History of Science

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Lord Rutherford (1871–1937): The Newton of the Atom and the Winner of the Nobel Prize for Chemistry, 1908

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1. Introduction

When Ernest Rutherford, later known as Lord Rutherford of Nelson, died unexpectedly in 1937, the *New York Times* stated: "*…It is given to but few men to achieve immortality, still less to achieve Olympian rank, during their own lifetime. Lord Rutherford achieved both. In a generation that witnessed one of the greatest revolutions in the entire history of science he was universally acknowledged as the leading explorer of the vast infinitely complex universe within the atom, a universe that he was first to penetrate.*"

And when Sir Mark Oliphant, a fellow Antipodean and student, colleague, and friend of Rutherford in Cambridge, who, along with Paul Harteck, discovered tritium, wrote a foreword to a definitive work[1] on Rutherford in 1999 he described him as "*the greatest experimental scientist since Faraday*". Oliphant also recalled that "*Max Born, whose own contributions to theoretical physics were formidable, told me that Rutherford was the greatest scientist he had ever known, including even Einstein.*"

Historians of science the world over, not to mention active scientists themselves, generally argue that Rutherford was the most accomplished experimental physicist since Faraday. Yet the case can be made (see Section 2.3) that of the three towering achievements associated with his name—the theory of nuclear disintegration (with Frederick Soddy, 1902–1903), his model of the nuclear atom (1911), and the discovery of the artificial disintegration of the nucleus (1919)—the first two, while based on experimental evidence, were theoretical concepts. Even more ironic is that Rutherford was awarded the Nobel Prize in Chemistry (not Physics) in 1908. When news of this award reached him he laughingly commented that he had observed many rapid transformations among radioelements, but none as rapid as his transformation from a physicist into a chemist.[2]

Distinctions between physics and chemistry are often arbitrarily drawn; and it is futile pedantically to emphasize them, especially where great scientists like Faraday and Rutherford are concerned. In this regard the comments made by Rutherford in August 1931, when the centenary of Faraday's discovery of electromagnetic induction was celebrated, are worth repeating:[3] "*The more we study the work of Faraday, with the perspective of time, the more we are impressed by his unrivalled genius as an experimenter and a natural philosopher. When we consider the magnitude and extent of his discoveries and their influence on the progress of science and of industry, there is no honour too large to pay to the memory of Michael Faraday—one of the greatest scientific discoverers of all time.*"

Rutherford, like Faraday, took out no patents even though he possessed the skills and made discoveries, especially early in his career, that would have interested businessmen. Rutherford himself did not see his discoveries as opening the era of atomic energy. But it was largely his "boys"—a term which he used affectionately to describe his students and collaborators—who had developed radar and other devices of strategic military significance. It was his assistants Chadwick and Cockcroft (later Nobel Prize winners each in their own right) who built the UK Atomic Energy Authority.

2. The Trajectory of Rutherford's Life

This section deals first with his place of birth, New Zealand, then his period as a researcher at Cambridge (1895–1898), followed by his professorships at McGill University, Montreal (1898–1907) and Manchester (1907–1919), and his position as the Cavendish Professor of Physics at Cambridge (1919–1937).

2.1. New Zealand (1871–1895)

The New Zealand of the Rutherford's youth was an agrarian society that had been settled by Europeans for only a few generations. Yet they brought to the Antipodes their English and Scottish values of hard work, thrift, and a respect for education, and endeavored to create the institutions that would reward their pioneering activities. Rutherford absorbed these qualities, and throughout his life he exhibited the energy and resourcefulness of his father and the thirst for knowledge of his mother, a former teacher.[2] A bright student, he won a scholarship to Nelson College (situated at the tip of the South Island). Another competitive scholarship allowed him in 1890 to enter Canterbury College in

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Christchurch, where he expanded his horizons culturally and intellectually.

After completing his BA degree in 1892 he proceeded to take his MA (in mathematics and mathematical physics), and in 1894 he began his first independent research. But he had further cause to remain in Christchurch, for his heart was captivated by Mary Newton, his landlady's daughter. (He was to marry her in 1900). His research centered on the magnetization of iron by high-frequency discharge, work which enabled him to devise a sensitive method of detecting radio waves. He had recognized that an already magnetized needle would lose some of the strength, in an alternating magnetic field, making it a suitable detector for wireless signals and a device of potential commercial applicability. He published two papers on this topic in the *Transactions of the New Zealand Institute*.[4]

Rutherford applied for an 1851 Exhibition Scholarship in 1894; the rules had just been changed to allow candidates from the British Commonwealth to apply for such prestigious awards. In addition, Cambridge University had also just changed its statutes and now permitted graduates from other universities to pursue research there. Enrolling in 1895, Rutherford was the first research student under the new regulations. He joined the Cavendish Laboratory, whose Director was J. J. Thomson (Figure 1).[5]

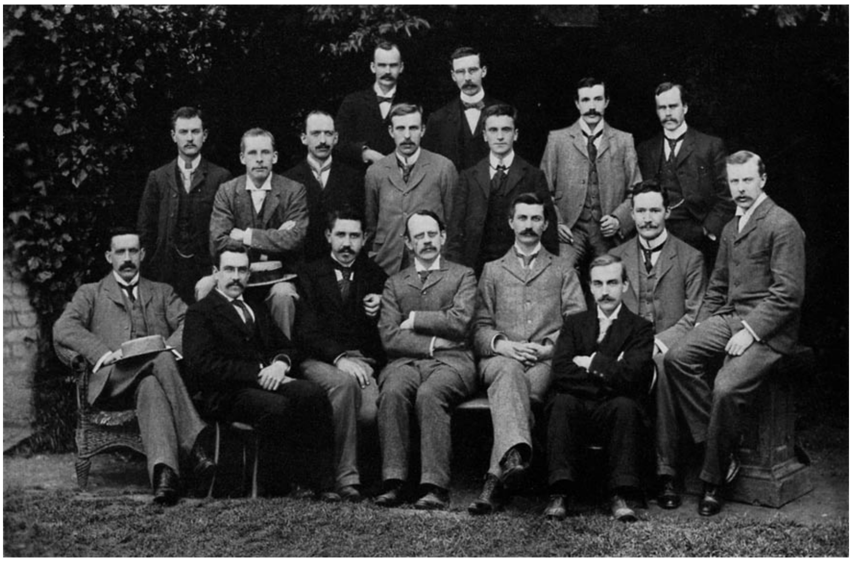

Figure 1. J. J. Thomson's research group in the Cavendish Laboratory, Cambridge, 1898. Rutherford is fourth from the left in the middle row; to his right is C. T. R. Wilson, of cloud-chamber fame, who won the Nobel Prize in Physics in 1927. Of him, P. M. S. Blackett, another Cavendish physicist to win the Nobel Prize (1948), said: *"Of the great scientists of his age, he was perhaps the most gentle and serene, and the most indifferent to prestige and honours."* The polymathic Paul Langevin (1872–1946) was also a member of the Cavendish Research group at that time (bottom row, third from the left, next to J. J. Thomson).

