It is a great honour and privilege to present the Rutherford Memorial Lecture here; and doing so has provided me with many opportunities to revive memories and to re-examine the whole range of Rutherford’s monumental contributions to science, a subject that is evergreen and an endless source of interest, enlightenment and inspiration. This has given me much pleasure and gratification.

As my title indicates, what I shall say is essentially of an historical nature, and this perhaps needs some justification before a scientific audience. It might be more appropriate – as indeed has been the practice of many Rutherford Memorial lecturers – to describe or review some recent developments that represent in some way a sequel to Rutherford’s life-work. There are two obstacles to my doing this: first, it is several years since I have been actively engaged in research, so that anything that I might attempt in this direction would be stale, or perhaps worse, second-hand. Second, it is no simple task to delineate the sequel to Rutherford’s scientific opus: there is little in physics or chemistry today in which one cannot trace the profound influence of Rutherford’s discoveries, or those of his collaborators and disciples. Much of modern science forms, in one way or another, the sequel to his life’s work. Even to review retrospectively the immense scope of this work itself, and the genesis and growth of its influence, is quite a challenge. So I have not only to justify the choice of an historical discourse, but, still more demanding, to try to do justice to a most impressive subject.

I knew, or rather saw and watched, heard and listened to Rutherford only during the last five years of his life, from 1932 to 1937 when sudden, tragic death, at age 66, terminated it all too abruptly. These were the last of Rutherford’s ‘golden years’ as Cavendish Professor of Experimental Physics at Cambridge. I was then a lowly undergraduate at Cambridge, and Rutherford – the
Professor – was one of the greatest living scientists: the discoverer of the laws of radioactivity, the identifier of and explorer with the α-particle, the first (with disciple Geiger) to count individual atoms, the propounder of the nuclear atom, and the first to demonstrate the artificial transmutation of one element into another. And apart from his own discoveries, there was a great body of scientific work by his co-workers, disciples and students, that brought him immense respect and affection at Cambridge, and esteem and renown worldwide.

To a young undergraduate in the 1930s Rutherford presiding over the Cavendish was a most impressive, commanding figure; and also a fatherly, vaguely Victorian, perhaps grandfatherly one. But to present this picture of Rutherford would be a most personal, subjective impression; moreover, it is one that has, over the years, been largely displaced from my own mind, even from my memory, by a much livelier, more powerful image. Time has brought a steadily changing perspective. It is now more than 50 years since Rutherford died; about as long a period as that which separated his birth from the time when I had the privilege of being a student in Rutherford’s Cavendish. The 40 years that separated Rutherford in the 1890s from Rutherford in the 1930s seemed an enormous chasm to a student not yet 20; but it has now shrunk to such a degree that Rutherford’s whole life-span now seems like a single coherent era. And there have been innumerable occasions – at Cambridge, at Manchester, at Montreal and elsewhere – to become aware of, to recollect, to appreciate more deeply, and to share the memories of others of the great Rutherford historical legacy. Now all this later perception and acquaintance has become merged with, animated by and virtually inseparable from the impressions of those distant days when I first listened to the voice and words of a great scientist. It is this total impression of Rutherford as a historical figure that I would like to share with you.

FIGURE 1. Lord Rutherford’s birthplace, Brightwater (now demolished).
In history, one problem is always where to begin. Here there is an obvious choice: the year 1895, when Rutherford, aged 24, made the journey half way around the globe to enter the world scientific scene. Rutherford's own landmark work of 1930, *Radiations from radioactive substances* (written with his disciple-colleagues James Chadwick and Charles D. Ellis), was in the early 1930s the 'bible' of radioactivity: the term 'nuclear physics' did not enter into general currency until a few years later. The book opens with a brisk review of the 'history of the rapid progress of our knowledge of atomic physics'. There is no doubt then about where to begin; 1895. It is as Rutherford recalls, the year Röntgen astonished the world with his X rays; followed within weeks by Becquerel's mysterious uranium radiations; and a year or so later by 'the proof of the independent existence of the negative electron'.

The year 1895 was as momentous for science as it was for Rutherford. It was also a milestone year for Cambridge University, to which Ernest Rutherford was transposed from remote Canterbury College, New Zealand, thanks to an Exhibition of 1851 scholarship, awarded in recognition of his 'outstanding industry and exceptional talents' (plus a lucky turn of events!). That same year, the University for the first time, in a radical departure from precedent, admitted students who had already graduated elsewhere, without requiring them to 'read for a degree'. It was a new category, 'Research student'; and Rutherford was to be one of the first so admitted. Indeed, characteristically, he seems to have arrived a little ahead of the change in regulations.

This conjunction of personal, scientific and institutional auguries portended well for the future of Rutherford, of Cambridge and of science. And so it would be.

**CAMBRIDGE, 1895–1898**

Rutherford was not inexperienced in experimental research when he arrived at Cambridge. With extraordinary 'fertility of resource' he had, at Canterbury College, Christchurch, mounted his own, independent investigations in a field very much in the forefront at that time: high-frequency electrical oscillations. Just a few years earlier the young Heinrich Hertz had provided a spectacular climax to, and convincing vindication of, Maxwell's electrodynamics (and the assimilation thereunto of optics). Electricity now seemed to be the universal force; electrodynamics might even rival Newtonian mechanics as the bedrock on which to build physics. It was a natural starting-out base for physical research at that time.

At Cambridge also electrical phenomena and electrical theory were the dominant theme; not least in the investigations of J.J. Thomson, Maxwell's successor (after Rayleigh's brief term) as the presiding inspiration of the
Cavendish; and Rutherford’s first real ‘professor’. Integrating what one might now be designated as ‘classical’ Maxwellian electrodynamics, based on macroscopic phenomena, with the variegated, puzzling, and more intimately molecular phenomena – particularly those associated with the conduction of electricity through gases and the production of cathode rays – seemed to be a major challenging task. It had engaged Faraday, Hittorf, Goldstein, Crookes, et al., and had fully taxed the efforts of Hertz before his tragically premature death. The work was being continued by his disciple–assistant Philipp Lenard; and it now occupied centre-stage at the Cavendish.

