when an atom absorbs or gives off energy (as in light or heat), the electron jumps to higher or lower orbits. Bohr published these ideas in 1913 to mixed reaction. Many people still hadn't accepted the idea of quanta, or they found other flaws in the theory because Bohr had based it on very simple atoms. But there was good evidence he was right: the electrons in his model lined up with the regular patterns of light emitted by real hydrogen atoms (see below).

Over the years other investigators refined Bohr's theory, but his bold application of new ideas paved the way for the development of quantum mechanics. Bohr went on to make enormous contributions to physics and, like Rutherford, to train a new generation of physicists.





Bohr's theory that electrons existed in set orbits around the nucleus was the key to the periodic repetition of properties of the elements. The shells in which electrons orbit have different quantum numbers, hold only certain numbers of electrons -- the first shell holds no more than **2**, the second shell up to **8**, the third **10**, the fourth **14**. Atoms with less than the maximum number in their outer shells are less stable than those with "full" outer shells. Elements that have the same number of electrons in their outermost shells appear in the same column in the periodic table of elements and tend to have similar chemical properties.

1. Inherent Instability of the Atom

According to Rutherford's theory, electrons could orbit the nucleus at any distance. When the electrons circle round the nucleus, they are constantly changing their direction. According to classical electrodynamics (which deals with the motion of electrons), such electrons which either constantly change their direction or their velocity or both should continuously emit radiation. While doing so, they should lose energy, and thus spiral into the nucleus. This means *every atom is unstable*, quite contrary to our observation! [1]

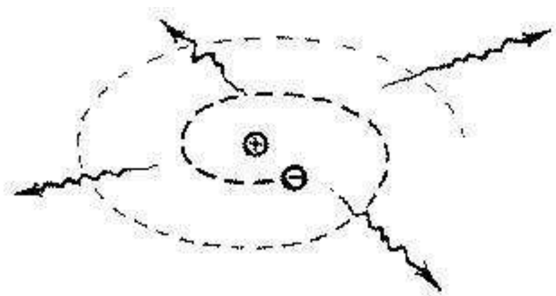


Fig. 4-2: Rutherford's atom is inherently unstable [2]

2. Atomic Spectra - Rutherford's description of the atom could not be entirely correct because it did not account for some observations that had already been made. Perhaps the most important of these observations concerned the behavior of certain gases. These gases at low pressure emit light in a set of discrete bands *of the electromagnetic spectrum. This is quite different from the radiation emitted by solids, which is spread evenly across the electromagnetic spectrum. The radiation emissions of these gases were important because they showed that at least under some circumstances, the orbits of the electrons could not be at just any distance from the nucleus, but were confined to discrete distances (or* energy states*).*

Fig. 4-3: A. Continuous spectrum and B. line spectrum of hydrogen [3]

Niels Bohr

If the electrons in these gases were free to orbit at any distance, then the light emitted from them would have been spread evenly across the electromagnetic spectrum. Instead, what experimenters saw was that the light from these gases showed a distinct *line pattern*. That is to say that the light being emitted was only seen in a certain set of wavelengths, with empty spaces in between.

These line-spectra were different for each gas, and was found to be the characteristic of its atom. Today, astronomers use line-spectra to detect the elements present in stars.

Bohr's Explanation

Niels Bohr quickly seized upon this problem and used it to propose a *quantised* description of the atom.

1. Bohr proposed that while circling the nucleus of the atom, electrons could only occupy certain *discrete* orbits, that is to say energy levels [**2**]. Bohr used Max Planck's equations describing quanta of radiation to determine what these discrete orbits would have to be. *As long as electrons stay in these energy levels, they are stable.*
2. Further, Bohr said electrons give or take energy only when they change their energy levels. If they move up, they *take* energy (say from light), and if they move down, they *release* energy. This energy itself is released in discrete packets called *photons*, which were introduced in the previous chapter.
3. Furthermore, Bohr also said that an electron which is not in its native energy level (in other words, which has been *excited* to a higher energy level) *always* has to fall back to its original, stable level.

Bohr interpreted the lines in the spectra of gases as formed by the *transitions* of electrons to and from various energy-levels. This has been verified thoroughly with the hydrogen atom, *and found to be correct*. Bohr's formulae agreed excellently with observed line positions.

Niels Bohr (1885 – 1962) was born and educated in Copenhagen, Denmark. He lived, worked, and died there, too. But his mark on science and history was worldwide. His professional work and personal convictions were part of the larger stories of the century. At the University of Copenhagen, he studied physics and played soccer (though not as well as his brother, who helped the 1908 Danish soccer team win an Olympic silver medal). After receiving his doctorate in 1911, Bohr traveled to England on a study grant and worked under J.J. Thomson, who had discovered the electron 15 years earlier.