2.2. Cambridge (1895–1898)

Two months after Rutherford's arrival in Cambridge, X-rays were discovered (in November 1895) by Wilhelm Conrad Röntgen. And since this new radiation exerted a marked effect upon the discharge of electricity in gases (a topic of great interest to Thomson),[6] Rutherford was quick to seize the opportunity of collaborating with "J.J". The collaboration yielded a classic paper in 1896 on the theory of ionization.[7] X-rays generate the positive and negative ions, which are attracted to electrodes, so that he could readily measure currents. Work of this kind continued for much of 1896 and 1897, with Rutherford examining the ions' velocities, their rates of recombination, the electrification of different gases, and other relevant characteristics.

In 1896 radioactivity was discovered by Becquerel, and soon both Marie Curie, in Paris, and Rutherford, in Cambridge, pursued quantitative studies of the phenomenon. The attention of the world's scientific community, especially after Pierre and Marie Curie (and Gustave Bémont) discovered polonium, was now riveted to radioactivity. For the next four decades Rutherford and his colleagues focused on radioactivity through its connections with atomic physics, nuclear physics, and nuclear chemistry.

In his work on uranium, using absorption experiments (with rays impinging on foils of various thicknesses) he observed that one type of radiation was readily stopped, another penetrated further. He named the two types of radiation alpha and beta, because, he exclaimed, he was a simple man and liked simple experiments and explanations!

A physics professorship at McGill University in Montreal fell vacant in 1898. Thomson's advice was sought, and he gave a glowing reference for Rutherford.[8]

2.3. Montreal (1898–1907)

By the time Rutherford found his feet in McGill University, the omens were particularly good. First, the laboratories of the Department of Physics there were exceptionally well equipped: they were arguably the best in North America at the time. This was because of the munificence of Sir William MacDonald, a rich benefactor who had said that he wanted McGill to have the resources in physics comparable to those of the Cavendish Laboratory in Cambridge. Not only was there the most advanced equipment, even the stores had chemicals that hardly a department of physics or chemistry anywhere in the world could rival, there being a good supply of the then very costly radium bromide, for example. Second, the 21-year-old Frederick Soddy, a former student of Aberystwyth in Wales and Merton College, Oxford, and a brilliant experimentalist, had just been appointed lecturer in chemistry at McGill. Rutherford and Soddy entered into a most rewarding eighteen-month collaboration from October 1901 to April 1903, during which time they produced nine major papers laying the foundations for the serious study of radioactivity.[9]

The nature of radioactivity in 1901 was profoundly enigmatic. Its discoverer, Becquerel, interpreted it as a form of long-lived phosphorescence. And the Curies favored the idea that an unknown ethereal radiation pervaded space, causing a resonance in the heaviest elements which resulted in the emission of alpha, beta, and gamma rays as secondary radiations. Rutherford and Soddy felt that radioactivity was an atomic phenomenon. Their famous theory, sometimes called disintegration, and sometimes transformation or transmutation, claimed that the atomic process involved spontaneous chemical changes that produced new substances.[9i] Thus, thorium decayed into thorium X, while thorium emanation (see below) decayed sequentially into thorium A, B, C, and so forth. Each, they asserted, was a different chemical element. Such views were quite revolutionary. Was it not the case that atoms were indestructible and immutable? The theory of Rutherford and Soddy, based on experimental work of rabbinical complexity, had more than a whiff of alchemy associated with it; and had not the ghost of alchemy had long been exorcized by 1901? But the graphs of radioactive decay of a parent element and the rise of a daughter one were irrefutable. The quantitative work of the 30- and 24-year-olds was of inexpugnable validity. However, some powerful voices, notably that of Lord Kelvin, were raised against them. He said: *"I venture to suggest that ethereal waves may supply energy to the radium"*. Where did the law of conservation of energy fit into all this? By saying that *all* radioactive elements, including uranium, ultimately would change into an inactive end product, Rutherford and Soddy satisfied this cardinal law of nineteenth-century physics. There was energy inside the atom.

Another important consequence of the Rutherford–Soddy collaboration centered on the heating effects of radium (and other radioactive elements). The amount of radium present in igneous and sedimentary rocks is sufficient to diminish the rate of cooling of the earth. By noting this fact, Rutherford went on to clarify the estimated age of the earth, a topic to which we return in Sections 3 and 4.

It was at McGill University that Rutherford coined the word "emanation". His colleague in the Department of Electrical Engineering, R. B. Owens, obtained erratic ionization measurements until Rutherford traced the cause to air currents in the room, and recognized that something from thorium was being blown about. Uncertain if it was a gas or a cloud of particles, he called it thorium emanation (in 1900), and European physicists soon discovered emanation from radium and actinium. When Sir William MacDonald donated a liquid-air machine to McGill, Rutherford and Soddy showed, by condensation experiments, that emanation was a gas. Great excitement later ensued when this gas was recognized to belong to that family of inert gases found by Sir William Ramsay.[6] (Soddy in 1903 joined Ramsay in the UK where, by spectroscopic examination of the emanation, they determined it to be helium).

Rutherford's magnetic personality and superb experimental skills, aided by the chemical virtuosity of Soddy, attracted worldwide attention. Otto Hahn, who had discovered the radioactive element thorium, and who, decades later, received the Nobel Prize for the discovery of nuclear fission, joined Rutherford in 1905–1906. And the redoubtable Bertram Boltwood, soon to teach at Yale University, collaborated with Rutherford by mail; they proved circumstantially that uranium and radium were related, thereby linking the two radioactive families. At McGill also, Rutherford was hospitable to women in his laboratory, Harriet Brooks being a notable representative in a period when gender prejudice remained strong. In this respect, Rutherford and Rayleigh exhibited the same degrees of kindness, generosity of spirit, and practical common sense.[6]

2.4. Manchester (1907–1919)

In 1907 when Sir Arthur Schuster[10] retired early from the chair at the University of Manchester he stipulated that Rutherford should succeed him (Figure 2). Schuster had made his department the second best physics de-