Rutherford’s own virtuosity in the realm of electricity would make him quite at home in this setting, and indeed some remarkable achievements with Hertzian waves, in continuation of work he initiated in New Zealand, made quite an impression on his new Cambridge associates. As one put it: ‘There is a rabbit here from the antipodes; and he is burrowing mighty deep.’

Electricity would always appeal to Rutherford as the force ‘par excellence’, at both macroscopic and atomic levels; and his confident familiarity with electromagnetic technique would stand him in good stead in all his subsequent researches.

The new Röntgen X rays were soon co-opted at the Cavendish as a powerful tool in the exploration of this electrical–molecular domain; and the opportunity to participate directly in this development – to collaborate personally with his new professor, J.J. – drew Rutherford’s attention away from Hertzian waves to a field that would soon become his main life’s work.

In this first collaboration for Rutherford and for J.J. Thomson – a masterly experimental study and interpretation of the electrical conductivity induced in gases by X-ray ionization – it is not hard to recognize the mark of Rutherford’s direct, vigorous probing (with a bare minimum of fancy instruments), as well as the mature, guiding hand of the more sophisticated J.J. And J.J. recognized this clearly: ‘I have never met a student with more enthusiasm or ability for original work’. There is little doubt that this early thorough investigation of the ionization process was an invaluable preparation for the future task of unravelling the innumerable subtleties and complexities associated with radioactive radiations. It would help Rutherford probe more deeply, and with seemingly assured intuition, phenomena that so often baffled contemporary, oft-times rival, investigators.

From ionization by X rays to ionization by ultraviolet rays was but a short step. In the meantime, however, the discovery of X rays had led Henri Becquerel more or less directly, if ‘accidentally’, to the discovery of the mysterious uranium radiation (soon to become the archetype of radioactivity). The connection in Rutherford’s work between X rays and uranium was almost as direct, though less fortuitous. Becquerel had observed that his uranium rays,
like the X rays of Röntgen, could induce an electrical discharge. This, to the Cavendish investigators, immediately spelled ions and ionization, and grist for their exploratory mill. Thus, from X rays and ultraviolet to uranium rays and uranium. And this step soon bore fruit: a recognition of the complex nature of the new uranium rays, and its separation into the easily absorbed and strongly ionizing \( \alpha \) rays and the more penetrating, and correspondingly weakly ionizing, \( \beta \) rays. Virtually from their birth, and christening by Rutherford, he would adopt the \( \alpha \) rays as his cherished own. And they would remain his cherished companions throughout almost the whole of his research.

When Rutherford would leave Cambridge for Montreal, he would take with him not only the invaluable experience of his own work at the Cavendish, of his association with his first real professor, J.J., and with his peers (John Townsend, C.T.R. Wilson, H.A. Wilson, Paul Langevin and many others) but also what might be called its ‘ionization cult’. I can vividly recall my first participation, in 1936, in the annual Cavendish Dinner, where the whole Cavendish ‘research family’ joined in dining and wining, and post-prandially, in reviving – or perhaps keeping alive – the early triumphs of the Cavendish. With Rutherford presiding and J.J. at his side, seemingly peering absentmindedly into the nostalgic past, the ions of the 1890s were celebrated in boisterous song, with the hearty chorus lines:

There the atoms in their glory,  
Ionize and recombine.  
Oh my darlings, oh my darlings,  
Oh my darlings, ions mine.

sung to the tune of the music-hall song ‘Clementine’. Atoms, molecules and ions with their universal elemental charges were, for the Cavendish and for Rutherford, no mere philosophical abstractions; they were true and trusted companions in a task whose outlines were now beginning to emerge.

MONTREAL, 1898–1907

His Cambridge experience and his own firm purpose notwithstanding, the prospects facing the young Rutherford at McGill University, Montreal, must have been pretty daunting, as he occasionally confesses in his letters home, to his family and fiancée in New Zealand. He was about to compete – on his own now – with the experienced authorities on radioactivity at the established European centres in France and Germany; and especially with the pioneers of the subject, Becquerel and Marie and Pierre Curie in Paris, whose expertise was matched by incomparable resources of radioactive materials.

But one of Rutherford’s most outstanding characteristics was his resource-
With extraordinary speed Rutherford arouses the interests, enlists the services and secures the collaboration of his new colleagues, in what was, for them, a wholly new venture. With a very modest supply of thorium – which seems then to have been the subject of less attention than uranium – and with simple, improvised yet effective instrumentation, he soon makes a major discovery. It is of a sort of gas or vapour – he non-committingly dubs it ‘emanation’ – emitted by thorium. This ‘emanation’ in turn, yields an electrically charged carrier of further radioactivity; a ‘radioactive deposit’. This result is the reward of picking up, and tracking down with typical perspicacity and tenacity an accidental clue, the erratic electrometer manifestations of some thorium radioactivity, which are traced to the disturbing effects of the draught from an open door!
This early foray into territory of which Rutherford is soon to take full possession, is remarkable in other respects: his full mastery of ionization techniques, which enables him to find his way unerringly amid these bizarre phenomena; his ability to differentiate clearly between diffusion of uncharged molecules and the drift motion of charged ions, although the one rapidly transforms into the other; and most important, his confident use of electrical-ionization measurements to follow (in contrast to the then much used photographic technique) the rapid time development of the processes involved. Indeed here for the first time appears what is to become a symbol of Rutherford’s radioactivity: the exponential curves of growth and decay. In this first example encountered, however, it is not radioactive ‘growth and decay’ strictly speaking: diffusion through the simple paper-envelope container provides the ‘growth’ which balances the short-lived radioactive ‘decay’.

