Ernest Rutherford

his genius shaped our modern world

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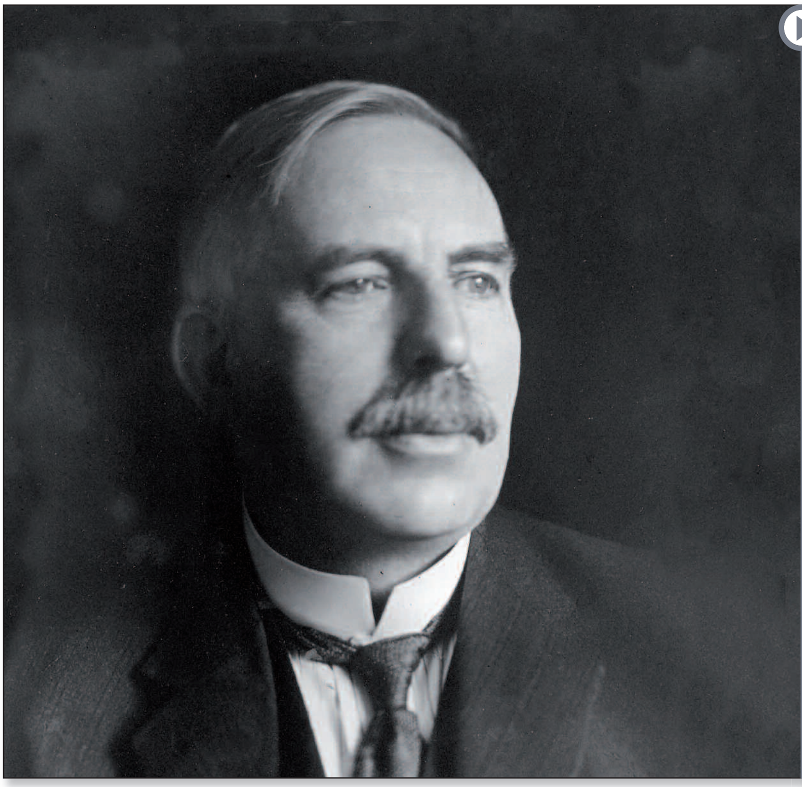
2011 marks the 100th anniversary of the publication of Rutherford's seminal paper [1] which first identified the atomic nucleus and its essential role in the structure of matter. This crucial discovery marked the birth of nuclear physics and lead to enormous advances in our understanding of nature. Rutherford's legacy has profound and far reaching influences on the shape of the modern world we live in.

Ernest Rutherford was born on 30th August 1871 in Spring Grove, near Nelson, New Zealand. His father, James was a farmer who had emigrated from Perth, Scotland, and his mother, Martha Thomson, was a school teacher from Essex, England. In 1893 Ernest graduated with an M.A. from the University of New Zealand in Wellington and gained a B.Sc. the following year. He was awarded a prestigious "1851 Exhibition Scholarship" to work as a research student at the Cavendish Laboratory, Cambridge, under J. J. Thomson. In 1898 he took up a chair at McGill University, Montreal, where he worked till 1907. He moved back to the UK, to accept the Langworthy Professorship at Manchester University, where he carried out his most famous work. In 1919 he returned to Cambridge as an inspirational leader of the Cavendish Laboratory, building up its reputation as an international centre of scientific excellence. He was awarded the Nobel Prize for chemistry in 1908 and was knighted in 1914. He was president of the Royal Society 1925-30 and became Lord Rutherford (1st Baron of Nelson) in 1931. He died on October 19th 1937 in Cambridge. The radioactive element Rutherfordium (Rf, Z=104) was named in his honour, sixty years after his death.

▼ E. Rutherford



Note

This is the first of a series of articles to commemorate the centenary of nuclear physics. This paper describes how Rutherford deduced the existence of a dense, highly charged nucleus at the heart of the atom and outlines the enormous impact his work has had on science and society. This brief account presents only a small selection of his work. Further information is contained in references at the end.
The second article will be a forward-looking discussion of future prospects for nuclear research in Europe, featuring an interview with Prof. G. Rosner, chair of NuPECC (an expert committee of the European Science Foundation) on its new long range plan [2] for Nuclear Physics research. A further article will show how Rutherford's scattering ideas are being applied to experiments at CERN (European Organisation for Nuclear Physics) to study the properties and substructure of nucleons.