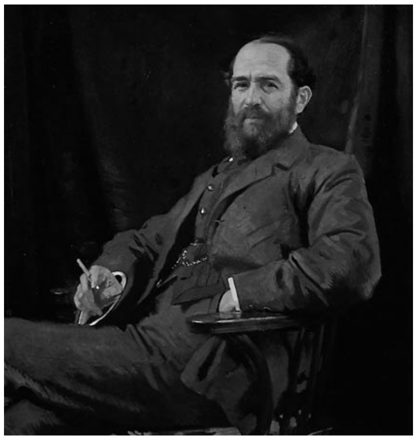

Figure 2. Sir Arthur Schuster (1851–1934), who resigned prematurely from the chair of physics in Manchester on condition that Rutherford be invited to take his place. For further details see Ref. [10].

partment (after the Cavendish) in the UK. He was independently wealthy and an engaging personality;[10] and he left his personal assistant, Hans Geiger,[11] to the laboratory and also endowed it with a readership in mathematical physics (filled later by Niels Bohr). Four men from Germany alone, and many other overseas workers, came to study with Rutherford during his first year in Manchester.[2]

The Austrian Academy of Sciences, in an act of magnanimity, sent Rutherford a generous amount of radium chloride (extracted from the Joachimsthal uranium mines under its control). This enabled him, with Geiger in particular, to focus on the study of alpha particles. These were, in relative terms, massive particles and unlike beta particles, of atomic dimensions; Rutherford thought they might hold the key to a deeper understanding of the nature of matter. With Geiger he built in 1908 a long brass tube having an insulated wire along the axis connected to an electrometer. A particle passing through the gas caused ionization, and initiated a brief discharge in the gas, and the resulting pulse of current could be detected on a meter. (In 1928 Geiger improved this prototype and made it more sensitive with his co-worker W. Müller.) The key result of Rutherford and Geiger's work was that alpha particles are doubly charged helium atoms.

These experiments of 1908 confirmed that each alpha particle caused a flash of light to occur when it struck a fluorescent screen, such as one composed of zinc sulfide or the mineral willemite. Thus scintillation counting, already known as a means of recording radioactive events, was validated as reliable. It became much more convenient than the primitive device that evolved into the famous Geiger counter and more readily usable even than the Geiger–Müller counter. In an ingenious experiment Rutherford arrived at the value of the basic unit of charge *e* (even before Millikan's famous oil-drop method). He measured the charge from a radium sample and divided it by the number of alpha particles emitted to obtain the charge of each particle.

Technically skilled chemists in the new field of radioactivity were attracted to Rutherford's Manchester laboratory. One was Boltwood from Yale who visited in 1909–1910, another was Kasimir Fajans, the Polish-American physical chemist, and the Hungarian, German-educated Georg von Hevesy,[12] inventor (with F. A. Paneth) of the technique of isotopic labeling and radioactivation analysis, all of whom contributed to an understanding of the group displacement laws and the concept of isotopy. (The word isotope was coined later by Soddy, who like Heuesy, also won a Nobel Prize).

An exercise in Rutherford's category of *"any damn fool experiment"* was that which he assigned to the undergraduate Ernest Marsden in 1909. He was asked to look for large-angle scattering of alpha particles by a thin film of gold. To everyone's astonishment, Marsden observed occasional scatterings at angles greater than 90° whereupon Geiger excitedly joined him to complete the investigation. Rutherford's reaction, doubtless somewhat exaggerated in its repetitious telling, is famous:[13] *"It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."*

It took Rutherford well over a year of considerable cogitation before he could say that he knew what the atom looked like. In 1911 he revealed a new model, the nuclear atom, which is arguably his greatest achievement. The alpha particles were deflected from their paths by encounters with single atoms of the target (Figures 3 and 4). For this to occur the electrostatic attraction or repulsion must be concentrated in a volume that was minute compared with the volume of the entire atom. So, in a sense, the atom was akin to our solar system.

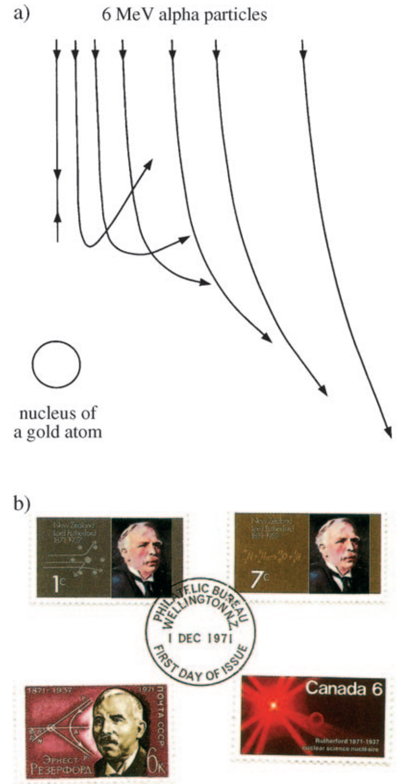

Figure 3. a) The scattering of alpha particles by the atomic nucleus (from Ref. [1]). b) The postage stamps (lower left) issued in 1971 by the Soviet Union coincided with the sixtieth anniversary of Rutherford's enunciation of the nuclear atom. Rutherford's image also appears in Canadian and New Zealand stamps shown here.

It seems that, outside Manchester, this discovery was received without excitement.[2] But everything changed in 1913 when Niels Bohr published his famous theory. He had visited Manchester in 1912 and returned as a staff member (1914–1916). At home in Denmark he knitted together radioactivity, atomic physics, spectroscopy, quantum theory, and chemistry. Radioactivity originated in the nucleus, while ordinary chemical and physical properties were dependent upon the electrons in orbit. The orbits, he claimed, were stable, (in blatant contradiction to classical electrodynamics) and the angular momentum of electrons in them was quantized. Line spectra were due to quantized energy emission or absorption. This was the dawn of a new era, one that gained spectacular support shortly thereafter from H. G. J. Mosley's work (alongside Rutherford) on X-ray spectra, when he made a compelling case for the central importance of the concept of the atomic number.

World War I emptied Rutherford's laboratories. He himself devoted much of his time to the so-called Admiralty Board of Invention and research on antisubmarine warfare as well as work on underwater acoustics. In 1919, however, Rutherford was to publish the results of yet another epoch-making experiment, again made with alpha particles. He showed that when the particles collided with atoms of nitrogen, protons and oxygen were produced [Eq. (1)].

$$ {}^{2}_{4}\mathrm{He} + {}^{7}_{14}\mathrm{N} \rightarrow {}^{1}_{1}\mathrm{H} + {}^{8}_{17}\mathrm{O} \qquad (1)$$

The swift protons produced in this first ever example of "artificial disintegration" (of the normally stable nitrogen nucleus) was so revolutionary and so pregnant with far-reaching implications, that it clearly needed to be supported by very complete experimental evidence, which Rutherford and his colleagues duly provided. This work was done after he moved to take up the Cavendish chair in Cambridge, when he succeeded his former mentor J. J. Thomson.