Here too we see a remarkable example of Rutherford’s celebrated intuition: although the carriers of the ‘active-deposit’ appear (puzzlingly, because the radiation itself carries positive charge) to be positively charged, Rutherford is able to put this puzzle aside, pro tem., so that he can concentrate his attention on matters he judges to be of primary importance. Not without justification it has been said of Rutherford, as it was of Michael Faraday, that he could ‘smell the truth’. And, recalling Rutherford’s work at Cambridge with J.J. – blowing ions down a tube to measure mobilities and recombination rates – this ‘lucky’ Montreal episode can be read as a model illustration of Pasteur’s dictum that ‘Accident favours the prepared mind’ (and nose?).

A more profound understanding of the new radioactivity demands a more quantitative appreciation of the ionization process. By combining measurements of X-ray absorption and of X-ray ionization currents in gases, Rutherford is able to estimate the energy required to produce each ion pair; and hence from quadrant-electrometer measured currents produced by his thorium emanation, he can estimate its rate of generation of energy. Furthermore, by quoting the reported factor of 100,000 in the activity of the new element radium, as compared with that of uranium, he can deduce that one gram of radium would liberate some 3200 calories a year. ‘No substance’ he concludes ‘can continue emitting energy at such a rate for many years’ (barring some external source of energy). This is a conclusion somewhat at odds with the Curies’ assertion (which hints at some external agency) that radioactivity is a constant property of the element exhibiting it (as befits an elemental property).

Meanwhile ‘emanation’ phenomena in uranium, similar to those observed in thorium, have been reported by Dorn in Germany, and by the Curies and Debierne in Paris; where also, the regrowth of radioactivity from depleted uranium has been observed by Becquerel. The characteristic times for these processes – days for radium emanation, minutes for thorium emanation, etc. –
are quite different; but the recurrent and quite unprecedented pattern of growth and decay is now clearly emerging.

All these measurements of radioactivity were, at that time, essentially macroscopic; typically electrometer ionization currents. Yet for Rutherford, with his Cavendish experience and background, it was natural enough to visualize the whole process in atomic-molecular terms. But how could atomic changes be related to these observed dramatic phenomena? The inside of an atom was, then, essentially terra incognita; indeed the very notion of atomic change — except, perhaps, for temporarily induced vibrations associated with light emission — was virtually excluded, by definition!

PHYSICS AND CHEMISTRY

In 1900 atoms lie primarily in the domain of chemistry: the irreducible and unchangeable pieces of the chemist’s elements. The physicist’s ultimate piece of matter is the molecule, as, for example, in the gas kinetic model. Becquerel and the Curies had shown, and insisted, that radioactivity was essentially an element-related, i.e. an atomic, process; not a molecular one, not related to atomic interactions, as, for example, occur in chemical compounds. In Rutherford’s vivid imagination, radioactivity was no doubt already pictured as some sort of atomic change, and if so there would be associated chemical change. Chemistry must therefore be capable of providing the means of further experimental exploration. Providentially at this juncture (1902), a gifted young chemist presented himself at Montreal, and Rutherford lost no time in infecting Frederick Soddy with his own boundless enthusiasm of the new science of radioactivity. For two years Rutherford and Soddy, physicist and chemist, joined forces, and with matchless skill and vigour, with bold imagination and breathless excitement began to unravel the subtleties and mysteries of radioactivity; and to open up whole new vistas in physics and chemistry. Providence had also already provided Rutherford with a remarkable, singular tool in the apparent chemical insensitivity of his newly discovered ‘emanation’. Now more thorough chemical tests showed it to be essentially inert, chemically. ‘Emanation’ was, it seemed, not only an exotic radioactive gas, but as a chemical substance a member of a chemically exotic class. Barely three or four years earlier (in 1898) the celebrated chemist William Ramsay had isolated and identified a series of such inert gases: neon, krypton, xenon. Argon had been discovered a little earlier (1894) by Rayleigh and Ramsay. Helium had been identified terrestrially as recently as 1895. Rutherford’s ‘emanation’ could be adopted as the heaviest member of this strange family.

Radium emanation (radon) appeared to be the direct product of the highly radioactive radium (rather than uranium itself); might there not be a similar
more active precursor of thorium emanation, one that might be chemically separable from thorium as was radium from uranium? Such indeed was thorium-X, isolated by Rutherford and Soddy, and displaying the now expected growth and decay phenomenon, in this case with characteristic period of three to four days. (‘X’, as previously in X rays, now begins to appear ubiquitously – uranium-X, thorium-X, etc. – as a token of partly revealed mystery.)

From this emerging general pattern of radioactive change, growth and decay, Rutherford and Soddy perceived and enunciated their famous generalization, articulated in 1902 under the bold title: ‘The cause and nature of radioactivity’. Radioactivity was a spontaneous process, a manifestation of ‘sub-atomic, chemical change’; a process in which chemical atoms, in certain cases, spontaneously break up with the evolution of unprecedented amounts of energy. Rutherford and Soddy insisted that there was nothing here

... contrary to anything that is known about the properties of atoms ... since the causes that bring about these disruptions are not amongst those that are yet under control, whereas the universally accepted idea of the stability of the chemical atom is based solely on the knowledge we possess of the forces at our command.

But none of these forces could influence in the slightest degree the radioactive process itself; controlled, presumably, by far more powerful, inaccessible intra-atomic forces. So what at first sight might have been regarded as a radical overthrow of basic chemical principle – the permanent immutability of the atom – was rather its generalization: namely, the immutability of both the stability and the (radioactive) instability of atoms; immutable, that is, by any known physico-chemical means. To be added then to the dicta of the ‘Conservation of energy and the conservation of matter and the elements’ was another: the ‘Conservation of radioactivity’.