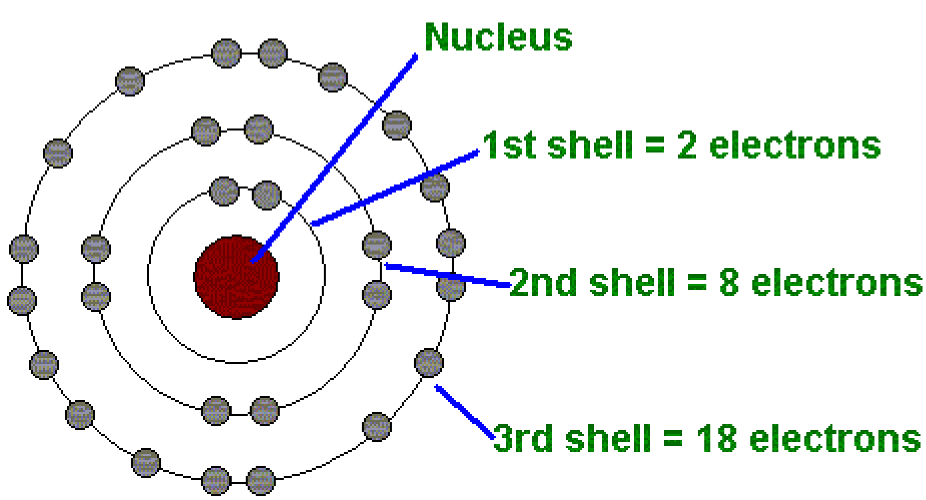
Bohr began to work on the problem of the atom's structure. Ernest Rutherford had recently suggested the atom had a miniature, dense nucleus surrounded by a cloud of nearly weightless electrons. There were a few problems with the model, however. For example, according to classical physics, the electrons orbiting the nucleus should lose energy until they spiral down into the center, collapsing the atom. Bohr proposed adding to the model the new idea of quanta put forth by Max Planck in 1901. That way, electrons existed at set levels of energy, that is, at fixed distances from the nucleus. If the atom absorbed energy, the electron jumped to a level further from the nucleus; if it radiated energy, it fell to a level closer to the nucleus. His model was a huge leap forward in making theory fit the experimental evidence that other physicists had found over the years. A few inaccuracies remained to be ironed out by others over the next few years, but his essential idea was proved correct. He received the Nobel Prize for this work in 1922, and it's what he's most famous for. But he was only 37 at the time, and he didn't stop there. Among other things, he put forth the theory of the nucleus as a liquid drop, and the idea of "complementarity" -- that things may have a dual nature (as the electron is both particle and wave) but we can only experience one aspect at a time.

In 1912 Bohr married Margrethe Nørlund. They had six sons, one of whom, Aage, followed his father into physics -- and into the ranks of Nobel Prize-winners. Bohr returned to Denmark as a professor at the University of Copenhagen, and in 1920 founded the Institute for Theoretical Physics -- sponsored by the Carlsberg brewery! Bohr remained director of the institute for the rest of his life, except for his absence during World War II. Bohr's personal warmth, good humor ("Never express yourself more clearly than you can think," he once said), and hospitality combined with world events to make Copenhagen a refuge for many of the century's greatest physicists.

After Hitler took power in Germany, Bohr was deeply concerned for his colleagues there, and offered a place for many escaping Jewish scientists to live and work. He later donated his gold Nobel medal to the Finnish war effort. In 1939 Bohr visited the United States with the news from Lise Meitner (who had escaped German-occupied Austria) that German scientists were working on splitting the atom. This spurred the United States to launch the Manhattan Project to develop the atomic bomb. Shortly after Bohr's return home, the German army occupied Denmark. Three years later Bohr's family fled to Sweden in a fishing boat. Then Bohr and his son Aage left Sweden traveling in the empty bomb rack of a British military plane. They ultimately went to the United States, where both joined the government's team of physicists working on atomic bomb at Los Alamos. Bohr had qualms about the consequences of the bomb. He angered Winston Churchill by wanting to share information with the Soviet Union and supporting postwar arms control. Bohr went on to organize the Atoms for Peace Conference in Geneva in 1955.

In addition to his major contributions to theoretical physics, Bohr was an excellent administrator. The institute he headed is now named for him, and he helped found CERN, Europe's great particle accelerator and research station. He died at home in 1962, following a stroke.

"An expert is a man who has made all the mistakes which can be made, in a very narrow field."



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James Chadwick

The neutron. One final problem remained. In the Bohr model, there must be an equal number of protons and electrons. This balance is the only way to be sure that an atom is electrically neutral, which we know to be the case for all atoms. But if one adds up the mass (total amount of matter) of all the protons and electrons in an atom, the total comes no where near the actual mass of an atom. Where then is the remaining mass? It turned out to be in a still yet to be discovered particle, the neutron.

The solution to this problem was suggested by English physicist James Chadwick (1891–1974) in 1932. The reason for mass differences, Chadwick found, was that the nuclei of atoms contain a particle with no electric charge. He called this particle a neutron. The neutron had likely evaded discovery up until this point, because of its lack of charge, it was hard to detect.

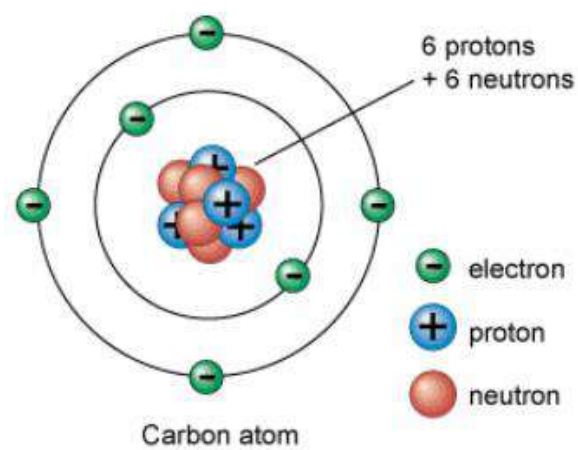
Chadwick's discovery resulted in a model of the atom that is fairly easy to understand. The core of the atom is the atomic nucleus, in which are found one or more protons and neutrons. Outside the nucleus are electrons traveling in discrete orbits.