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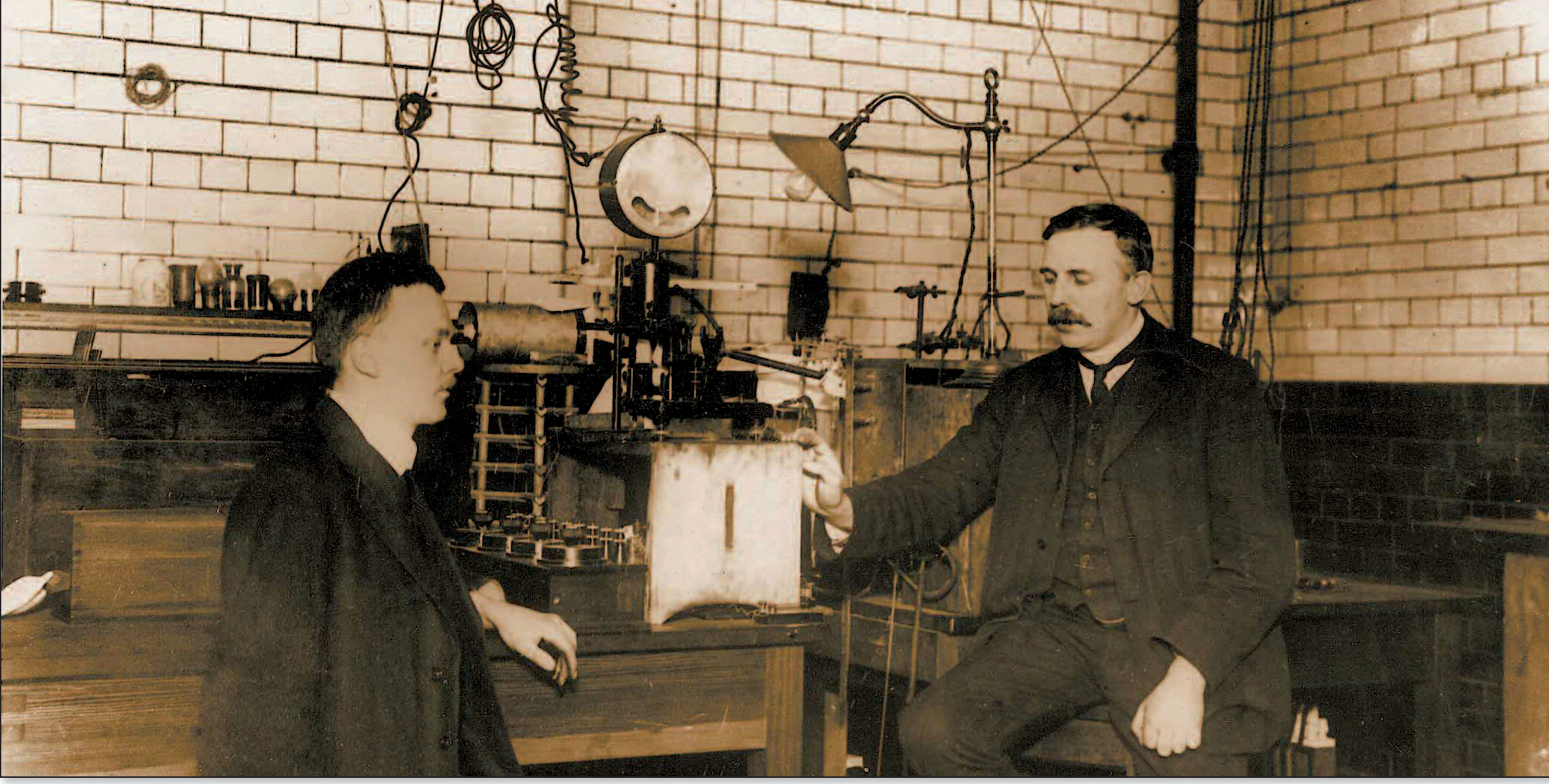


