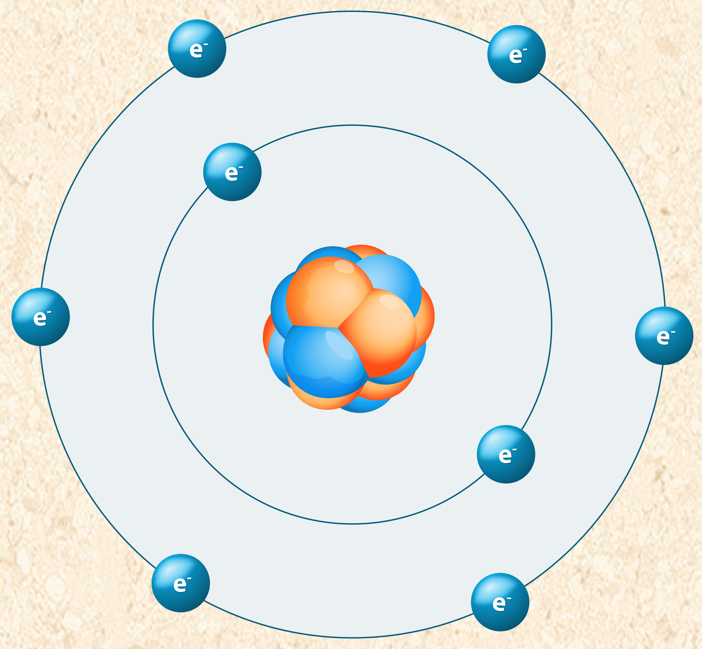
MODULE V. 1870-1930

THE ATOM

In the 1860s, the equations that describe electricity and magnetism were written down by Scottish physicist James Clerk Maxwell. These summarized more than a century of investigation in Europe. Most importantly, it was clear from the equations that electromagnetic waves could be generated and propagated. These were first demonstrated experimentally by Heinrich Hertz in the late 1880s. This was the birth of our modern technological society based on Wi-Fi, cellphones and GPS.

NIELS BOHR (1885-1962)

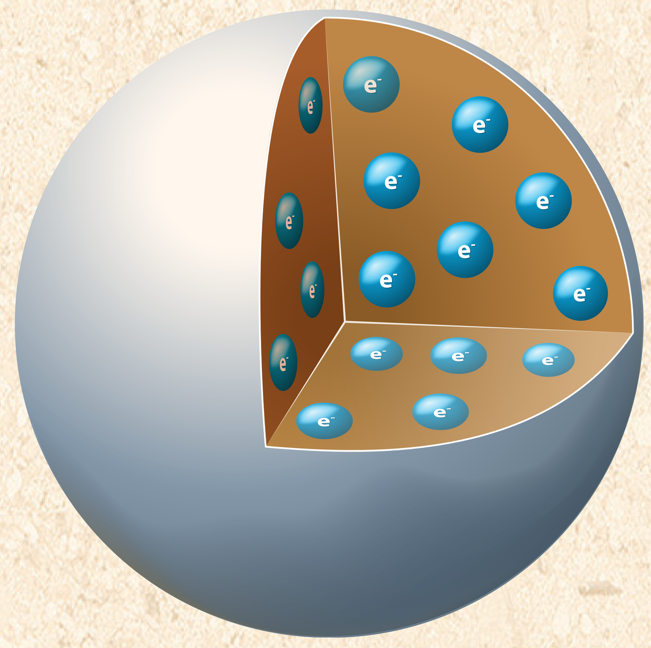
was a Danish physicist in 1913 who proposed his model of the atom. A radical departure from earlier, classical descriptions, it was the first that incorporated quantum theory and was the predecessor of wholly quantum-mechanical models. The Bohr model and all its successors describe the properties of atomic electrons in terms of a set of allowed, discrete values. Atoms absorb or emit radiation only when the electrons abruptly jump between allowed, or stationary, states. Direct experimental evidence for the existence of such discrete states was obtained in 1914 by the Germanborn physicists James Franck and Gustav Hertz. A success of the Bohr model was its ability to explain the spectral lines of the hydrogen atom as illustrated at right. When electrons jump from one orbit to another, they gain or lose energy by specific amounts. Thus, the visible spectral lines are the result of electrons losing energy when transitioning between orbits. The Bohr theory predicted the simple formulae that had been developed previously from data. This was a major milestone in explaining the spectral lines in terms of a quantum theory of the atom. However, the number of lines observed experimentally was mysteriously double what was predicted by the Bohr theory.