Modern theories

This model of the atom can be used to explain many of the ideas in chemistry in which many people are interested. But the model has not been used by chemists themselves for many decades. The reason for this difference is that revolutionary changes occurred in physics during the 1920s. These changes included the rise of relativity, quantum theory, and uncertainty that forced chemists to rethink the most basic concepts about atoms.

As an example, the ***principle of uncertainty*** says that it is impossible to describe with perfect accuracy both the position and the motion of an object. In other words, you might be able to say very accurately, where an electron is located in an atom, but to do so reduces the accuracy with which you can describe its motion.

By the end of the 1920s, chemists had begun to look for new ways to describe the atom that would incorporate the new discoveries in physics. One step in this direction was to rely less on physical models and more on mathematical models. That is, chemists began to give up on the idea of an electron as a tiny particle carrying an electrical charge traveling in a certain direction with a certain speed in a certain part of an atom. Instead, they began to look for mathematical equations which, when solved, gave the correct answers for the charge, mass, speed, spin, and other properties of electrons were known to have.



Chadwick's Model

Mathematical models of the atom are often very difficult to understand, but they are enormously useful and successful for professional chemists. The clues they have given about the ultimate structure of matter have led not only to a better understanding of atoms themselves, but also to the development of countless innovative new products in our daily lives.

Chadwick discovers the neutron 1932

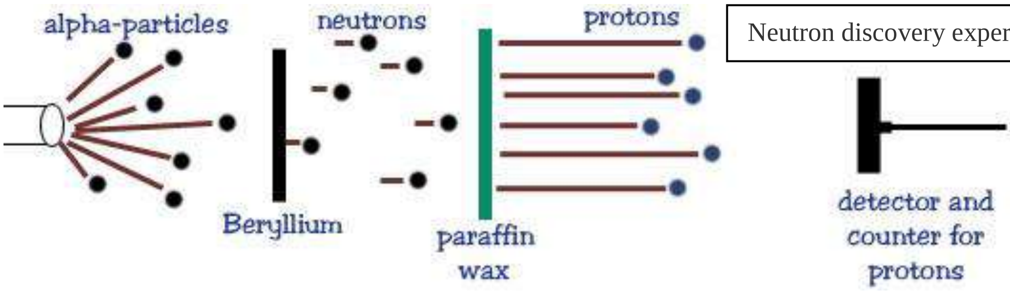
For four years, James Chadwick was a prisoner of war in Germany. When World War I ended, he returned to his native England to rejoin the mentor of his undergraduate days, Ernest Rutherford. Now head of Cambridge University's nuclear physics lab, Rutherford oversaw Chadwick's PhD in 1921 and then made him assistant director of the lab.

Chadwick's own research focused on radioactivity. In 1919 Rutherford had discovered the proton, a positively charged particle within the atom's nucleus. But they and other researchers were finding that the proton did not seem to be the only particle in the nucleus.

As they studied atomic disintegration (*atoms breaking down*), they kept seeing that the atomic number (number of protons in the nucleus, was equal to the positive charge of the atom and was less than the atomic mass (average mass of the atom). For example, a helium atom has an atomic mass of **4**, but an atomic number (or positive charge) of **2**. How could this be? Since electrons have almost no mass, it seemed that something besides the protons in the nucleus were adding to the mass. One leading explanation for the hidden mass of the atom was that there were electrons and additional protons in the nucleus as well still unaccounted for. If the protons were bound up with additional electrons, their charges would cancel and perhaps they would stay hidden from detection. So in the helium example, there would be four protons and two electrons in the nucleus to yield a mass of 4 but a charge of only 2. Rutherford also put out the idea that there could be a particle with mass but no charge yet to be discovered. He called it a neutron, and imagined it as a paired proton and electron. There was no evidence for any of these ideas yet however.

Chadwick kept the problem in the back of his mind while working on other things. Experiments in Europe caught his eye, especially those of Frederic and Irene Joliot-Curie. They used a different method for tracking particle radiation. Chadwick repeated their experiments but with the goal of looking for a neutral particle -- one with the same mass as a proton, but with zero charge. His experiments were successful. He was able to determine that the neutron did exist and that its mass was nearly equal to a proton's. He published his findings with characteristic modesty in a first paper entitled "Possible Existence of Neutron." In 1935 he received the Nobel Prize for his discovery.

His findings were quickly accepted. Werner Heisenberg then showed that the neutron could not be a proton-electron pairing, as suggest by Rutherford but rather its own unique particle. This new idea dramatically changed the picture of the atom and accelerated discoveries in atomic physics. Physicists soon found that the neutron made an ideal "bullet" for bombarding other nuclei. Unlike charged particles, it was not repelled by similarly-charged particles (negative repel other negatives. It could smash right into the nucleus of an atom. Before long, neutron bombardment was applied to the uranium atom, splitting its nucleus and releasing the huge amounts of energy predicted by Einstein's equation $E = mc^2$.