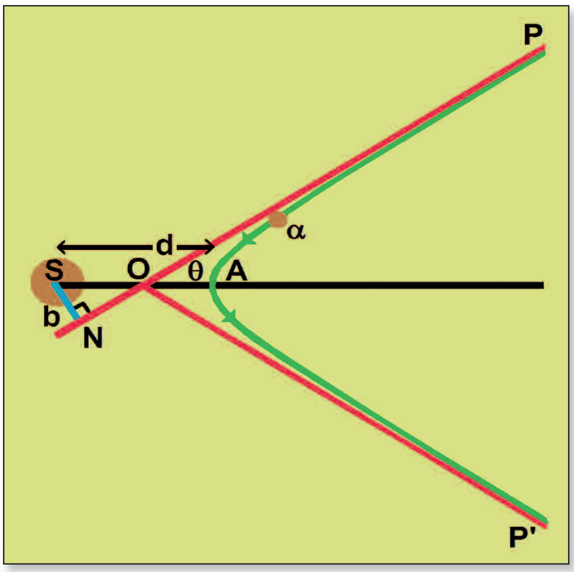
Rutherford's model of the atom

Rutherford published his model of the atom [1] in 1911 as an interpretation of the α-scattering work carried out by Geiger and Marsden [3] two years earlier. The puzzle centred on finding a convincing explanation for the small fraction of α particles (around 1 in 20,000) which were deflected through large angles, after passing through gold foil only 0.00004 cm thick. He argued that the probability of occasional large-angle scatters was inconsistent with multiple small angle scattering, and could only be explained by a single scattering event. This required an "intense electric field" and led him to propose his model of an atom with a charge of $\pm Ne$ at its centre surrounded by a uniformly distributed sphere of the opposite charge.

His arguments did not depend on the charge at the centre, but he chose the correct sign: **"...the main deductions of 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."** He was aware that there were unanswered questions about how such a structure could exist: **"The question of the stability of the atom proposed need not be considered at this stage…"** These questions were only fully answered much later.

Using a reasonable estimate for the nuclear charge he calculated the distance of closest approach (~34 fm) for a typical head-on α particle to be completely stopped and provided the first ever order-of-magnitude estimate of the size of the nucleus. He showed that the trajectory taken by an α particle was hyperbolic and related the angle of deviation δ to the perpendicular distance b between the line of approach and the centre of the nucleus. He showed the scattering probability was proportional to $\mathrm{cosec}^4(\delta/2)$ and inversely proportional to the 4th power of velocity. An important test of his model was to calculate the dependence of the relative number of scattered particles n on the atomic weight A. The ratio $n/A^{2/3}$ should be constant. The measured values for eight elements between Al and Pb ranged from 208 to 250 with an average of 233. He concluded: **"Considering the difficulty of the experiments, the agreement between theory and experiment is reasonably good."**

Following the publication of his ground-breaking paper [1], Rutherford worked closely with other leading physicists of the day. Niels Bohr visited Manchester in 1912 and again 1914-16. Bohr's model of stationary non-radiating electron orbits [4] added credence to Rutherford's atom and answered the question of why the electrons do not fall into the nuclear core. Subsequent developments in the theory of quantum mechanics gave this an even sounder footing. However, understanding the small size and strong binding of the nucleus would have to wait till the 1930s, when the neutron was discovered and Yukawa first described the strong attractive force binding neutrons and protons together in terms of meson exchange.



▲ **FIG. 1:** Photograph of Hans Geiger (left) & Ernest Rutherford (right) in their laboratory at Manchester University circa 1908.

◄ **FIG. 2:** The α particle, experiencing an inverse square repulsive force, follows a hyperbolic trajectory (green) as it approaches the nucleus located at S, the external focus of the hyperbola. It enters along the asymptotic direction PO (red) reaching its closest approach d=SA at the apse of the hyperbola before exiting along the second asymptote OP'. The angle of deviation δ=π-2θ depends on the energy of the alpha particle and its impact parameter b=SN.

► While Rutherford carried out (α,p) reactions, changing the elemental composition of the target, the term "splitting the atom" is more usually associated with nuclear fission. In 1934 Fermi carried out experiments bombarding Uranium with neutrons. The results of this early work were not clear. However in 1938 Hahn and Strassmann reported detecting Barium in the products of similar experiments. This was subsequently interpreted by Meitner and Frisch as nuclear fission. The extraction of large amounts of energy from the fission process required the development of a chain reaction process. This was researched during the second world war and resulted in the production of nuclear weapons. Later, in 1951, electricity was generated from a nuclear reactor and the phrase "atoms for peace" gained wide currency.

