# A centennial of Rutherford's Atom

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On March 22, 2011, the New York Times published the article *"A Nucleated Century"* on its Editorial page, celebrating the hundredth anniversary of Rutherford's 1911 manuscript [23]. The quoted article read at the start: "*...If you asked someone to draw an atom, he or she would probably draw something like a cockeyed solar system (see figure 1). The sun  the nucleus  is at the center, and the planets  the electrons  orbit in several different planes. The critical discovery in this atomic model emerged a century ago in a talk before the Manchester Literary and Philosophical Society in March 1911 and a paper published soon after in the Philosophical Magazine. Both were by Ernest Rutherford, who had won the 1908 Nobel Prize in Chemistry in part for his discovery of the alpha particle, which he later proved was the nucleus of a helium atom...*". The title of New York Times editorial article emphasized the discovery of the nucleus of the atom, and the beginnings of Nuclear Physics, which is certainly a true fact. On the other hand, the 1911 article of Rutherford did much more than that, it gave rise to modern atomic physics and it contributed enormously to push the beginnings of Quantum Mechanics.

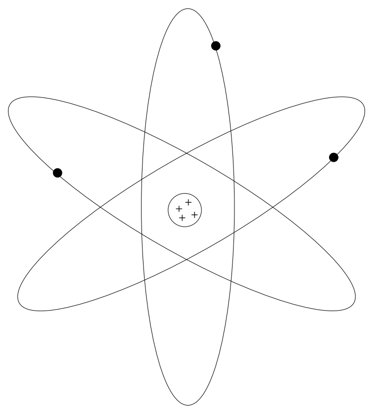

Figure 1

Although conceived more like a philosophical idea by Democritus of Abdera and others in Ancient Greece, the idea that matter is formed by atoms, was first used in Physics by Daniel Bernoulli at the beginning of the XVIIIth century to obtain from first principles in microscopic physics the law of ideal gases, giving birth to Kinetic Theory (later developed to full extent by Maxwell and Boltzmann in the XIXth century). The discovery of photosynthesis by Jan Ingenhousz and Joseph Priestley in 1779 [16] prompted the discovery of oxygen, the introduction of the idea of chemical elements by Lavoisier, and the foundations of *modern chemistry* by John Dalton [8]. By that time, the concept of atoms was taking a proper place in physics and chemistry, and these atoms were much more than just small bodies whose restless motion would explain thermodynamic quantities like temperature and pressure. They had a structure, they could combine to form molecules, and the rules for combination were laid down by Dalton.

During the XIXth century there were contributions from many people in different disciplines of physics that shed some light on the rich structure of the atom. In March of 1820 a crucial experiment of Hans Christian Oersted showed that Electricity and Magnetism were not independent phenomena [19], and that one could produce a magnetic field by driving a current through an electric circuit. Electromagnetism was born, and with it an extraordinary chain of pure and applied discoveries, including the first electric motors, which culminated in August of 1831, with the discovery of electromagnetic induction by Michael Faraday. A key figure of this period was Ampere who, among many contributions, introduced the idea of microscopic currents inside a metal to make the connection between Oersted's experiment and the properties of a magnet. The discovery of electrolysis by Humphry Davy, and the crucial observation by Michael Faraday that the amount of matter deposited on the cathodes of the electrolysis experiment is proportional to the total charge (current times time) applied to the electric terminals was the first experimental observation that electric charge in matter is quantized. In the meantime many key ideas were crystalizing in chemistry, among them, the introduction of the Avogadro number in 1811 [1] (i.e., when gaseous masses, at the same temperature and pressure, occupy equal volumes, they all contain the same number of molecules), the observation of Proust that the mass of any chemical element is an integer number times the mass of hydrogen, and the skilled accumulated work by many people on chemical reactions that lead D. Mendeleev to establish the Periodic Table of Chemical Elements in 1869.