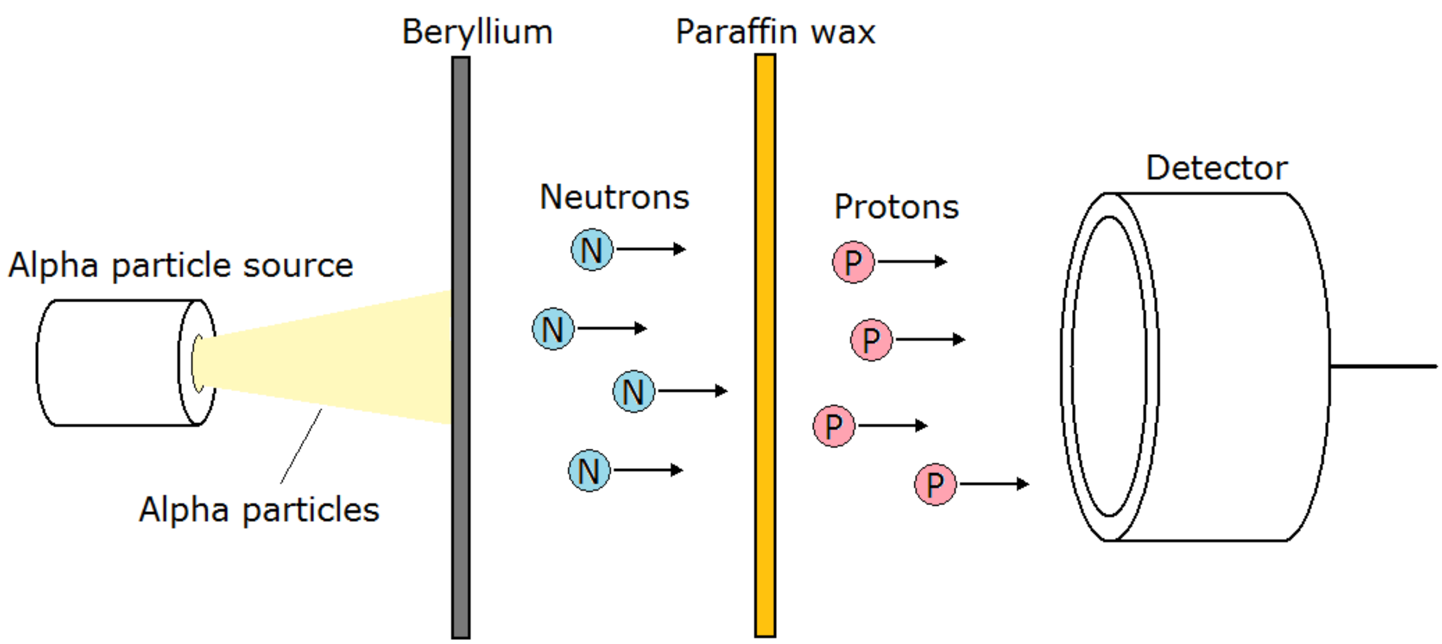
Neutron discovery experiment

Chadwick cont.

In 1920, Ernest Rutherford hypothesized that there were neutral, massive particles in the nucleus of atoms. This conclusion came from the difference between an element's atomic number (protons = electrons) and its atomic mass (usually found to be far greater than the mass of the known protons present). James Chadwick was assigned the task of tracking down evidence of Rutherford's tightly bound "proton-electron pair" or neutron. We know now a neutron is not a bound pair and that the unaccounted for mass was simply unseen yet to be discovered neutron all along.

In 1930 it was discovered that Beryllium, when bombarded by alpha particles, emitted a very energetic stream of radiation. This stream was originally thought to be gamma radiation. However, further investigations into the properties of the radiation revealed contradictory results. Like gamma rays, these rays were extremely penetrating and since they were not deflected while passing through a magnetic field, like an electron or proton would be due to their charge, Chadwick realized they had to be neutral.

One of the experiments that led Chadwick to these conclusions was not his own. Madam Marie Curie the scientist that discovered radiation had a daughter name Irene Curie. Irene and her husband discovered that when a beam of this radiation hit a substance rich in protons, for example paraffin, protons were knocked loose which could be easily detected by a Geiger counter (detector).



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PEOPLE AND DISCOVERIES

A SCIENCE ODYSSEY

Werner Heisenberg's high school years were interrupted by World War I, when he had to leave school to help harvest crops in Bavaria. Back in Munich after the war, he volunteered as a messenger for democratic socialist forces that fought and ousted the communist government that had taken control of the Bavarian state. He was involved in youth groups trying to rebuild German society out of the ashes of World War I, including the "New Boy Scouts" which hoped to renew German life through direct experience of nature, Romantic poetry, music, and thought.