2.5. Cambridge (1919–1937)

Rutherford left Manchester with many regrets, for it was the place of great achievements and the home of many friends. Of this change Niels Bohr later wrote:[14] *"I remember on a visit to Manchester of hearing Rutherford speak with great pleasure and elation about the prospect of his going to Cambridge, but expressing at the same time a fear that the many duties connected with this central position in the world of British physics would not leave him those opportunities for scientific research which he had understood so well how to utilize in Manchester. Everybody knows that this fear was unfounded. The powers of Rutherford have never manifested them-*

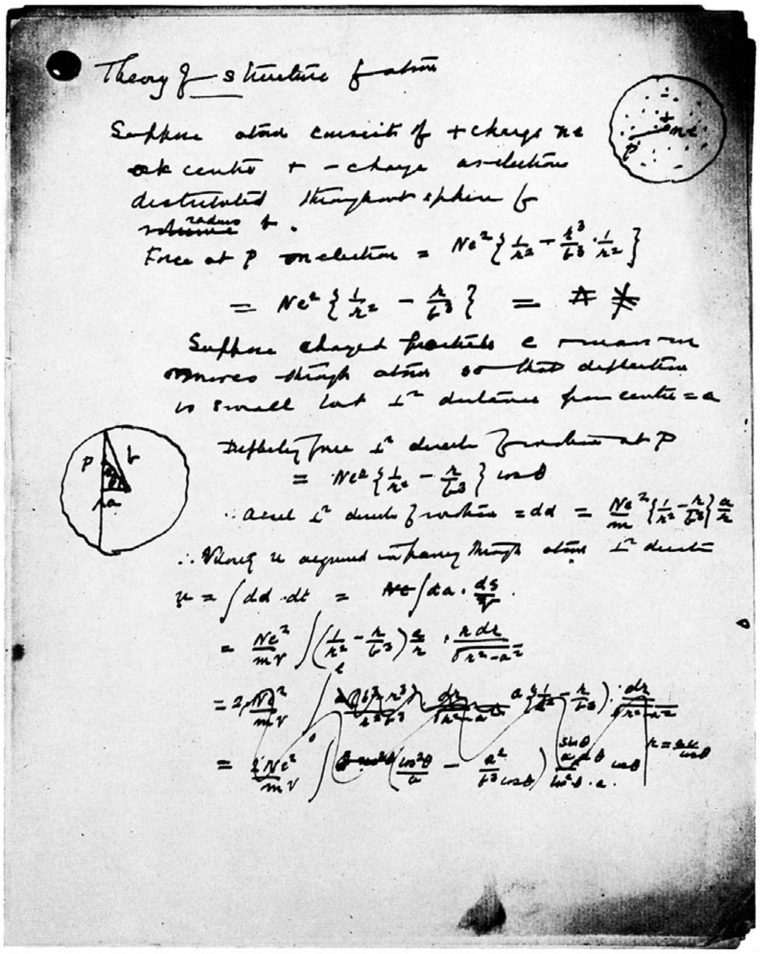

Figure 4. Rutherford's first rough note on the nuclear theory of atomic structure, written, probably, in the winter of 1910–1911.

selves more strikingly than in his leadership of the Cavendish Laboratory the glorious tradition of which he has upheld in every way."

In 1920, Rutherford suggested the existence of a neutral particle (in his second Bakerian Lecture to the Royal Society) with the properties of a neutron, to explain the building up of nuclei of heavy elements. Chadwick, who had moved from Manchester with Rutherford, made several attempts to detect such particles but initially had no luck. Later in 1932 when he bombarded beryllium with alpha particles, very penetrating radiation was produced. That year Iréne and Frédéric Joliot-Curie found that this radiation could eject protons with high velocities from matter containing hydrogen. Chadwick showed that this radiation could be explained if the particles had nearly the same mass as protons but no charge. (It was for this work that Chadwick was awarded the Nobel Prize for physics in 1935.)

During the early 1920s Rutherford and Chadwick succeeded in disintegrating several of the lighter elements, but it was not known at that time whether the alpha particles escaped the explosion unscathed or combined with the target nucleus before the latter transformed. P. M. S. Blackett in 1925 used the cloud-chamber apparatus developed by C. T. R. Wilson to photograph the tracks of some 400000 α encounters. Most were ordinary elastic collisions but eight involved disintegration. Leaving the point of disintegration were two tracks, disintegration fragments, proving that the alpha particle had been absorbed into a compound nucleus.

During this era in the Cavendish Laboratory, the Welshman Wynn-Williams, a new recruit of Rutherford's, made great advances in instrumentation (Figure 5). As Oliphant put it:[15] *"Techniques for counting alpha particles and protons were revolutionised by Wynn-Williams. … He and Ward developed the Cavendish linear amplifier which could respond quantitatively to the very small current-pulse produced in a shallow ionization chamber by the passage of a single fast particle…The amplitude of the pulse was proportional to the ionizing power of the particle, so that protons could be readily distinguished form alpha-particles… All this revolutionized the rate at which statistically significant results in nuclear physics were obtained."*

Rutherford and Chadwick failed to disrupt any elements heavier than argon and realized that alpha particles from naturally decaying radioelements, with their two positive charges, were repelled by the large positive charges on the nuclei of elements with large atomic numbers. Thanks to a visit to the Cavendish Laboratory by George Gamow, who explained that wave mechanics