BOHR MODEL OF THE ATOM

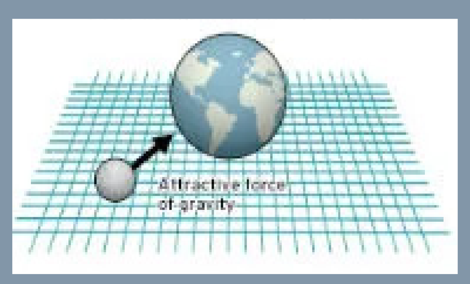
INITIAL STEPS TOWARD THE STRUCTURE OF THE ATOM

During the 1880s and '90s, scientists studied streams of discharge, called cathode rays, for the carrier of the electrical properties in matter. Their work culminated in the discovery of the electron by English physicist J.J. Thomson in 1897. The existence of the electron showed that the 2,000-year-old concept of the atom as a homogeneous particle was wrong and that, in fact, the atom has a complex structure. In 1904, Thomson published his plum pudding model of the atom: "the atoms of the elements consist of a number of negatively electrified corpuscles enclosed in a sphere of uniform positive electrification." The plum pudding model usefully guided Thomson's student, Ernest Rutherford, to devise experiments to further explore the composition of atoms.

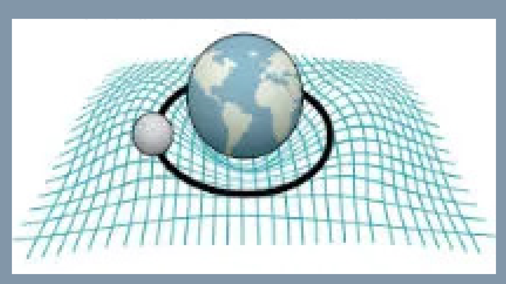


PLUM PUDDING MODEL OF THE ATOM

NEWTON'S THEORY OF GRAVITY VERSUS EINSTEIN'S



To Newton, space and time were fixed and gravity was a force pulling objects together.



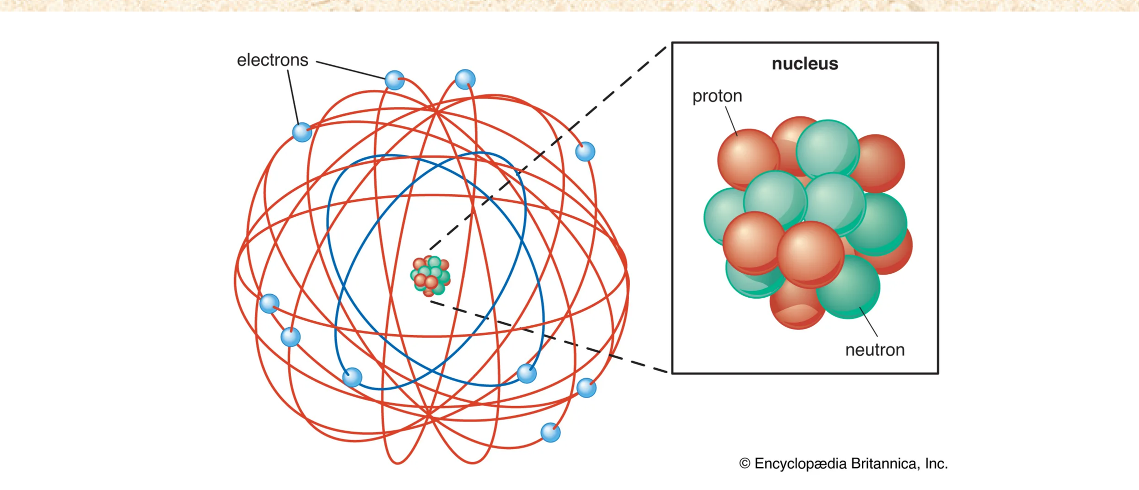
Einstein determined that space and time are like a fabric and massive objects can warp space-time.

PARTICLES MOVING CLOSE TO THE SPEED OF LIGHT

In 1905, Albert Einstein developed a theory of how the laws of physics depend on moving reference frames. In particular, his theory considered particles that move with velocities close to the speed of light. He concluded that the speed of light in vacuum is the same for all observers, regardless of the motion of light source or observer. This theory was a profound modification of Newton's laws, which had stood since the 17th century; was universally accepted within a short amount of time; and was an essential element of all subsequent models and theories.