These world-changing facets of nuclear physics were not developed until after Rutherford's death. However, Al-Khalili [5] has discussed whether Rutherford was aware of the possibilities. In the early 1930's Rutherford said "**anyone who expects a source of power from the transformation of these atoms is talking moonshine**". Certainly this is true for a single reaction. It requires a chain reaction to transform the scenario. Al-Khalili notes that Rutherford took a close interest in the work of Fermi and Bohr and reports some comments he made which confirm Rutherford was aware of the possibilities of extracting energy from atoms.

▼ TABLE 1: Nobel Prizes for work in atomic structure, nuclear physics, quantum physics or fields which have developed out of nuclear physics. Physics Prizes are in grey and Chemistry prizes in blue.

Year	Recipient	Year	Recipient
1901	W. Röntgen	1954	M. Born & W. Bothe
1902	H. Lorentz & P. Zeeman	1955	W. Lamb & P. Kusch
1903	H. Becquerel, P. Curie & M. Curie	1957	C. Yang & T-D. Lee
1908	E. Rutherford	1958	P. Cherenkov, I. Frank & I. Tamm
1911	M. Curie	1959	E. Segrè & O. Chamberlain
1917	C. Barkla	1960	D. Glaser
1918	M. Planck	1961	R. Hofstadter & R. Mössbauer
1921	A. Einstein	1963	E. Wigner, M. Goeppert-Mayer & H. Jensen
1921	F. Soddy	1964	C. Townes, N. Basov & A. Prokhorov
1922	N. Bohr	1965	S-I. Tomonaga, J. Schwinger & R. Feynman
1922	F. Aston	1967	H. Bethe
1927	A. Compton & C. Wilson	1968	L. Alvarez
1929	L. de Broglie	1969	M. Gell-Mann
1932	W. Heisenberg	1975	B. Mottelson & J. Rainwater
1933	E. Schrödinger & P. Dirac	1976	B. Richter & S. Ting
1934	H. Urey	1979	A. Salam & S. Weinberg
1935	J. Chadwick	1980	J. Cronin & V. Fitch
1935	F. Joliot-Curie & I. Joliot-Curie	1983	S. Chandrasekhar & W. Fowler
1936	V. Hess & C. Anderson	1984	C. Rubbia & S. van der Meer
1938	E. Fermi	1988	L. Lederman, M. Schwartz & J. Steinberger
1939	E. Lawrence	1990	J. Friedman, H. Kendall & R. Taylor
1943	O. Stern	1991	R. Ernst
1944	I. Rabi	1992	G. Charpak
1944	O. Hahn	1994	B. Brockhouse & C. Shull
1945	W. Pauli	1995	M. Perl & F. Reines
1948	P. Blackett	1999	G. 't Hooft & M. Veltman
1949	H. Yukawa	2002	R. Davis, Jr., M. Koshiba & R. Giacconi
1950	C. Powell	2004	D. Gross, D. Politzer & F. Wilczek
1951	J. Cockroft & E. Walton	2008	Y. Nambu, M. Kobayashi & T. Maskawa
1952	F. Bloch & E. Purcell		

Nobel Prizes

Nobel prizes are the ultimate accolade for scientific discovery. Atomic structure lies at the boundary between Physics and Chemistry and prizes in both subject areas have been awarded for atomic and nuclear research. It is somewhat surprising that **Ernest Rutherford did not receive a Nobel Prize for his work on the structure of atoms**. He did, however, receive the 1908 Nobel Prize for Chemistry [6]. This was in recognition of his earlier work into the disintegration of the elements and the chemistry of radioactive substances.

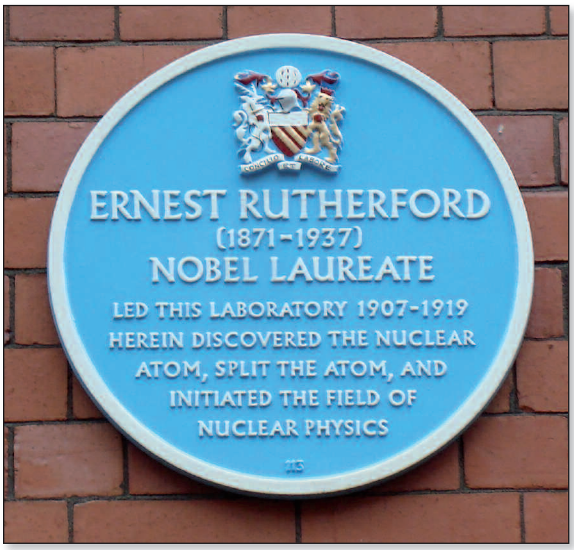
However, the true importance of Rutherford's contribution can be gauged by the fact that 8 Nobel Prizes in Chemistry and over 50 in Physics have been awarded for work directly related to atomic structure, nuclear physics, quantum physics and other fields which have developed from nuclear physics (see table 1).