To Rutherford’s colleagues at McGill such bold ideas were quite startling; some even urged him not to publish them lest he expose the University to ridicule. But Rutherford’s own confidence infected others, and prevailed. For Rutherford himself this was perhaps his most exhilarating discovery. When some 30 years later he is ‘elevated’ to the peerage the familiar curves of growth and decay figure prominently in his coat-of-arms, although the conventions of heraldry seem to have demanded that they be turned through 90°! (See figures 3 and 4.)

NEW SCALES OF ENERGY AND ATOMICITY

This perception of radioactivity, not as a consequence of some physico-chemical change, but as the (atomic) change itself, as a property of the state of an element divorced from any perceptible cause, was the key to unravelling the
whole complex of radioactive processes. And although the immense task of identifying the exact nature of each individual process would take decades, the principle of spontaneous decay itself soon opened up whole new domains of large and small magnitudes, previously inaccessible or even unimagined. Their profound impact was soon to be felt in astronomy and geology, as well as in physics and chemistry. Indeed all 'physical' science was about to be transformed, and the transformation would, in a decade or so, be given a further great impulse forward by Rutherford's own new concept of atomic structure.

The older apparent constancy of radioactivity was, in the new scheme of things, interpreted as a dynamic (radioactive) equilibrium between the parent radioactive substance and its (radioactive, in most instances) descendants; with the primary parent sufficiently long-lived (e.g. more than $10^9$ years for uranium and thorium), any change in its amount would be unnoticeable. In such a dynamic equilibrium the transition rate is the same for all stages, so that the amount of each substance present is inversely proportional to its rate of decay; and these could span a range of some $10^{18}:1$. Yet all the substances in the series would be comparably detectable. And thanks to the great sensitivity of the electrical-ionization technique, quantities of radioactive material as small as $3 \times 10^{-18}$ g – far beyond the scope of traditional chemical technique – could now be detected. And because radioactivity was accompanied by chemical change, it could likewise be used as a detector of such change of unprecedented sensitivity.

Rutherford would live to see, some 30 years later with the discovery of artificial radioactivity, this possibility extended from the few special, heavy, natural radioactive elements to the whole range of chemical elements. The
recognition that the vigorous radioactive energy release could be associated with infinitesimally small (by traditional chemical standards) amounts of matter served to highlight the immense energy, per atom, released in a radioactive change: about a million times that of an energetic chemical change, Rutherford estimated. What if this enormous store of atomic energy could be concentrated and released in a controlled way? It was tempting to speculate, as Rutherford occasionally did: one pound of radium emanation could propel a steamship across the Atlantic! And to dream, as Soddy did almost to the point of obsession.

In this early recognition of two vastly different atomic energy scales in the two domains, the ordinary chemical and the radioactive, one can see an adumbration of the later distinction between the two seats of atomic and atomic-nuclear processes, and of the corresponding size–energy correlation. All this is now so familiar in the context of the later Rutherford atom, that it is hard to realize that this was perceived while all that went on inside the atom was still complete mystery.

**CHANCE**

The new law of ‘spontaneous transformation’ – an effect without a cause – was seemingly related to little else in physics or chemistry; indeed, by some ‘authorities’ it was challenged as contrary to the principles of any science. And although expressed, formally, as an ‘exact’ law,

\[ \frac{dn}{dt} = -\lambda N, \]

and one inferred, in 1902, from empirically observed ‘macroscopic’ effects (ionization currents), it was conceived in terms of discrete atomic explosions or eruptions: at any instant, \( dt \), a very few, \( dN \) (an integral number!) of the very many, \( N \), radioactive atoms exploded. Which ones? Presumably any of the \( N \), at random; and if so the law of radioactive transformation would be a statistical one. Statistical laws were, of course, not unknown to physics at the time (for example, those of Maxwell and Boltzmann) but were generally associated with minute, subtle, barely perceptible phenomena. Here, by contrast, the phenomenon was one of powerful ‘explosions’, due, indeed to forces too powerful to be influenced by any known means.

In a real sense the Rutherford–Soddy law of spontaneous decay can be seen (as would become evident some 20 years later) as an early experimental discovery of a general quantum mechanical principle: the statistical nature of elementary transitions. Lest this may seem too much like history by hindsight, one may recall that in Einstein’s treatment, in 1917, of the basic processes of spontaneous and induced emission of radiation from excited atoms, he refers to their essentially probabilistic nature as their ‘radioactive’ character, in clear
reference to the Rutherford–Soddy law. Again, in 1929, at a celebration of the 50th anniversary of Planck's doctoral thesis, in a discussion of the experimental foundations of basic quantum-mechanical principles, Pascual Jordan stressed that the Rutherford–Soddy decay law,

\[ N(t) = N_0 e^{-\lambda t}, \]

was the first experimental result that had an immediate, quantum-mechanical probabilistic-type interpretation. In 1902, Rutherford and Soddy could quote earlier analogous ‘exponential’ laws; Rutherford in physics (the growth-decay of induced electromagnetic currents), Soddy in chemistry (in monomolecular chemical reactions).

When propounded by Rutherford and Soddy, the law of spontaneous decay could call on no direct atomistic evidence. Only several years later, at Manchester, did Rutherford and Geiger, after detecting and counting individual α particles, verify, as von Schweindler had earlier proposed, that fluctuations in the rate of α emission were indeed consistent with an entirely random process; and so, apparently, beyond the reach of traditional dynamics. Well might Rutherford write to Geiger, (actually of the ‘happy Manchester days’) that ‘they wrought more than they realised’.