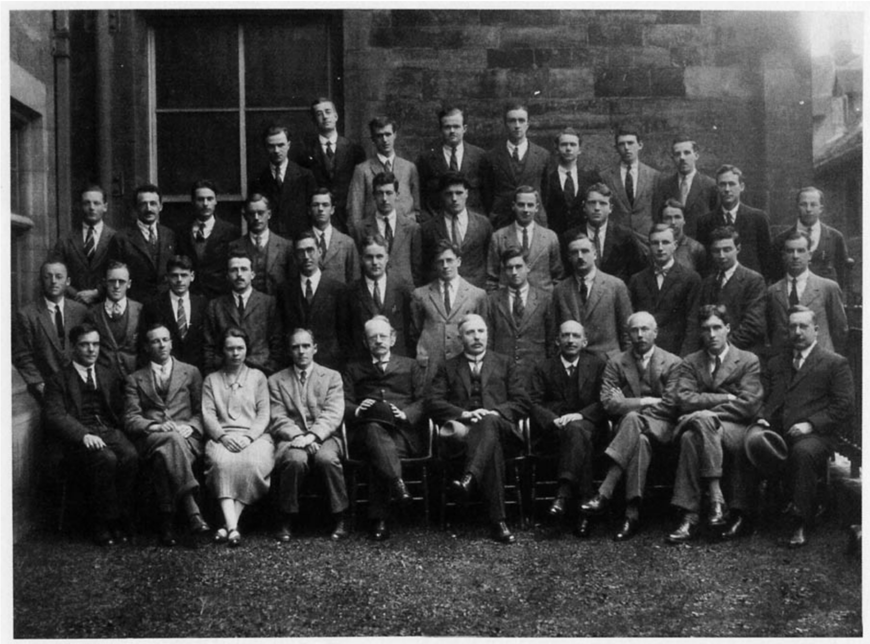

Figure 5. Rutherford's Cavendish Laboratory photograph, 1926. Seated in the front row are seven Nobel laureates along with the redoubtable G. I. Taylor. C. E. Wynn-Williams is the first from the left in the top row.

predicted the possibility that a projectile of relatively low energy could tunnel through the potential barrier of the nucleus instead of going over it, Rutherford's team ceased to raise the voltage beyond a certain high and attainable value. And so accelerated electrons, protons, and alpha particles began to be used by the Cambridge physicists. A new breed of research student arose in the persons of T. E. Allibone, P. Kapitsa, J. D. Cockcroft, and E. T. S. Walton, with engineering expertise, and they constructed accelerators capable of hurling protons and electrons with energies of several hundred thousand volts. The Cockcroft–Walton machine[16] succeeded in disintegrating lithium atoms by so-called "swift protons". The lithium disintegrated according to Equation (2). The energy released was de-

$$ {}^{1}_{1}H + {}^{7}_{3}Li \rightarrow 2\,{}^{4}_{2}He \qquad (2) $$

scribed by Cockcroft and Walton (who shared the Nobel Prize in physics in 1951) thus:[16] *"The evolution of energy on this view is about sixteen million electron volts per disintegration, agreeing approximately with that to be expected from the decrease of atom mass involved in each disintegration."*

This was the first experimental proof of Einstein's long-famous relationships $E = mc^2$, a fact which convinced Rutherford (hitherto sceptical of the power of theoreticians) that quantum and wave mechanics were valuable, even if he himself understood them only imperfectly. It also induced him to invest in the future in the form of a cyclotron, which was developed by E. O. Lawrence in Berkeley, California.

Although Rutherford himself was not directly involved in the Nobel-Prize-winning work of Chadwick, Cockcroft, and Walton (and later Blackett for his beautiful work on cosmic ray showers) he lent tremendous enthusiasm, academic authority, and moral support to all his neophytes and established collaborators. He continued his experimental endeavors, however, and, with Oliphant (thanks to a gift of heavy water made by G. N. Lewis) he formed, on bombarding deuterium with deutrons, evidence for the existence of a hydrogen isotope of mass 3 and a helium isotope of mass 3. In all this he felt deeply satisfied intellectually: the transmutation of the elements so long and so often sought and at last achieved was in one sense the crowning triumph of his life's work. He conveyed something of this satisfaction and boundless enthusiasm in his last book *"The Newer Alchemy"* published in 1937.

Insofar as it was possible to do so within the accommodation and resources of the laboratory, Rutherford sought to encourage other important lines of work. Among these was the work of Kapitsa, the colorful Russian physicist (winner of the Nobel Prize for Physics in 1979 for his discovery of superfluidity, and formidable opponent of Stalin) to search for methods of producing high magnetic fields to send the alpha particles in their paths, and Appleton (Nobel Prize winner in 1947) and Ratcliffe in radio research (and a forerunner of the later work on radio astronomy at the Cavendish). He also backed Kapitsa's project to build a plant for the production of liquid helium and his work in achieving, for short durations, magnetic fields of over 300 kilogauss. This was done in the early 1930s and was made possible by funds from the Mond Bequest for magnetic and low-temperature work (see Figure 6). Rutherford, like his predecessors Maxwell, Rayleigh, and Thomson, also undertook work as a Visiting Professor of Experimental Physics in the Royal Institution of Great Britain in London. He lectured fre-

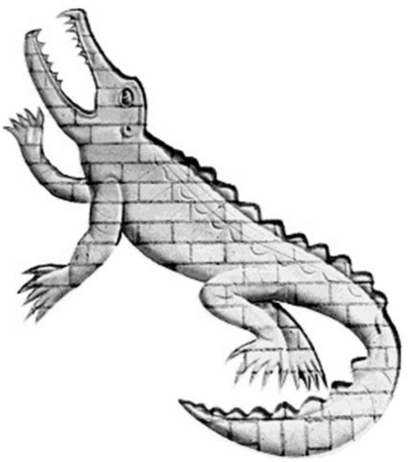

Figure 6. A striking feature of the old Cavendish site is the carving of a crocodile on the outer wall of the Mond Laboratory. This laboratory was built in 1933 by the Royal Society for Kapitza to continue his work on intense magnetic fields (see text). "The crocodile" was Kapitza's pet name for Rutherford, either because of his fear of having his head bitten off by him, or because his voice could be relied to precede his visits, just like the crocodile's alarm clock in "Peter Pan" (from the Cavendish Laboratory web site, 2008).

quently (with copious demonstrations) from behind the kidney-shaped bench that was the spot from where Davy and Faraday had made science and its appreciation so fascinating among the literati and general public in London (see Figure 7).

Rutherford published some 180 research papers and five books—the first being his Silliman Lectures (1905) in Yale University entitled *"Radioactivity"*. He was awarded over two dozen honorary degrees and was elected to membership of most of the national academies of science in the world. King George V conferred upon him the Order of Merit in 1925 and he served as president of the Royal Society from 1925 to 1930. He was raised to the peerage in 1931 as Baron Rutherford of Nelson (a small town in New Zealand). He served as president of the Academic Assistance Council from 1933 (which involved him in a political issue, since the body was created to help scientists who fled Nazism[17]).

He died in a nursing hospital in Cambridge on October 19, 1937, of complications following an operation for a strangulated hernia. His ashes were placed alongside those of Newton, Kelvin, Darwin, and Sir John Herschel in Westminster Abbey.