Rutherford worked closely with many of the leading scientific brains of the early 20th century (J.J. Thomson, R.B. Owens, F. Soddy, O. Hahn, H. Geiger, E. Marsden, N. Bohr, H.G. Moseley, G. de Hevesy, A. Szalay, J. Chadwick, P. Blackett, J. Cockroft, R. Walton, G.P. Thomson, E.V. Appleton, C. Powell, F.W. Aston, C.D. Ellis and others). This close interaction played an important part in the rapid development of physics during and after his lifetime. It is reported in [6] that he played an influential role at the Cavendish "steering numerous future Nobel Prize winners towards their great achievements". It is clear that Rutherford was present at the heart of a very large number of fundamental scientific discoveries.

Rutherford's legacy

Rutherford's work provided the key to an exciting new world of science and applications. The physics of the atom is governed by the rules of quantum physics, taking us into domains classical physics cannot predict or describe. This has produced a step change in our understanding of nature and a host of previously unimagined applications. As studies advanced our understanding of atoms, chemical elements, radioactivity and isotopes has been transformed.

Milestones in the development of nuclear science included the discovery of the neutron, the positron and antimatter. The field of particle physics was spawned as a separate research discipline. Energy production in stars and the creation of light and heavy elements in stellar processes rely on nuclear reactions. Direct applications such as medical imaging have transformed the diagnosis of disease and radiotherapy has advanced the treatment of cancer. Detector and accelerator technologies have found wide application in industry. The fields of solid state physics, electronics, computing and modern optics all depend on quantum physics which was initially developed to explain phenomena in nuclear and atomic systems. The Institute of Physics (IOP) has commissioned a report "Nuclear physics and technology – inside the atom" [7] which details the impact on society of research into the atomic nucleus. There is scarcely an area of modern physics which does not owe a debt of gratitude to Ernest Rutherford.



◀ **FIG. 3: Blue Plaque at Manchester University commemorating the achievements of Ernest Rutherford.**

Celebrations of Rutherford's Achievement

Many events have been organised to celebrate the centenary of Rutherford's famous publication[1] .The EPS Nuclear Physics Division has commissioned a website [8] to collate information on this notable anniversary.
A reception, bringing together politicians and scientists, was held in the House of Commons on 29th March 2011. The reception was hosted by E. Vaizey M.P., whose constituency includes the Rutherford Appleton Laboratory, and sponsored by the New Zealand High Commission, the IOP, and the UK STFC Research Council. Ernest Rutherford's family was represented by his great granddaughter, Prof. M. Fowler. Speakers from science (Prof. B. Cox), the IOP (Dr. B. Taylor), politics (E. Vaizey M.P.) and diplomacy (D. Leask, the New Zealand High Commissioner) highlighted the sheer genius of Rutherford in unlocking the structure of the atom. At the event the STFC announced the creation of the Ernest Rutherford Fellowship Scheme to support early-career researchers in the UK [9].
On 5th April 2011 Al-Khalili gave a highly acclaimed public lecture [5] on "Nuclear Physics since Rutherford" at the IOP Nuclear and Particle Physics Divisional Conference, in Glasgow. This conference brought together many separate scientific disciplines which owe their origins to Rutherford's work. The Rutherford Appleton Laboratory, which takes its name from the two scientific pioneers, Ernest Rutherford and Edward Appleton, organised a Schools meeting on 19th May 2011, where Al-Khalili was again the guest speaker.
The main celebration was the Rutherford Centennial Conference [10] (Manchester, 8—12 August 2011). This brought the commemorations back to the city where Ernest Rutherford carried out his pioneering work. The conference highlighted the anniversary with talks by leading international speakers on a wide range of topics which have developed out of Rutherford's work.■

Acknowledgments

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About the author

Douglas MacGregor is a reader in Nuclear Physics at the University of Glasgow. He serves on the Rutherford Centennial Conference organising committee, is secretary of the EPS Nuclear Physics Division and chairs the IOP Nuclear and Particle Physics Division.

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