An unusual start for a great contributor to twentieth-century physics. In 1920 he entered the University of Munich to pursue a degree in math. But the math professor wouldn't allow him into an advanced seminar, so he quit. He transferred to physics. He immediately took an interest in theoretical physicists, and soon met many scientists whose work would dominate the coming decades, including Niels Bohr. One of his chief interests was working out problems involved in the Bohr-Rutherford model of the atom. He just barely received his PhD in 1923 -- nearly failing because he had neglected his laboratory work. His advisor argued on his behalf and he was granted the degree. He became a professor at the University of Gottingen at age 22. Because he suffered from severe seasonal allergies, during pollen season he left Bavaria for the island of Heligoland. While there he had time to think and work out problems with the atomic model. He realized the limitations of visual models and suggested working strictly with experimental data and mathematical results. To do this he applied a mathematical system to atomic physics, called matrix mechanics. It was a turning point for physics. Many in the field disliked it because it didn't provide a physical model to relate to. Erwin Schrödinger came up with the theory of wave mechanics about a year later. Those uncomfortable with Heisenberg's system jumped on the wave mechanics side. The conflict between the theories was resolved when Schrödinger proved that they were, in fact, identical.

In 1926 Heisenberg joined Bohr at the Institute for Theoretical Physics in Copenhagen. This turned out to be one of the most productive periods in Heisenberg's life. In 1927 he was puzzling over the basic quantum properties of electrons. He realized that the act of measuring an electron's properties by hitting it with gamma rays would alter the electron's behavior. Indeed, you could measure the position of an electron (or other particle) OR you could measure its momentum. But the more precisely you measure one property, the more you throw the other off. He tied this up in an equation using Planck's constant, and called it the ***uncertainty principle***. While many resisted this idea, it eventually became accepted as a fundamental law of nature.

Later in 1927 Heisenberg returned to Germany and became the youngest full professor in the country. With the political turmoil in Germany and World War II, Heisenberg's life became complicated. There was a mass exodus of German scientists in the 1930s, but Heisenberg was one of the few top-notch scientists who decided to remain. Along with Max Planck, he expressed hope of being able to preserve Germany's scientific traditions and institutions. At first he and others tried to resist Hitler's efforts to "purify" science and academics, but soon the Nazis controlled the universities. His own position was shaky since the Nazis viewed theoretical physics as

"Jewish" and suspect. Efforts to promote him met with violent opposition from political leaders and even some colleagues. There were times his personal safety was uncertain.

But as the war began the government recognized, suspect or not, the importance of Heisenberg's knowledge. He was made director of the German atom bomb project. He spent five years working on it.

At war's end, Heisenberg was captured by the Allies and was imprisoned in England for six months. He was released and returned to Germany where he reestablished the Kaiser Wilhelm Institute for Physics, but renamed it the Max Planck Institute, in honor of his friend and colleague. He held many administrative posts in West Germany and represented his country at international meetings. He retired in 1970, and died in 1976 survived by his wife of 39 years and seven children.

"Natural science does not simply describe and explain nature; it is part of the interplay between nature and ourselves; it describes nature as exposed to our method of questioning."

Heisenberg states the uncertainty principle
1927

PEOPLE AND DISCOVERIES

A SCIENCE ODYSSEY

In 1927, Werner Heisenberg was in Denmark working at Niels Bohr's research institute in Copenhagen. The two scientists worked closely on theoretical investigations into quantum theory and the nature of physics. Bohr was away on a skiing holiday, and Heisenberg was left to mull things over himself. He had a shocking but clear realization about the limits of physical knowledge: the act of observing alters the reality being observed. At least at the subatomic level. To measure the properties of a particle such as an electron, one needs to use a measuring device, usually light or radiation. But the energy in this radiation affects the particle being observed. If you adjust the light beam to accurately measure position, you need a short-wavelength, high-energy beam. It would tell you position, but its energy would throw off the momentum of the particle. Then, if you adjust the beam to a longer wavelength and lower energy, you could more closely measure momentum, but position would be inaccurate.

This principle punctured the centuries-old, firmly held belief that the universe and everything in it operates like clockwork. To predict the workings of the "clock," one needs to measure its qualities and parts at a specific point in time. Classical physics assumed that the precision of measuring is theoretically unlimited. But Heisenberg stated that since you could never with great certainty measure more than one property of a particle, you could only work with probability and mathematical formulations. (Heisenberg called this matrix mechanics, soon shown to be equivalent to Erwin Schrödinger's more visualizable wave theory.)

The uncertainty principle was hard even for scientists to accept at first. After struggling with it, however, Bohr developed complementarity theory. This stated that there was a dual nature to things -- an electron was a wave *and* a particle, for example -- but we could only perceive one side of that dual nature. A sphere, for instance, has a convex and concave aspect. We can sense the convex from outside the sphere, but from inside it appears completely concave. This theory would affect much more than physics, but other fields of science, as well as art and philosophy. It is often referred to as the particle-wave duality theory.

Heisenberg and Bohr's theories were compatible and became known together as the Copenhagen interpretation and accepted as the foundation for quantum theory.

From the New York Times, September 2, 1927

DETAILS CONCEPTS OF QUANTUM THEORY

By Waldemar Kaemppfert

 By Wireless to The New York Times.

LEEDS, England, Sept. 1. -- Of thirty addresses delivered today before the various sections of the British Association for the Advancement of Science, one of the most important was that of a young German, Dr. W. Heisenberg. Fully 200 mathematical physicists listened to his brief exposition of a conception which will make it necessary to modify belief in what we are pleased to call "common sense" and "reality."