MODIFICATION OF NEWTON'S LAW OF UNIVERSAL GRAVITATION

By the beginning of the 20th century, Newton's law of universal gravitation had been accepted for more than 200 years as a valid description of the gravitational force between masses. In Newton's model, gravity is the result of an attractive force between massive objects. Although even Newton was troubled by the unknown nature of that force, the basic framework was extremely successful at describing motion. In 1915, Albert Einstein published a new theory of gravitation based on the warping of space and time due to the presence of mass. Experiments and observations show that Einstein's description of gravitation accounts for several effects that are unexplained by Newton's law, such as minute anomalies in the orbits of Mercury and other planets. General relativity also predicts novel effects of gravity, such as gravitational waves, gravitational lensing, and an effect of gravity on time known as gravitational time dilation. Many of these predictions have been confirmed by experiment or observation, most recently gravitational waves in 2015.



RUTHERFORD MODEL OF THE ATOM

DISCOVERY OF THE NUCLEUS

In a series of experiments involving the scattering of charged particles from a thin gold foil, performed by undergraduate Ernest Marsden under the direction of Rutherford and German physicist Hans Geiger in 1909, the atom was found to contain a small, dense core, called the nucleus. Thus, the Rutherford model of the atom, also called the Rutherford atomic model, nuclear atom, or planetary model of the atom proposed by Rutherford in 1911. The model described the atom as a tiny, dense, positively charged core called a nucleus, in which nearly all the mass is concentrated and around which the light, negatively charged electrons circulate at some distance, much like planets revolving around the sun. Rutherford's classical planetary model had a fundamental problem. The charged electrons, as they moved in closed orbits in the field of the nucleus, must radiate energy. Thus, eventually they would lose all their energy and the atom would collapse. This was a significant motivation to develop quantum mechanics.

Picture of the famous physicists Wolfgang Pauli (originator of the Pauli exclusion Principle) on the left and Niels Bohr (one of the originators of quantum mechanics) on the right studying a child's spinning top. The picture was taken at the opening of the new institute of physics at the University of Lund on May 31, 1951. Credit: Photograph by Erik Gustafson, courtesy AIP Emilio Segre Visual Archives, Margrethe Bohr Collection

THE QUANTUM WORLD STARTS TO REVEAL ITSELF

In 1900, Max Planck proposed that light with frequency ***v*** is emitted in quantized bundles of energy that come in integer multiples of the quantity ***hv***, where h is a tiny number known as Planck's constant. In 1905, Einstein stated that the quantization was in fact inherent to the light, and that the lumps can be interpreted as particles, which we now call *photons*. As we see above, Bohr's model in 1913 had atomic electrons in discrete, quantized states. In 1922, Otto Stern and Walther Gerlach carried out their famous experiment of passing a beam of silver atoms through an inhomogeneous magnetic field and observing a separation into two beams. At the time, the experiment was interpreted as a crucial validation of the Bohr theory over the classical theory of the atom. It showed clearly that spatial quantization exists, a phenomenon that can be accommodated only within a quantum mechanical theory. Spatial quantization is the basis of MRI, the laser, optical pumping, atomic clocks and the GPS. In 1924, Louis de Broglie proposed that all particles are associated with waves, where the frequency of the wave is given by the same relation we found above for photons, namely ***E = hv***. In 1925, Werner Heisenberg formulated a version of quantum mechanics based on matrices. In 1926, Erwin Schrödinger formulated a version of quantum mechanics that is based on waves. In 1926, Paul Dirac showed that Heisenberg's and Schrödinger's versions of quantum mechanics were equivalent. In 1928, Dirac derived a relativistic wave equation to describe the electron, which was valid for particles moving close to the speed of light, implicitly required the electron to have spin and implied the existence of the anti-electron, called the positron.

SPIN

The concept of spin originated in 1925 with young graduate students named Samuel Goudsmit and George Uhlenbeck in the group of Prof. Paul Ehrenfest at the University of Leiden in the Netherlands. Against the criticisms of renowned physicists, but with the firm support of Ehrenfest and Niels Bohr, Goudsmit and Uhlenbeck postulated that the electron had an intrinsic orbital angular momentum (i.e., spin of 1/2) to explain a mysterious doubling observed in the spectral lines of atoms. Ehrenfest is quoted by Uhlenbeck as saying: "This is a good idea. Your idea may be wrong, but since both of you are so young without any reputation, you would not lose anything by making a stupid mistake." In 1928, the English physicist Paul Dirac showed that spin was a natural consequence of a relativistic theory of the electron. Fully relativistic theories of the electron and a non-relativistic theory of the protons and neutrons in the nucleus were developed by 1950.

Created by: Rolf Ent and Richard Milner

Massachusetts Institute of Technology

Jefferson Lab