3. Rutherford and the Controversy Concerning the Age of the Earth

Lord Kelvin (formerly William Thomson) was an exceptionally gifted mathematician, physicist, and businessman. So authoritative were his pronouncements, and so frequently was their validity established, that lesser scientists tended to accept all his calculations and estimates as sacrosanct. Kelvin had estimated the age of the earth to be about a hundred million years, though he did publish even lower estimates. In the last few decades of the 1800s he was on record as having said: *"Consolidation of the earth took place more than 20 million and less than 40 million years ago."*

He arrived at such figures by assuming that when the earth was first formed all the rocks were molten and that they cooled according to the ineluctable laws of radiation physics. Knowing present-day temperatures and the temperature gradient at the surface of the earth as well as the average conductivity and specific heat of the materials of the earth, it is possible with the aid of Fourier's theorem to deduce the interval that has elapsed since the earth was a molten mass. But biologists and palaeontologists were unhappy with Kelvin's estimates. They knew in their bones that Kelvin was wrong: fossil and mineralogical evidence pointed to an older age. In his celebrated *The Origin of Species*, Charles Darwin wrote: *"In all probability a far longer period than 300 million years has elapsed since the latter part of the secondary period."* This statement is in flagrant contradiction to Kelvin's estimates.

Since Rutherford and Soddy knew (and had measured) the rate at which radioactive isotopes decay, and since they could readily measure the amount of residual parent radioactive (or accumulated daughter) isotopes, the age of the earth could be determined directly. In effect, Rutherford and Soddy had uncovered a steadily ticking clock. One determines the age of the earth simply by measuring either the residual radioactivity or the amount of accumulated helium in the (radioactive) mineral. But Rutherford had also identified an unjustified (or erroneous) assumption made by Kelvin in his estimates: namely that there was an extra source of heat *in* the earth which delayed the cooling by radiation alone. This source is radium.

In a brilliantly argued article entitled *Some Cosmical Aspects of Radioactivity*,[18] the write-up of a lecture he gave to the *Royal Astronomical Society of Canada* in 1907, he showed that there is a very large quantity of radium and other radioactive matter distributed over the surface of the earth, so that this matter is continuously supplying heat to the earth. Rutherford showed that: *"A quantity of radium supplies enough heat to melt more than its weight of ice per hour. A pound of radium in the course of a year will emit as much heat as that resulting from the combustion of 100 pounds of good coal."*

In a startling denouement to his lecture Rutherford says: *"Consider, for example, a very dense radioactive mineral from which the helium continuously generated by the radium cannot escape. The amount of helium in the mineral will steadily increase with time, and the total amount present should be proportional to the age of the mineral and the amount of radium contained in it. I have some crystals of a new mineral, thorianite, found a few years ago in Ceylon, which contains about 12 percent of uranium and about 70 percent of thorium. This mineral on heating evolves a remarkably large quantity of helium—more than 10 cc per gram of the mineral. Now it is almost certain that the helium stored up in this mineral has been produced by the breaking up of the radium, contained in it since the formation of the mineral. Assuming the rate of production of helium by radium already mentioned, it can be calculated with some confidence that the mineral thorianite is at least 500 million years old, that is, this interval of time must have elapsed since the formation of the mineral in the earth's crust. This is a minimum estimate, for probably some of the helium has in the course of ages escaped from the mineral… When the constants involved in these calculations are accurately determined, I feel great confidence that this method will prove of utmost value in determining with accuracy the age of the radioactive minerals and indirectly of the geologic strata in which they are formed."*

It is noteworthy that all other radioactive clocks used by earth scientists—potassium/argon, uranium/lead—originate from Rutherford's seminal work.

4. An Incident at the Royal Institution

Rutherford's work did not, at first, please Kelvin. There is an amusing story, told by Rutherford in a letter to his wife, concerning his visit to the Royal Institution in 1904.[19] That year, when the 33-year-old Rutherford came to Britain from Montreal to deliver the Bakerian Lecture of the Royal Society, the Royal Institution took the opportunity of inviting him there also. As Rutherford entered its famous theater he spotted the 80-year-old Kelvin in the audience (see Figure 7). This is what Rutherford felt: *"I came into the room, which was half dark, and presently spotted Lord Kelvin in the audience and realised that I was in for trouble at the last part of my* *speech dealing with the age of the earth, where my views conflicted with his. To my relief Kelvin fell fast asleep but as I came to the important part, I saw the old bird sit up, open an eye and cock a baleful glance at me. Then a sudden inspiration came and I said Lord Kelvin has limited the age of the earth,* provided *no new source was* discovered. *That prophetic utterance referred to what we are now considering tonight, radium! Behold! The old boy beamed upon me."*

The kind of audience that would have confronted Rutherford when he entered the theater at the Royal Institution would have been similar to that which typically attended Sir James Dewar's and others' Friday Evening Discourses (Figure 7). Lord Kelvin and Lord Rayleigh, along with other celebrities (including the Prime Minister of the day, A. J. Balfour, who was Lord Rayleigh's brother-in-law), were frequent attendees at such events.

The story is told that, after Rutherford's lecture in which he raised the issue of the age of the earth, Lord Rayleigh mentioned to Lord Kelvin that it would not be long before he (Kelvin) would accept Rutherford's estimate as being more nearly correct than his own. In fact, Rayleigh said that he would arrange an English Edwardian weekend party at his (baronial) home (Terling Place) and bring together Kelvin and Rutherford. This event did indeed take place, as the visitor's book (now in the possession of the present Lord and Lady Rayleigh) testifies (Figure 8), from which we see that the Schusters also attended.

A little after this event, Rutherford reported to his wife:[19] *"Lord Kelvin has talked radium most of the day and I admire his confidence in talking about a subject of which he has taken the trouble to learn so little… He won't listen to my views on radium, but Strutt (i.e. Lord Rayleigh) gives him a year to change his mind. In fact they placed a bet to that effect."*

The argument was basically whether the energy emitted by radium was derived solely from within the atom's internal structure or whether the energy was somehow collected and redistributed by the radioactive atoms from some "ethereal" source. To Kelvin's great credit, he publicly abandoned his theory at the British Association meeting later that year (1904); and, moreover, he paid up his five-shilling bet!