It was clear from all the previous observations that atoms and molecules ought to have an internal structure, yet to be discovered, that could explain these experimental facts. Still a whole new set of experiments and ideas would enter into the picture and help understanding this internal structure. These came from studying the interaction of light with matter. Using the idea of Newton that light could be decomposed into different colors letting it pass a prism, Wollaston and Fraunhofer introduced the field of spectroscopy, and determined the typical emission lines of incandescent gases. Moreover, in 1859, Gustav Kirchhoff posed the problem of determining the spectral decomposition of light emitted by a heated body. And, in 1887, Heinrich Hertz [15] discovered the photoelectric effect, i.e., the emission of an electric spark by a metal plate when illuminated by visible or ultraviolet light. The intensity of this spark was larger, the higher the frequency of the incident light.

During the last decade of the XIXth century and the first one of the XXth century, the study of these three problems gave birth to the new Quantum Physics. In 1885, J. Balmer [2] classified the spectrum of Hydrogen in a simple phenomenological expression, which started to put some order in the huge experimental literature in atomic spectroscopy. By 1896, W. Wien, gave the first answer for the black body radiation [27], which reproduced appropriately the experimental data available at the time. However, better experimental results due to Kurlbaum, Pringsheim, and Rubens in 1900, showed small disagreements, at low frequencies, with Wien's theoretical results. In fact, for low frequencies, the experimental results were in agreement with, the then, recent results of Jeans and Rayleigh (based on the spectral asymptotics of the eigenfrequencies of electromagnetic cavities). By October of 1900, M. Planck [22] derived an interpolation between Wien's results (for high frequency) and the Rayleigh–Jeans results (for low frequency), which reproduced very precisely the experimental curves of Kurlbaum, Pringsheim, and Rubens. Planck's formula for the emission of a black body marked the beginning of Quantum Physics. In 1905, Albert Einstein [11], introduced the quanta of light (i.e., the present day *photons*) to explain the experimental results of H. Hertz on the photoelectric effect). The same year Einstein [12] gave a solution to the Brownian motion problem (observed independently by Robert Brown in 1827, and by Jan Ingenhousz in 1784), showed that the root mean square displacement of a Brownian particle is proportional to time, and the diffusion constant is inversely proportional to the Avogadro Number. This dependence of the diffusion constant allowed Perrin [20] to make the first accurate experimental determination of the Avogadro number (see also [21], and the review article of Duplantier [10]).

In the meantime, the discovery of radioactivity by H. Becquerel in 1896 [3] and the electron by J. J. Thomson in 1897 [25], prompted a renewed interest in trying to determine the internal structure of atoms. Thus, at the beginning of the XXth century several people (including J .J. Thomson [26], and H. Nagaoka [18]), introduced different models of atoms (basically neutral systems with positive and negative charge distributions interacting via a Coulomb potential). It is at this point in this history that Rutherford's contribution enter. By 1907, Ernest Rutherford had become a successor of Arthur Schuster (a leading spectroscopist of the time) as Professor of Physics at the University of Manchester. At Manchester, Rutherford continued his research on the properties of the radium emanation and of the alpha rays and, in conjunction with Hans Geiger, a method of detecting a single alpha particle and counting the number emitted from radium was devised (see the biography of Rutherford at the end of this manuscript). In order to try to determine the inner structure of the atom, Rutherford suggested to Geiger an experiment involving the scattering of alpha particles by a thin gold foil.

Collisions have always played a major role in physics. Already in 1668, The Royal Society of London established a competition in order to determine the laws of collisions in classical mechanics. The Royal Society received the memoirs of John Wallis (November 26, 1668), Christopher Wren (December 17, 1668), and Christiaan Huygens (January 4, 1668) who solved different aspects of the problem (see, e.g. [9], Chapter V). And the consideration of elastic collisions in special relativity yields the classical formula $p = mv/\sqrt{1-(v/c)^2}$, for the momentum of a relativistic particle. Even today, smashing elementary particles at very high energy is the method to discover the physics at very small scales.