The layman without knowledge of higher mathematics, listening to Dr. Heisenberg and those who discussed his conclusions, would have decided that this particular section of the British Association is composed of quiet and polite but determined lunatics, who have created a wholly illusory mathematical world of their own. ...

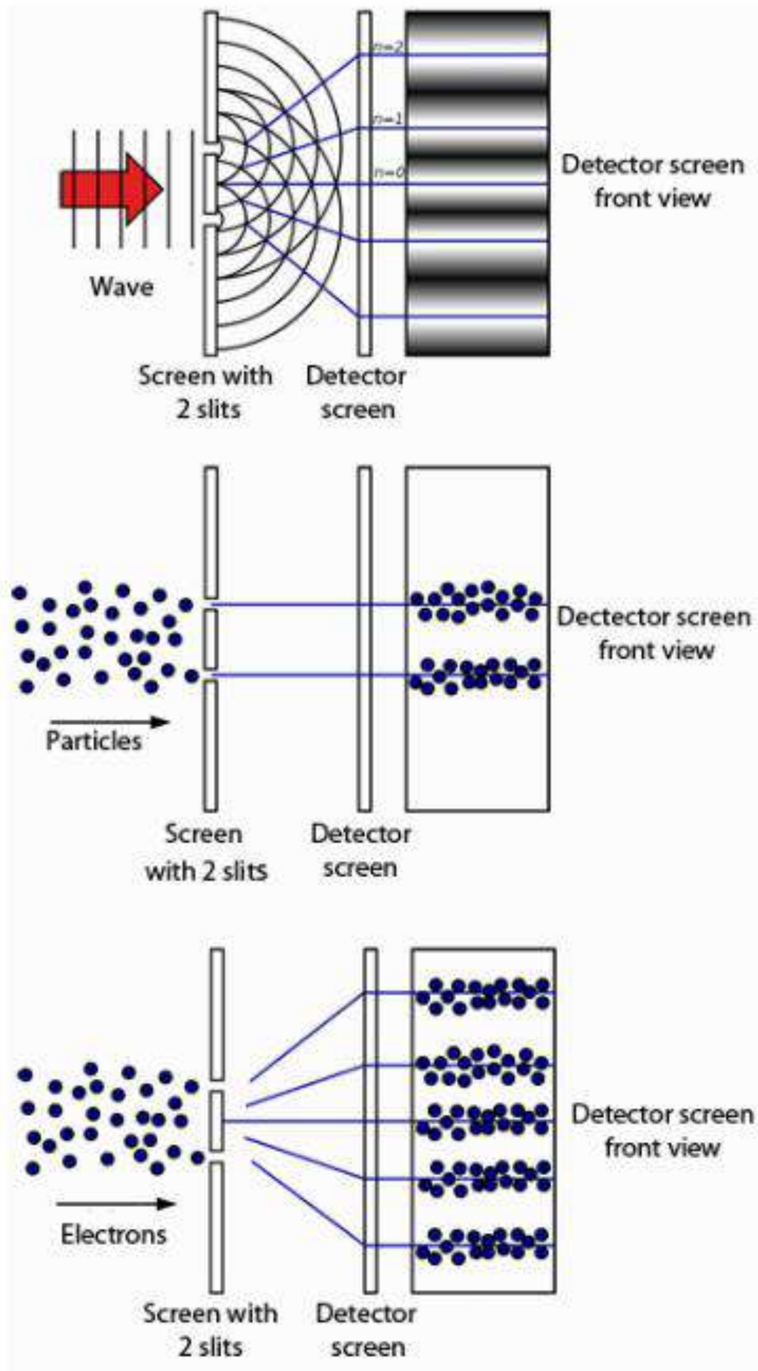
To explain the quantum theory and its modification by Dr. Heisenberg and others is even more difficult than explaining relativity. It is much like trying to tell an Eskimo what the French language is like without talking French. In other words, the theory cannot be expressed pictorially and mere words mean nothing. One is dealing with something that can be expressed only mathematically.

The consequences, however, are startling. Electrons and atoms cease to have any reality as things that can be detected by the senses directly or indirectly. Yet we are convinced the world is composed of them.

In the new mathematical universe events are more important than substances, and energy more important than matter. Any mental picture you have of objects moving through space gets thrown into confusion. So simple a conception as a baseball flying from the pitcher to the batter turns out to be obscure, doubtful and even ridiculous.

Planck, the originator of the quantum theory, Heisenberg, Schrödinger, and De Broglie have shown that the whole science of mechanics must be rewritten. And when it is rewritten, no one but a mathematician will be able to understand it. The scientific world is faced with an upheaval as great as that brought about by Einstein.

The double slit experiment. Particle-wave duality



The double slit experiment: The top picture shows the interference pattern created by waves passing though the slits, the middle picture shows what you'd expect to see when particles are fired through the slits, and the bottom picture shows what actually happens when you fire particles such as electrons through the slits: you get the interference pattern you expect from waves, but the electrons are registered as arriving as particles.

PEOPLE AND DISCOVERIES

Max Planck
1858 - 1947

A SCIENCE ODYSSEY

Max Planck was told that there was nothing new to be discovered in physics. He was about to embark on a career in physics that would turn that idea upside down.