Figure 7. This scene depicts Sir James Dewar demonstrating the properties of liquid hydrogen ca. 1904 at the Royal Institution, London. The audience shown here (front row from right to left) includes Sir Oliver Lodge, Ludwig Mond, George Matthey, Lord Rayleigh, Sir James Crichton-Brown, Sir William Crookes, the Prime Minister (A. J. Balfour), Sir George Gabriel Stokes, and Lord Lister; Lord Kelvin is also shown, sixth from the center of the bottom left. When Rutherford gave his famous talk on "Radioactivity" in 1904 (see text), his audience would have been similar to this one. Where Dewar stands (holding the thermos flask named in his honor) is where Davy and Faraday also stood in lecture–demonstrations that they gave in the nineteenth century.

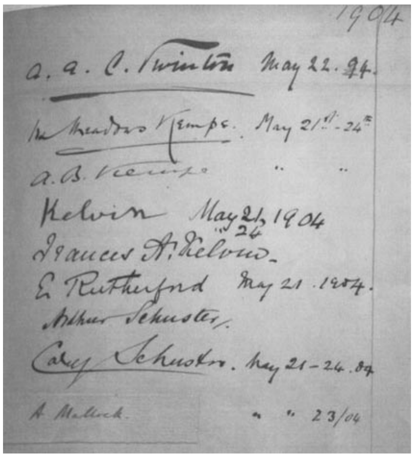

Figure 8. At Terling Place, Lord Rayleigh's home in the heart of Essex where he conducted many of his experiments, there were frequent Edwardian weekend parties. It was at one of these in May 1904 that Rayleigh brought the young Rutherford and Lord Kelvin together. Reprinted with kind permission of Lord and Lady Rayleigh.

5. Some Tributes to Rutherford

It was said that Rutherford, a unique blend of simplicity with greatness, never made an enemy and never lost a friend. He had a quick sympathy with the oppressed, and he was a friend to the outcast. He lived to be a center of universal affection as well as esteem.[14] He had volcanic energy, intense enthusiasm, and an immense capacity for work. Rutherford had no cleverness—just greatness. In addition, he had the three precious gifts of the poet—deep insight, powerful imagination, and a profound love of truth.[14]

Three specific comments will suffice to illumine this immortal scientist: the words of his collaborator Frederick Soddy, those of Samuel Devons, a student in the halcyon days of Rutherford's "Cavendish", and those of Sir James Jeans his friend and admirer.

Soddy's scientific spark went out after he had discovered the existence of (and invented the word) isotopes[20] in 1913, whereas Rutherford's star was always in the ascendant. Soddy generously remembered their revolutionary work in Montréal: *"My relations with the then youthful Ernest Rutherford were uniformly cordial and inspiring, and I came fully under the influence of his magnetic energetic and forceful person-*

ality, which at a later date was to cast a spell over the whole scientific world. My recollection of him was of an indefatigable investigator, guided by an unerring instinct for the relevant and important, and as an unequalled experimentalist seeing amidst all the difficulties, the simplest lines of attack… By the time our cooperation ended, radioactivity, which had already become a considerable jigsaw puzzle, had been put together, and my chief impression of those days remains of an intense mental exaltation as the pieces came together and they were fitted by the single theory of atomic disintegration into a convincing whole."

Samuel Devons, formerly (like Rutherford) Langworthy Professor of Physics, University of Manchester and Fellow of Trinity College, Cambridge was, until his death in 2006, Emeritus Professor of Physics at Columbia University, New York. He was an undergraduate at Cambridge in the mid-1930s, and of that period he recalled:[21] *"Education it seemed, then, to be more a matter of inspiration by example than instruction by precept. To a student of science, and particularly physics, it was Ernest Rutherford who symbolised and exemplified this living greatness, and in the recollection of my undergraduate days it is impossible to separate Rutherford, Cambridge, and the Cavendish Laboratory. …Rutherford was not only one of Cambridge's illustrious Professor's he was* the *Professor. … The Cavendish was Rutherford's domain; his sphere of influence… Benevolent guidance, leadership and intellectual authority flowed from him, and loyalty was returned. One would no more question his influence on those around him than one would that of the sun on the satellite planets. Rutherford, the Cavendish Professor, was the centre of light and warmth and life. It was the natural order if things. Young undergraduate student were way out on the periphery of this constellation but we could bask in the sunlight just the same."*

"In truth," said Sir James Jeans, *"most of his investigations were key ones, each brilliant in its simplicity of conception and far-reaching in its consequences."* Then he proceeds, shortly after Rutherford's death, to say: *"Voltaire once said Newton was more fortunate than any other scientist could ever be, since it could fall to only one man to discover the laws which govern the universe. Had he lived in a later age, he might have said something similar of Rutherford and the realm of the infinitely small; for Rutherford was the Newton of atomic physics. In some respects he was more fortunate than Newton; there was nothing in Rutherford's life to compare with the years which Newton spent in a vain research for the philosopher's stone, or with Newton's output of misleading optical theories, or with his bitter quarrels with his contemporaries. Rutherford was ever the happy warrior—happy in his work, happy in his outcome, and happy in its human contacts."*

6. Epilogue

When I joined the University of Cambridge in 1978 and became a member of the Royal Society Dining Club in 1980, I gradually came into close contact with scientists who had either worked with Rutherford, or who had observed him in action and had been indirectly influenced by his personality, principles, and attitudes. Those who worked with him, like T. E. Allibone, or with his associates (like D. Shoenberg, who was Kapitsa's PhD student) never ceased to express their admiration of him as a charismatic leader and inspiring role model. Others, like Max Perutz,[22] who worked with J. D. Bernal in the Cavendish starting in 1936, talked of the time, shortly after Rutherford's untimely death, when his reprints were made available to anyone who wanted to have them at the Cavendish Laboratory. Perutz said that, on reading them, he was immediately struck by the key principles that animated Rutherford's research: 1) a clear vision of what it was, in a given investigation, that he was trying to prove; 2) the supreme ability to carry out the right economical experiment that yielded that proof; 3) a thoroughness of purpose in his research papers which settled all the ambiguous issues. For Rutherford, the introduction to a paper was the most important part of it. What is it that you are trying to do, learn, or convey?

Perutz and others recalled that Rutherford discouraged people from working late in the laboratory. The department was closed from about 6 pm onwards. *"Do not stay here in the laboratory until late, thinking that you are working hard. Go home and clear your mind and be ready for fresh action the following day."* This is what he often said.

In addition to his numerous admirable attributes, Rutherford could pick, attract, and encourage winners. One has only to look at the department photographs in the Cavendish Laboratory (from 1919 onwards) to realize the truth of that statement. But he did make the occasional mistake. J. Robert Oppenheimer, U.S. theoretical physicist, for example, although he was a student at Harvard, he was turned down as a PhD student by Rutherford. He was, however, taken on by J. J. Thomson, with whom he did experimental work of little significance, before he went off to Göttingen where he collaborated most effectively with Max Born.