The gold foil experiment was conducted under the supervision of Rutherford at the University of Manchester in 1909 by Hans Geiger and the undergraduate student Ernest Marsden. In this experiment, most of the alpha particles passed straight through the foil. However, Geiger and Marsden [14] found that some alpha rays were scattered directly backwards, even from a thin film of gold. It was, a surprised Rutherford stated, "*as if one had fired a large naval shell at a piece of tissue paper and it had bounced back*". In his famous 1911 paper, Rutherford

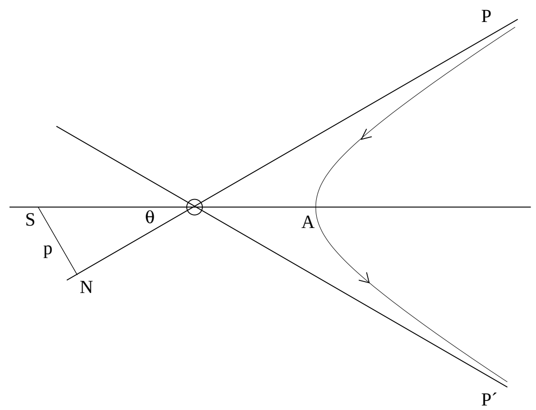


FIGURE 2

[23] starts comparing the results of the gold foil experiment with the theoretical predictions based on the Thomson model (which is usually referred to as the "plum–pudding model"), ruling it out. He then proceeds introducing the now classical picture (*the Rutherford atom*) in these words: "*...Consider an atom which contains a charge* $\pm Ne$ *at its centre surrounded by a sphere of electrification containing a charge* $\mp Ne$ *supposed uniformly distributed throughout a sphere of radius R. Here, e is the fundamental unit of charge, which in this paper is taken as* $4.65 \times 10^{10}$ *E.S. unit. We shall suppose that for distances less than* $10^{-12}$ *cm, the central charge and also the charge on the alpha particle may be supposed to be concentrated at a point. It will be shown that the main deductions from the theory are independent of whether the central charge is supposed to be positive or negative. For convenience, the sign will be assumed to be positive.* **The question of the stability of the atom** *proposed need not be considered at this stage, for this will obviously depend upon the minute structure of the atom, and on the motion of the constituent charged parts...*" (see [23] for details). He then calculated the scattering cross section of a charged particle by a fixed target made of a charged point (finding a dependence like $\csc(\theta/2)^4$, where $\theta$ is the deflection angle in figure 2). Of course, Rutherford used Classical Mechanics for his computation of the scattering cross section, and he found an excellent agreement with the experimental data of the paper of Geiger and Marsden. It is a mayor coincidence that for the Coulomb potential, the results derived using Classical Mechanics (see, e.g., [17], p. 53, for the classical derivation), and the results using Quantum Mechanics (see, e.g., [13], Problem 110, pp. 290 ff) for the derivation using Quantum Mechanics) are the same. This is connected with the hidden symmetry ($SO(4)$ symmetry) of the motion of a particle moving in the presence of the Coulomb field. If this were not the case, it would have been an extra (may be impossible) puzzle to interpret the experimental results of Geiger and Marsden.

In 1911, Niels Bohr had obtained his Ph.D. at the University of Copenhagen, and joined the group of Ernest Rutherford in Manchester in 1912, attracted by the 1911 paper of Rutherford. As pointed out by Rutherford himself, his model has obvious stability problems, since in classical mechanics the accelerated electrons around the nucleus must radiate energy and fall to it in a very short time. It was in part to solve these stability problems that Niels Bohr introduced his model of the atom [4, 5, 6, 7], giving birth to the *Old Quantum Mechanics.* The *Bohr Atom* not only was an attempt to solve the stability problems of *Rutherford's Atom*, moreover, it was able to explain the Balmer series. The fact that the *semiclassical analysis* of Bohr could explain precisely the Balmer Series, and thus the spectrum of the Hydrogen Atom is again a happy coincidence due to the $SO(4)$ symmetry alluded to above.