As a young student Planck had shown great promise in music, but a remarkable mathematics teacher turned his interest toward science. After gaining degrees from the Universities of Berlin and Munich, he focused on thermodynamics (the study of heat and energy). He was especially interested in the nature of radiation from hot materials. In 1901 he devised a theory that perfectly described the experimental evidence, but part of it was a radical new idea: energy did not flow in a steady continuum, but was delivered in discrete packets Planck later called quanta. That explained why, for example, a hot iron poker glows distinctly red and white. Planck, a conservative man, was not trying to revolutionize physics at all, just to explain the particular phenomenon he was studying. He had tried to reconcile the facts with classical physics, but that hadn't worked. In fact, when people refer to "classical physics" today, they mean "before Planck." He didn't fully appreciate the revolution he had started, but in the years that followed, scientists such as Albert Einstein, Niels Bohr, and Werner Heisenberg shaped modern physics by applying his elegantly simple, catalytic new idea.

Planck was an extremely successful physicist, receiving the Nobel Prize in 1919, but his personal life was marked by tragedy. He and his first wife Marie Merck had two sons and twin daughters; Marie died after 23 years of marriage. He remarried and had one more son. Planck's eldest son was killed during World War I, and both daughters died in childbirth. In 1944 his second son was executed for involvement in a plot to assassinate Hitler. Planck himself openly opposed Nazi persecutions and intervened on behalf of Jewish scientists. He praised Einstein in contradiction to the Nazis, who denounced Einstein and his work. He even met with Hitler to try to stop actions against Jewish scientists, but the chancellor went on a tirade about Jews in general and disregarded him. Planck, who had been president of the Kaiser Wilhelm Institute since 1930, resigned his post in 1937 in protest. After the war, the research center was renamed the Max Planck Institute and he was appointed its head.

"A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

Planck discovers the quantum nature of energy
1900

A SCIENCE ODYSSEY

In 1899 Max Planck became a professor at the University of Berlin, after nine years at the University of Munich and Kiel University, in Germany. In his research there, he turned to a thermodynamic problem raised by one of his old teachers. The problem was that of a "black body," something that absorbs all frequencies (or wavelengths) of light. When heated it should then radiate all frequencies of light equally -- theoretically. But the distribution of energy radiated in "real life" never matched up with the predictions of classical physics. Several distinguished physicists had created complex equations trying to work it out, but none solved the problem.

Planck was as steeped in traditional physics as his colleagues, but he had an open mind. The older way wasn't working. So he changed one basic assumption: energy, instead of being continuous, comes in distinct particles. These were later called "quanta," from the Latin for "how much?" Though it sounded outlandish, applying this idea to the problem of heated bodies revealed a simple relationship that explained previous puzzles. Planck found that the energy radiated from a heated body is exactly proportional to the wavelength of its radiation. So, a black body would *not* radiate all frequencies equally. As temperature goes up, energy increases and it's more likely that quanta with higher energy will be radiated. So, as an object heats up, the light given off is orange, then yellow, and eventually bluish. The wavelength emitted is a function of the energy times a constant (h), now known as Planck's constant. Though Planck's idea was not immediately believed by most physicists, it is now accepted as one of the fundamental constants in the universe. In fact, Planck himself wasn't sure if it was more than a little mathematics that resolved his own particular problem.

In 1905, Albert Einstein used the theory of quanta to accurately describe the photoelectric effect. In 1913, Niels Bohr incorporated Planck's idea into his revision of model of the atom, resolving inconsistencies that classical physics could not.

Murray Gell-Mann 1929 -

Photo courtesy of AIP Emilio Segre Visual Archives

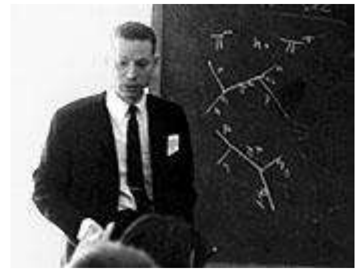
Murray Gell-Mann started early. He entered Yale University at age 15. After receiving his B.S. there, he worked with Enrico Fermi at the University of Chicago. He obtained his PhD from MIT and in 1955 married archaeologist J. Margaret Dow. He has been a professor of physics and theoretical physics at California Institute of Technology for much of his career.

During the 1950s, discoveries of new subatomic particles were proliferating so quickly such that scientists spoke of a "particle zoo." Gell-Mann turned his attention to some particles that behaved particularly strangely. He proposed a new quantum property of particles he called the "strangeness number." While studying particles, he found even more general characteristics that allowed him to sort them into eight "families." He called this grouping the eightfold way, referring to Buddhist philosophy's eight attributes of right living. Then he found that the eightfold way could really best be explained by a particle, undiscovered as yet, that had three parts (hadrons), each holding a fraction of a charge. He called them "quarks" with a nod to James Joyce, whose novel *Finnegan's Wake* contains the passage: "Three quarks for Muster Mark!" Fractional charge seemed an outrageous suggestion at first, but proof came for his theoretical quarks in 1974.