It is interesting to reflect that the scientists who are described as *"the father of the (U.S.) atom bomb"* (Oppenheimer) and *"The father of the (Soviet) atom bomb"* (Khariton) were both research students in Rutherford's Cavendish Laboratory, though their tenures did not overlap.[23] It seems from recently available records of Soviet science[24] that the *annus mirabilis* of 1932, when Chadwick discovered the neutron and Cockcroft and Walton split the atom at the Cavendish Laboratory—and when Lawrence built his cyclotron, Anderson identified the positron, and Urey discovered deuterium all in the U.S.—prompted great excitement in Leningrad and Moscow. The eminent Soviet physicist, A. I. Ioffe, as a consequence, organized an All-Union conference on the atomic nucleus. A meeting took place shortly thereafter attended also by eminent foreign speakers including Joliot, Dirac, Rasetti, and Weisskopf.

I am grateful for stimulating discussions with Professors E. A. Davis and A. Howie.

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[2] L. Badash in *Oxford Dictionary of National Biography*, Oxford University Press, **2004**, 48, 381.
[3] *The Times*, London, 31 August, **1931**.
[4] a) E. Rutherford, *Trans. N. Z. Inst.* **1894**, *27*, 481; b) E. Rutherford, *Trans. N. Z. Inst.* **1894**, *28*, 182.
[5] J. M. Thomas, *Angew. Chem.* **2006**, *118*, 6951; *Angew. Chem. Int. Ed.* **2006**, *45*, 6797.
[6] J. M. Thomas, *Angew. Chem.* **2004**, *116*, 6578; *Angew. Chem. Int. Ed.* **2004**, *43*, 6418.
[7] J. J. Thomson, E. Rutherford, *Philos. Mag.* **1896**, 392.
[8] Thomson later described Rutherford as the best student in research he had ever had.[2]
[9] a) E. Rutherford, F. Soddy, *Trans. Chem. Soc.* **1902**, *81*, 321; b) E. Rutherford, F. Soddy, *Trans. Chem. Soc.* **1902**, *81*, 837; c) E. Rutherford, F. Soddy, *Philos. Mag.* **1902**, 370; d) E. Rutherford, F. Soddy, *Philos. Mag.* **1902**, 569; e) E. Rutherford, F. Soddy, *Proc. Chem. Soc.* **1902**, 219; f) E. Rutherford, F. Soddy, *Philos. Mag.* **1903**, 441; g) E. Rutherford, F. Soddy, *Philos. Mag.* **1903**, 445; h) E. Rutherford, F. Soddy, *Philos. Mag.* **1903**, 561; i) E. Rutherford, F. Soddy, *Philos. Mag.* **1903**, 576.
[10] Schuster was descended from an old Jewish business family and received his schooling in Frankfurt and Geneva. He attended college in Manchester then went to Heidelberg to study for his doctorate under Kirchhoff. During 1876–1881 he worked with James Clerk Maxwell at the Cavendish Laboratory, Cambridge, and collaborated with Lord Rayleigh in determining the absolute value of the ohm. He moved on to Manchester University where, inter alia, he investigated the spectra of gases at low pressures. After resigning from his professorship he devoted himself to administrative matters at the Royal Society, succeeding Larmor in 1912 as its Secretary.
[11] Hans Wilhelm Geiger was born in Neustadt, Germany, and studied physics at the universities of Munich and Erlangen before moving to Manchester. In 1912 he returned to Germany, from then until his death holding a series of important positions, including that of director of the German Physical Laboratory, the Physikalisch Technische Reichanstalt in Berlin (1912) and Professor of Physics at Kiel (1925).
[12] Hevesy studied water exchange between goldfish and their surroundings and within the human body; this was the first application of stable isotopes in biology (1934).
[13] "Forty Years of Physics": E. Rutherford in *Background to Modern Science* (Eds.: J. Needham, W. Pagel), MacMillan, New York, **1938**, p. 68.
[14] "Lord Rutherford. 1871–1937": A. S. Eve, J. Chadwick, *Obituary Notices of Fellows of the Royal Society*, **1938**, *2*, 394–423.
[15] M. Oliphant, *Rutherford Recollections of the Cambridge Days*, Cambridge University Press, **1972**.
[16] J. D. Cockcroft, E. T. S. Wilson, *Nature* **1932**, *129*, 242.
[17] He created a post in the Cavendish Laboratory for Max Born, who had to flee from Göttingen, owing to the antisemitism of the Nazi regime.
[18] E. Rutherford, *J. R. Astron. Soc. Can. 1907*, 145.
[19] D. Wilson, *Rutherford: Simple Genius*, MIT Press, Cambridge, **1983**.
[20] After working with Rutherford in Montreal and William Ramsay in London, Soddy took up an appointment at Glasgow University. He later moved to the chair of chemistry in Aberdeen University in 1914 where he remained until 1919 when he became the Dr. Lee's Professor of Chemistry at the University of Oxford. Even as early as 1913 he had said:[19] "*It would not be surprising if the elements… were mixtures of several homogenous elements of similar but not completely identical atomic weights.*" He was the first to call such chemically identical elements with slightly differing atomic weights, isotopes. He showed for example that radium D and thorium C were isotopes of lead. Notwithstanding the award of the 1921 Nobel Prize for Chemistry for his work on the origins and nature of isotopes, Soddy became disillusioned with science and his role within it. He took to writing exclusively in the fields of economics and sociology. In contrast to Rutherford, whose remarks in New York in 1933 where he claimed that anyone who thinks that energy may be extracted from the atomic nucleus is *"talking moonshine"*,[19] Soddy was an ardent believer in nuclear energy and nuclear power. As early as 1912 he commented[19] that "*the still unrecognised 'energy problem' awaits the future*". He saw as man's only hope, atomic energy which *"could provide anyone who wanted it with a private sun of his own."*
[21] See the University of Cambridge web site (for Physics, the Cavendish, Crocodile), **2008**.
[22] J. M. Thomas, "M. F. Perutz (1914–2002); In Memoriam", *Protein Sci.* **2003**, *12*, 1.
[23] I am grateful to Professor Archie Howie for drawing my attention to this fact.
[24] D. Holloway, *Stalin and the Bomb*, Yale University Press, New Haven, **1994**, p. 34; *The Collected Papers of Lord Rutherford of Nelson* (Ed.: J. Chadwick), Allen & Unwin, London, **1962–1965** is an invaluable source of relevant information.