α PARTICLES AND ‘e’

This vivid picture of spontaneous atomic transformation, with the accompanying violent ejection of α (or β) particle, demanded, of course, thorough investigation of these particles themselves in addition to the atomic changes; and the α particle, which appeared to be associated with the most energetic radioactive changes, became the prime focus of Rutherford’s attention. By applying with persistence and ingenuity the established procedures of deflection by electric and magnetic fields, Rutherford is able (1902) to estimate the α particles’ specific charge and velocity; and he is led to suspect that his α particles are something akin to an ionized hydrogen or helium atom. He can also, using the rough value of the electron charge from his Cambridge colleagues, estimate the fraction of uranium atoms that decay in unit time, and so arrive at a fair estimate – ca. 10⁹ years – of the lifetime of uranium; and with this the suspicion that the helium associated with uranium-bearing rocks could be the products of radioactive disintegrations, accumulated over geological time-spans. Direct measurements by Ramsay and Soddy in the following year (1903), of the actual production of helium by radium (some one-fifth of a cubic centimetre per year, per gram of radium) strengthened this helium– α-particle association. And a few years later (1908), at Manchester, Rutherford and Royds provide the conclusive demonstration that α particles on losing their charge become the molecules of an inert gas exhibiting the true spectrum of
helium. So both the lightest and the heaviest of the inert gases – helium and radon – figure prominently in Rutherford’s work. And in the famous Birley portrait (figure 5) these friends of his youth seem not to be forgotten: at Rutherford’s side are shown the typical glass-ware for handling minute quantities of these (‘noble’) gases.

MANCHESTER

In 1907 Rutherford returned to England, to Manchester, to be ‘closer to the centre of things scientifically’; but in truth Rutherford is already carrying his own centre with him: when in Canada he had attracted and inspired Soddy (Oxford), Hahn (Germany) and Boltwood (Yale), inter alia. Now in England he is again in a new well-equipped laboratory, thanks to the munificence of his predecessor, Arthur Schuster, from whom he also inherits the priceless assets

FIGURE 5. Rutherford, the portrait painted by Oswald Birley in 1932, which hangs in the rooms of the Royal Society. (The Royal Society.)
of an experienced, talented and indefatigable research assistant, Hans Geiger; and incomparable laboratory steward, William Kay; as well as other colleagues – E.J. Evans, W. Makower, T. Royds – experienced in spectroscopy, radioactivity, etc. He brings with him no shortage of problems, and soon resources and tasks are united in fruitful harmony. Perhaps no one better exemplified Faraday’s sentiment, that it is

the great beauty of our science that advancement in it, whether in a degree great or small, instead of exhausting the subject of research opens the door to further, more abundant knowledge overflowing with beauty and utility.

‘Abundant knowledge’ soon begins to flow. Working with Geiger, Rutherford soon advances from detecting $\alpha$ particles in bulk to their individual detection and counting, by ionic magnification of the ionizing effects of the single particles. (Surely here one can recognize echoes of the work of earlier Cavendish fellow-student John Townsend?)

Counting $\alpha$ particles leads directly to the determination of their individual charges (Rutherford never seems to doubt that they all carry the same charge), and the result: $\pm 9.3 \times 10^{-10}$ electrostatic units, stands in intriguing relation to the then ‘Cavendish’ value for the electronic charge: $-3.4 \times 10^{-10}$ e.s.u. Here Rutherford’s celebrated intuition again prevails. Bolstered in his conviction by some additional evidence derived from the magnitude of the radioactive heating effect, and by a recent estimate from Boltwood for the life time of uranium, he chooses to endow his $\alpha$ particles with two electronic charges, and incidentally a mass 4 (H = 1) appropriate to helium; and thus a new value for the electronic charge of $4.63 \times 10^{-10}$ e.s.u. is put forward.

With this new atomic scale Rutherford and Geiger recalculate the then key quantities in radioactivity: volume of emanation in equilibrium with one gram of radium; rate of production of helium by uranium, heating effect and life-time of radium (1760 years); and so on. These, and the comparison with the cathode-ray and ion measurements would seem then (1908) to comprise the whole story. Not quite.

In a footnote to this landmark 1908 paper – entitled ‘The charge and nature of the alpha-particle’ – written, seemingly, as an afterthought, even a surprised one, there is the terse comment:

It is of interest to note that Planck deduced a value of $e = 4.69 \times 10^{-10}$ E.S. unit from a general optical theory of the natural temperature-radiation.

Rutherford’s attention had been drawn to Planck’s work by Joseph Larmor, then Secretary of the Royal Society and through whose hands Rutherford and Geiger’s paper had passed on its way to publication.

Indeed in Planck’s famous 1900 formula there are two ‘undetermined constants’, $h$ and $k$ (cf. W. Wien’s $c_1$ and $c_2$), whose values are determined by fitting
the formula to the experimental observations of F. Kurlbaum & H. Rubens, and of O. Lummer & E. Pringsheim. The value of \( k \), of course, relates directly to that of the electronic charge through the well-known ‘gas-constant’ \( R \), ‘Faraday’ \( F \), and Avogadro’s number \( N \), via the equations:

\[
k = \frac{R}{N}, \quad e = \frac{F}{N}, \quad \text{i.e.} \quad k = \left(\frac{R}{F}\right)e,
\]

so that now a single scale of atomicity ranged over all these phenomena.

But the reverberations of the new quantum physics had, in 1908, hardly spread beyond the Continental circle of Planck, Wien, Einstein, Stark, et al. Its ideas had, as yet, limited impact on, or appeal to, Rutherford, who had, for example, commented to W.H. Bragg, that the ‘... Continental people don’t seem in the least interested to form a physical idea of Planck’s theory’. But a value for the electronic charge; and one that was in startling agreement with his own. That had to be, for Rutherford, a quite different matter!