The names alone that Gell-Mann applies to his new theories and formulations reflect his sense of humor, immensely broad range of interests, and deep understanding. The theories themselves say that much more. A colleague once said, "Murray has no particular talent for physics, but he's so smart he's a great physicist anyway." His main avocational interest is historical linguistics, and hiking, camping, and bird-watching take up his time outside the lab. In fact in 1969, the same year he won the Nobel Prize in physics, Gell-Mann helped organize an environmental studies program sponsored by the National Academy of Sciences.

Steven Weinberg
1933 -

Photo by Mitchel Valentine, courtesy of AIP Emilio Segre Visual Archives



Steven Weinberg grew up in New York City, where his father worked as a court stenographer. His early interest in science was encouraged by his family and by his teachers at the Bronx High School of Science. One of his classmates there was Sheldon Glashow; about 25 years later they would share the Nobel Prize in physics.

By age 16, theoretical physics had grabbed Weinberg. He went to Cornell University (as did Glashow!), studied at the Niels Bohr Institute in Denmark, and got his PhD from Princeton. He embarked on a career of research and teaching that took him to some of the best centers for physics research in the country: Columbia, Berkeley, MIT, and Harvard. He is now a professor in the physics and astronomy departments at the University of Texas at Austin. His scientific interests were always broad, but his most noted work has been in unified field theory. Four forces were believed to drive the laws of physics: gravity, electromagnetism, the strong force (which holds an atom's nucleus together), and the weak force (which breaks an atom apart, as in radioactivity). Around 1967, Weinberg theorized that the electromagnetic and the weak forces are the same at extremely high energy levels. This electroweak theory was confirmed by particle accelerator experiments in 1973. This was one giant step closer to physicists' long-dreamed of goal of finding a single elegant equation to explain all the matter and forces in nature. Weinberg and others who worked on this theory, Sheldon Glashow and Abdus Salam, were awared the Nobel Prize in 1979.

"The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy."

A SCIENCE ODYSSEY

PEOPLE AND DISCOVERIES

Rutherford and Bohr describe atomic structure

1913

Photo: Niels Bohr's research notes for his new atomic theory

In 1911, Niels Bohr earned his PhD in Denmark with a dissertation on the electron theory of metals. Right afterwards, he went to England to study with J.J. Thomson, who had discovered the electron in 1897. Most physicists in the early years of the twentieth century were engrossed by the electron, such a new and fascinating discovery. Few concerned themselves much with the work of Max Planck or Albert Einstein. Thomson wasn't that interested in these new ideas, but Bohr had an open mind. Bohr soon went to visit Ernest Rutherford (a former student of Thomson's) in another part of England, where Rutherford had made a brand-new discovery about the atom.

Rutherford's find came from a very strange experience. Everyone at that time imagined the atom as a "plum pudding." That is, it was roughly the same consistency throughout, with negatively-charged electrons scattered about in it like raisins in a pudding. As part of an experiment with x-rays in 1909, Rutherford was shooting a beam of alpha particles (or alpha rays, emitted by the radioactive element radium) at a sheet of gold foil only 1/3000 of an inch thick, and tracing the particles' paths. Most of the particles went right through the foil, which would be expected if the atoms in the gold were like a plum pudding. But every now and then, a particle bounced back as though it had hit something solid. After tracing many particles and examining the patterns, Rutherford deduced that the atom must have nearly all its mass, and positive charge, in a central nucleus about 10,000 times smaller than the atom itself. All of the negative charge was held in the electrons, which must orbit the dense nucleus like planets around the sun.

In 1912 Bohr joined Rutherford. He realized that Rutherford's model wasn't quite right. By all rules of classical physics, it should be very unstable. For one thing, the orbiting electrons should give off energy and eventually spiral down into the nucleus, making the atom collapse. Or the electrons could be knocked out of position if a charged particle passed by. Bohr turned to Planck's quantum theory to explain the stability of most atoms. He found that the ratio of energy in electrons and the frequency of their orbits around the nucleus was equal to Planck's constant (the proportion of light's energy to its wave frequency, or approximately 6.626×10^{-23}). Bohr suggested the revolutionary idea that electrons "jump" between energy levels (orbits) in a quantum fashion, that is, without ever existing in an in-between state. Thus when an atom absorbs or gives off energy (as in light or heat), the electron jumps to higher or lower orbits. Bohr published these ideas in 1913 to mixed reaction. Many people still hadn't accepted the idea of quanta, or they found other flaws in the theory because Bohr had based it on very simple atoms. But there was good evidence he was right: the electrons in his model lined up with the regular patterns (spectral series) of light emitted by real hydrogen atoms.

Bohr's theory that electrons existed in set orbits around the nucleus was the key to the periodic repetition of properties of the elements. The shells in which electrons orbit have different quantum numbers and hold only certain numbers of electrons -- the first shell holds no more than 2, the second shell up to 8, the third 10, the fourth 14. Atoms with less than the maximum number in their outer shells are less stable than those with "full" outer shells. Elements that have the same number of electrons in their outermost shells appear in the same column in the periodic table of elements and tend to have similar chemical properties.

Over the years other investigators refined Bohr's theory, but his bold application of new ideas paved the way for the development of quantum mechanics. Bohr went on to make enormous contributions to physics and, like Rutherford, to train a new generation of physicists. But his atomic model remains the best known work of a very long career.