In the century that has passed since the introduction of Rutherford's Atom [23, 24], there has been a fruitful interaction between mathematics and physics. Even in the days of the *Old Quantum Mechanics*, there were several mathematical developments carried by A. Sommerfeld and others, and with the introduction of the Schrödinger equation in 1926, the developments in Functional Analysis were growing hand by hand with Physics to help understanding the spectral properties of Atoms, Molecules and Solids. Also, in the last half a century, there has been a vast mathematical physics literature around stability problems in Atomic Physics. In summary, the introduction of the Rutherford Atom, not only marked the beginning of Nuclear Physics as stated in the New York Times Editorial. It also played a crucial role in Atomic Physics, and established a fertile ground for many problems in Mathematical Physics.

**Ernest Rutherford** was born on August 30, 1871, in Nelson, New Zealand. He received his early education in Government schools and at the age of 16 entered Nelson Collegiate School. In 1889 he was awarded a University scholarship and he proceeded to the University of New Zealand, Wellington, where he entered Canterbury College. He graduated in 1893 with a double first in Mathematics and Physical Science and he continued with research work at the College for a short time, receiving the B.Sc. degree the following year. Growing up, he often helped out on the family farm, but he was a good student. After college he won a scholarship in 1894 to become a research student at Cambridge. Upon receiving the news of this scholarship, Rutherford is reported to have said, "That is the last potato I will ever dig". At Cambridge, the young Rutherford worked in the Cavendish laboratory with J. J. Thomson, discoverer of the electron. Rutherford's talent was quickly recognized, and in 1898 he took a professorship at McGill University in Montreal. There, he identified alpha and beta radiation as two separate types of radiation, and studied some of their properties. In 1901 Rutherford and chemist Frederick Soddy found that one radioactive element can decay into another. The discovery earned Rutherford the 1908 Nobel Prize in Chemistry. Rutherford returned to England in 1907 to become Professor of Physics in the University of Manchester, succeeding Arthur Schuster, and in 1919 he accepted an invitation to succeed J. J. Thomson as Cavendish Professor of Physics at Cambridge. At Manchester, Rutherford continued his research on the properties of the radium emanation and of the alpha rays and, in conjunction with H. Geiger, a method of detecting a single alpha particle and counting the number emitted from radium was devised. In 1910, his investigations into the scattering of alpha rays and the nature of the inner structure of the atom which caused such scattering led to the postulation of his concept of the "**nucleus**", his greatest contribution to physics. According to him practically the whole mass of the atom and at the same time all positive charge of the atom is concentrated in a minute space at the centre. In 1912 Niels Bohr joined him at Manchester and he adapted Rutherford's nuclear structure to Max Planck's quantum theory and so obtained a theory of atomic structure, giving rise to the "Old Quantum Mechanics". In 1919, during his last year at Manchester, he discovered that the nuclei of certain light elements, such as nitrogen, could be "disintegrated" by the impact of energetic alpha particles coming from some radioactive source, and that during this process fast protons were emitted. Blackett later proved, with the cloud chamber, that the nitrogen in this process was actually transformed into an oxygen isotope, so that Rutherford was the first to deliberately transmute one element into another. G. de Hevesy was also one of Rutherford's collaborators at Manchester. An inspiring leader of the Cavendish Laboratory, he steered numerous future Nobel Prize winners towards their great achievements: Chadwick, Blackett, Cockcroft and Walton. C.D. Ellis, his co-author in 1919 and 1930, pointed out "that the majority of the experiments at the Cavendish were really started by Rutherford's direct or indirect suggestion". He remained active and working to the very end of his life. Rutherford died in Cambridge on October 19, 1937. For more detailed biographical facts on Rutherford see the recent article online: *This Month in Physics History May, 1911: Rutherford and the Discovery of the Atomic Nucleus*, at the American Institute of Physics website: http://www.aps.org/publications/apsnews/200605/history.cfm

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