What was Planck’s reaction to the publication of Rutherford’s new atomic scale? Certainly in 1900, Planck was already well aware of his inference of ‘... the relatively worst known ... (quantity) ... the radiation constant \( k' \), and of the ‘important and necessary task for future research to test it by more direct methods’. But there seems to be no record of direct communication between Planck and Rutherford on this matter before their meeting in Como in 1927. Then, as Rutherford writes in a communication to the 1929 meeting mentioned earlier, Planck told him that Rutherford and Soddy’s publication in 1908 of

... the new determination of \( e \) and its agreement with his own deduction was a great encouragement to him, in confirming the correctness of his theory at a time when little confirmatory evidence was available.

And then, in 1929, referring to Planck’s ‘strange and almost fantastic concept of 25 years ago’, Rutherford confesses that

... the agreement on \( e \) early made me an adherent of the general idea of a quantum of action. I was, in consequence, able to view with equanimity – and even to encourage – Bohr’s bold application of quantum theory to explaining the origin of spectra ... a direct consequence of Planck’s hypothesis which has had such revolutionary consequences in Physics.

‘There was more’, as Rutherford would confide later to his ‘boys’, ‘to Planck than meets the eye’! Indeed two great roots of the new physics: the study of radioactivity and of ‘black-body’ radiation, were, it seems, interacting quite early, though below the surface.

But in Rutherford’s own forward drive, quantum notions were in 1908, still peripheral. He was still to exploit, most powerfully, traditional Newtonian, orbital mechanics in the service of what was emerging as the new (revolutionary?) physics. And before that there were some matters of technique to be settled.
PARTICLES AND SCATTERING

The detailed study of streams of \( \alpha \) particles brought into focus many questions and problems, and in turn provided new opportunities. Ever on the look-out for a new technique – and especially an inexpensive one – Rutherford’s attention is attracted to the work of Crookes, Regener and others on the fluorescence of zinc sulphide crystals under \( \alpha \) particle irradiation, and especially to the apparent detection of scintillations due to individual particles. With Geiger he explores this phenomenon and convinces himself that counting \( \alpha \) particles in this way can be, when attended with due care and patience, as dependable as, and potentially much simpler and more convenient than, the technically more elaborate electrical method. Once so convinced, Rutherford adopts this versatile technique and it is predominant in his work for the next couple of decades.

Attempts to deflect electrically his \( \alpha \) particles have stretched Rutherford’s ingenuity and technical resources to the limit; the \( \alpha \) particle trajectories are stiff, unyielding. And yet, time and again, in passage through diaphragms, slits and foils some deviation or scattering always seems to occur; indeed it cannot be avoided. Moreover the explicit observations of Geiger with student Ernest Marsden reveal that scattering occasionally occurs through surprisingly large angles; even backwards. Electric fields of some 25 000 volts per centimetre – the largest Rutherford had been able to mount – extending over many centimetres, could barely effect measurable deflection of the \( \alpha \) particles. And yet a foil a mere one-thousandth of a centimetre thick, or even thinner, can sometimes turn a particle backwards. What enormous forces there must be, somewhere within the atoms: electrical forces, of course. A simple, direct numerical calculation tells him that electron-size charges spread over typical atomic–molecular dimensions are insufficient. But if the charge is concentrated by a factor \( x \), the electric force would increase by a factor \( x^2 \), and although its duration decreases in the ratio \( 1/x \), the impulse would increase by this factor, \( x \). A factor of 10 000 or more is needed; electric fields of \( 10^{20} \) volts per centimetre!

This vivid conception of what went on inside the atoms traversed by the \( \alpha \) particle, found its full articulation, as everyone knows, in Rutherford’s nuclear atom and the famous scattering formula. It was brilliantly confirmed by the thorough measurements of Geiger and Marsden. And to everyone who worked within the range of Rutherford’s infectious enthusiasm, including Henry G.J. Moseley, Niels Bohr, Charles G. Darwin, et al., its appeal was irresistible.

Rutherford’s atomic theory did not have, in 1911, the dramatic impact of the earlier law of spontaneous, radioactive transformation. It was certainly novel, but hardly iconoclastic: the atomic models such as those of Kelvin and J.J.
Thomson scarcely ranked, even to their authors, as icons! And in any event these developments were cut short by the disaster of World War I; and by war's end Rutherford's, Moseley's and Bohr's ideas had percolated into general scientific awareness, and were accepted tacitly as starting points in the rapid post-war developments.

OLD AND NEW PHYSICS

Thus it was through this decidedly personal route that Rutherford's work, exploiting time-honoured, trusted Newtonian laws, with its $\alpha$-particle orbits strikingly reminiscent of Newton's cometary orbs, was to make its decisive contribution to the new revolutionary physics, with its dramatic realization that these Newtonian laws could not be trusted in the atomic domain.

Was it remarkable good luck that vouchsafed Rutherford's success? Only in the unique case of the inverse-square law does classical mechanics yield the 'correct' quantum-mechanical result; as was realized \textit{a posteriori}. Perhaps this sort of 'luck' is not so rare after all: and there were some outstanding examples in Rutherford's own time.

Had not Clerk Maxwell, the direct inspiration of so much of Cambridge physics, used the most outrageously non-relativistic model of space (or ether) to arrive at his immortal electrodynamic equations? Equations that were subsequently recognized as Lorentz (rather than Galilean) invariant, and that played such a prominent role in Einstein's relativity.

Had not J.J. Thomson, Maxwell's disciple and Rutherford's own teacher, used Maxwell's electrodynamics to interpret X-ray scattering by electrons in complete disregard (unawareness?) of their 'photon' character, so as to make very reasonable estimates of the (surprisingly small?) number of his minuscule electron 'corpuscles' in the vastly heavier atom? This 'lucky' accident was predicated on the availability of X rays of just the appropriate energy: large enough not to be seriously disturbed by atomic binding, and yet small enough, in comparison with the electron rest-mass, to be treated classically.

And this was possible, because $(e^2/\hbar c) \times Z_{\text{effective}}$ is much less than unity for the typical (light) atoms that J.J. explored.

And at about this same time, in 1896, and foreshadowing the discovery of the free electron, H.A. Lorentz provided a 'correct' interpretation of the first Zeeman observations using entirely classical physics. Neither the Rutherford scattering nor the Thomson classical electron radius, nor the Lorentz–Larmor frequencies are 'real' quantum phenomena (none involve $\hbar$ explicitly) but all helped to find a pathway into the new atomic science and thence to the new physics. Perhaps these examples should not be considered as 'accidents', but rather as typical of the manner in which new science grows out of old: of how
historically such ‘windows of opportunity’ are felt out and exploited? Perhaps these ‘successes’ are as essential as the more celebrated ‘breakdowns’ and ‘crises’ in the transition from the old science to the new?

CAMBRIDGE AGAIN

Rutherford’s nuclear atom may well represent the zenith of his achievement, but there were more prizes to be wrought from the mastery of simple, effective techniques, coupled with strenuous and imaginative concentration. By the time he left Manchester to return to Cambridge, now as J.J.’s successor, he had, with the help of his ever-faithful aides – William Kay and the α particle – obtained evidence that convinced him that he had achieved the long-dreamt-of goal of the deliberate control of atomic transformation; specifically of the nitrogen atom. In the path to this success he had set out from some clues picked up by E. Marsden in probing the limits of Rutherford’s atomic model based on simple inverse-square-law electrical forces.

Now at the Cavendish it would be a full exploration of these new ‘sub-atomic’ phenomena, together with a more systematic probing, by α-particle scattering, of the intra-atomic forces and more refined studies of radioactive radiations, that would occupy the main efforts of Rutherford and his collaborators, especially James Chadwick, P.M.S. Blackett and Charles D. Ellis. And in the 1920s these investigations were increasingly in the context of ‘spectroscopy’, in analogy with atomic (optical) spectroscopy with its ‘stationary-states’ and quantum ‘transitions’. This was especially so for the study of ‘nuclear’β and γ graditations, which were now more clearly distinguished and separable from ‘atomic’ phenomena; which latter were largely by-passed in Cavendish physics.

Rutherford himself continued, at times, in his vivid picturization of nuclear goings-on in terms of ‘classical’ orbits and satellites; but the tone is increasingly speculative and tentative, even apologetic. Increasingly the call is for more experimental knowledge, evocative of the view of his old mentor, J.J., that

A theory should be a policy not a creed – its most important work is to suggest things that can be tried by experiment; and for this they should be easily visualised.

But progressively, and inevitably, it would be the new quantum mechanics that would stimulate, guide and provide a basis for interpretation of experiment. It is not without some historical justice that two of earliest interventions of this sort concerned Rutherford’s own α radioactivity, and Rutherford and Chadwick’s studies of α-particle scattering. The first was the resolution of one of Rutherford’s long-standing puzzles: the apparent incompatibility of the well-explained scattering of α particles by, say, uranium with the spontaneous emission, by uranium, of α particles of even much lower energy. The interpre-
tation was, of course, in the context of quantum-wave mechanics; which also provided in this broad context a vindication of the Rutherford–Soddy law of spontaneous transformation, as well as its subsequent extension and particularization, e.g. in the Geiger-Nuttall law relating energy and life time.

The second case was an observation by Nevill Mott, at that time (1928) by Cambridge designation a mathematician, but who would later in 1953 succeed Rutherford as Cavendish Professor. Mott pointed out that the scattering of $\alpha$ particles by helium, because of the identity of impinging and target entities (both helium nuclei) should provide an opportunity to test, experimentally, the quantum-mechanical principle of interference (here of bosons).

These early successes, first introduced into the Cavendish by George Gamow in 1927, also led to the acceleration of the Cavendish efforts to achieve wholly artificial nuclear disintegration, which culminated in the success of Rutherford’s ‘boys’ – J.D. Cockroft and E.T.S. Walton – in 1932.

Rutherford's personal attitude to quantum mechanics remained ambivalent. Although in his own speculations and interpretations, the language of quantum mechanics – energy levels, quantum transitions and probabilities – progressively supersedes classical orbits, collisions, etc., he remains always circumspect of abstract theoretical formalism: ‘playing with symbols’; and yet he is willing, pragmatically if grudgingly, to accept the products of such theorizing. The ‘ultimate test’ he insists ‘is the ability to explain experimental fact’. Rutherford’s attitude to quantum theory (and perhaps also to relativity) is reminiscent of the story of the sceptical rationalist who, when he is derided by his friends for displaying on his door a crass token of superstition (a horseshoe), counters with the excuse that he has heard that these things work whether one believes in them or not!

So by 1930 Rutherford accepts, even welcomes, ‘our friends the theoreticians’ (who now include his own son-in-law, Ralph A. Fowler) at Cavendish discussions. Yet 1932, the ‘annus mirabilis’ of the Cavendish, witnessed a climactic discovery that owed nothing at all to the new arcane theories: that of the neutron by J. Chadwick. Stimulated initially and sustained by Rutherford’s ‘intuitive’ speculations of 1920; made technically feasible by the later (ca. 1930) development of electrical–electronic methods of amplifying and measuring the ionization of individual energetic protons and $\alpha$ particles; and brought to full and decisive realization by the challenging, mysterious radiations from beryllium (first observed by W. Bothe, et al.), and especially their extraordinary properties reported by Irene Curie and F. Joliot from Paris, Chadwick’s discovery was indeed the climax, perhaps the apotheosis, of the Cavendish-Rutherford tradition.

Characteristically opportunistic is the last work (1934–1937) in which Rutherford personally participated. For Rutherford, laboratory work was an
indispensable part of ‘living’. Realizing that relatively modest high-voltages sufficed to produce nuclear disintegrations, he had had built his own (small? ca. 200 kV) ‘personal’ accelerator. A timely gift from a visiting old friend the chemist G.N. Lewis, of a sample of the new ‘heavy water’, and collaborators Marcus L.E. Oliphant, Paul Harteck and others, allows him to exploit his modest equipment to explore the possibilities and novelties of a new projectile; the deuteron. (At last the old favourite, the $\alpha$ particle has been usurped!) Their experiments demonstrate not only the richness of the new phenomena, including the discovery of the new nuclei $^3$H and $^3$He, but also provide an effective experimental verification of that ‘strange theoretical abstraction’, the relativistic equivalence of mass and energy.

Ironically it is the nucleus of mass 3 that plays a key role in the cataclysmic release of energy in the ‘H-bomb’. Rutherford, although the first (1900) to recognize the atom(ic nucleus) as a seat of enormous energy, had all his life

**Figure 6.** Rutherford holding in his hands the apparatus with which the artificial disruption of the nucleus was first demonstrated. (The Cavendish Laboratory, Cambridge.)
emphatically discounted (so much ‘moonshine’) the possibility of its exploita-
tion as a practical source of energy. He insisted on the sharp distinction
between the observation of the (uncontrollable) release of this energy in
radioactivity; its occasional release, but by the expenditure of much larger
amounts of energy, in artificial disintegrations; and its controlled release as a
source of energy on a significant scale. No doubt this attitude was stiffened by
the need that he had felt to counter some of former colleague Soddy’s wilder
speculations and projections with a more sober appraisal of the actualities;
before the discovery of uranium fission, of course.

POSTSCRIPT

Rutherford has travelled the whole path, from the identification of the $\alpha$
particle, then its exploitation, first in probing the atom and then in opening up
the exploration of the nucleus. And now with the new science of nuclear physics
established, he has witnessed the replacement of this gift of nature – the $\alpha$
particle – by a whole new powerful technique; the artificial acceleration of
particles. It might have seemed natural to consider this same evolution repeated
on a higher energy scale; and indeed this was beginning to happen. Cosmic rays
had been discovered, investigated phenomenologically, their nature was on the
point of being identified and the earliest beginnings of their use as a probe,
beyond the nuclear domain, was emerging. But curiously, although aware of
their potential, Rutherford did not show too much enthusiasm for this field of
investigation. In his own life’s work he had amassed so vast an array of new
problems and unfinished tasks, in relation to his own discoveries, that perhaps
even Rutherford’s immense capacity and capabilities had become saturated.
In any event the exploitation of the new domain was to be the task of others,
among them some of Rutherford’s own disciples.

In 1936, in one of Rutherford’s last ‘public’ lectures (the Lockyer Lecture to
the British Science Guild), he recalls the changes of the previous 40 years, how
profoundly the face of physics (and chemistry?) has changed. Even in half that
time the change had been profound, as attested by the title of Rutherford’s
own address to the British Association (meeting in Australia) in 1914: ‘The
existence of the atom’.

One can hardly avoid speculating as to how Rutherford would have reacted
to the enormous changes in style, scale and organization of physics research
since his time; to the developments of the past 50 years that have transformed
the physics laboratory into something worlds apart from Rutherford’s Cavend-
ish, Schuster or MacDonald laboratories. Rutherford did live to see elaborate
and large-scale technique begin to permeate nuclear physics, and even to
accept it, reluctantly, in his own laboratory. Perhaps some premonition of the
even vaster engineering of ‘high-energy’ physics, that would in large measure succeed cosmic-ray research, made him more than circumspect.

The hall-mark of Rutherford’s own technique was simplicity, economy and minimal elaboration; although not to the exclusion of experimental subtlety. Large-scale instrumentation was for him both time and money consuming; and as the fullest understanding and mastery of one’s instruments was for him a sine qua non of successful experimentation, elaborate instrumentation could make large, and essentially diversionary, intellectual demands. Moreover large-scale expenditure implied financial accountability, and this in turn possible constraints in freedom of enquiry.

Science aside, Rutherford expressed a genuine indifference to personal wealth, beyond that needed to maintain his comfortable, unostentatious style of living, one which permitted him to do what gave him real satisfaction. Beyond that, he seemed to regard money as distraction or nuisance. Again one recalls Faraday’s sentiment: ‘I cannot afford to be wealthy’.

Everyone is familiar with the famous picture showing Rutherford, in 1919, holding in his hands the apparatus he used in the first demonstration of an atomic nucleus: and how this picture is often placed in juxtaposition with some contemporary view of a gargantuan installation of present-day ‘high-energy’ physics (such as the accelerators of CERN or FERMILAB), so as to dramatize the enormous changes of half a century or so. It is hard indeed to imagine Rutherford in this world of physics. And it is even harder to imagine Rutherford’s world of science without Rutherford. What remains indelible is not only the immense achievement of Rutherford himself and his innumerable colleagues, collaborators and disciples, but also the immense spirit and energy, the great personal enthusiasm that he shared so generously and genuinely with many others. As has often been declared, Rutherford’s career was a triumph of personality; of him it was said that ‘He never made an enemy or lost a friend’. And are not these qualities which Rutherford brought to the science of his day equally to be prized and esteemed in any era of science, and in any style or scale of scientific enterprise?

This surely is justification for keeping alive and evergreen the record of Rutherford’s unique contribution to science; and the reason why there will always be so much that we can learn from it.