Rutherford, Radioactivity and the Origins of Nuclear Physics

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Abstract

When Ernest Rutherford became Professor of Physics at Manchester University in 1907, he brought with him the research field in which he had played a leading role over the previous few years: radioactivity. Rutherford turned the Manchester physics lab over to studies of radioactivity and radiation, and through his own work and that of his many collaborators and students, established Manchester as a major international centre in atomic physics. It was out of this powerhouse that the nuclear theory of the atom emerged in 1911.

In 1917, Rutherford ‘disintegrated’ the nitrogen nucleus using α-particles, opening up the possibility of nuclear structure. At Cambridge’s Cavendish Laboratory from 1919, Rutherford and his co-workers began to explore the constitution of the nucleus. With Chadwick, Aston and others, Rutherford turned his research school to the emergent field of nuclear physics – a field he dominated (though not without controversy) until his death in 1937.

Exploring the intellectual, material and institutional cultures of early twentieth century physics, this paper will outline the background to Rutherford’s career and work, the experimental and theoretical origins of nuclear theory of the atom and the early development of nuclear physics.
Introduction

Opening the Rutherford Jubilee International Conference in Manchester 50 years ago in September 1961, Rutherford’s former student Ernest Marsden confessed that a funny thing had happened to him on the way to the lecture theatre. “Two of the lady staff were at the Airport to welcome visiting delegates and they placed aloft a board asking that the Rutherford Conference delegates should inquire there. One inquiry they received was from a good lady who came along and asked ‘Are you Jehovah’s Witnesses?’” He didn’t record the answer, but suggested the exchange revealed something about the public status of nuclear physics at that time. In a more pithy remark, he announced that “we are here at this Conference to discuss a very small thing, the atom’s nucleus and its properties. That atom … was born in Manchester of Rutherford.” In the infancy of that work, Marsden recalled [1]:

it was Tom Tiddler's Ground [a favourite term of Rutherford’s for an open area of enquiry]. An investigation was carried out in the old string-and-sealing-wax days with very little expenditure. ... But nevertheless it was easier to make progress in those days. Nowadays we have two lots of people: we have got some experimentalists here and they want machines costing two or three million pounds for further probing of the details of the atom's nucleus. And then we have those very rare people, those theoreticians who calculate in weird jargon and nomenclature of their own the properties of the inner nucleus. And they are quite expensive people because they also require costly computers. But, nevertheless, it is such men and women who are assembled here from all countries, as indeed happened in Rutherford's day ...

In one session of that first big commemorative conference, Marsden was joined by more of the great and the good from the history of early twentieth century Manchester physics, including James Chadwick, Edward Andrade, Charles Galton Darwin and Niels Bohr. In their talks, they too looked back to a golden era of string-and-sealing-wax before the days of big science (and, of course, the innocence of physics before the bomb). Fifty years on, sadly, none of the original players are left. So it’s my brief – and my privilege – today as a historian of science to talk about Rutherford, radioactivity and the origins of nuclear physics.

It’s very easy in celebratory meetings to abstract past science from its context and to focus on what matters to us now. But to do justice to the past and to learn anything from it, we need to look at the context too. And to understand Rutherford and the origins of nuclear physics we need to understand the institutions he worked in, the people he worked with, and the other factors that shaped who he could be and what science he could do. In this talk, I want to look at the various contexts in which Rutherford worked, and to show how these helped shape his science. Given the benefit of hindsight, it’s tempting to assume that with the discovery of the nucleus in 1910-11, nuclear physics came into being fully fledged, with the proto-characteristics of what it later came to be. Yet, as so often with familiar historical episodes in science, the “discovery” of the nucleus was a complex, protracted affair, and “nuclear physics” as a disciplinary label didn’t become established until the early
1930s [2]. The nuclear atom and nuclear physics emerged out of a rich and dynamic scientific context, involving an international cast of characters, brilliant success, controversy, ambition, frustration and sheer hard work: the stuff of lived science. I want to tell you that story. And at the end of it, we may have a slightly different idea of what it is we commemorate this year.

New Zealand and Cambridge

Let me start by saying a bit about Rutherford’s background [3]. He was born in rural New Zealand in 1871, the son of British emigrants and one of twelve children. Educated at Nelson College, then Canterbury College, part of the University of New Zealand, he graduated in 1894 at the age of 23. His thesis was on the “Magnetization of Iron by High Frequency Discharges” – a subject closely related to the contemporaneous work of the electrical engineer Marconi.

In 1895 Rutherford applied for an ‘1851 Exhibition Scholarship’ to travel to Europe to continue his scientific studies, but he came second in the competition. He might have become a schoolteacher in New Zealand, but for the fact that the winner of the 1851 Scholarship decided to get married and stay in New Zealand. So Rutherford got the scholarship. When the news came, he was in the garden digging potatoes. His mother brought out the telegram, and Rutherford flung down his spade and reputedly declared “That’s the last potato I’ll dig” [4]. In that he was right – and for the rest of his life he never did like gardening.

Rutherford had thought of going to Berlin to further his studies – German scientific education was regarded as the best in the world in the 1890s. But instead he decided to go to the Cavendish Laboratory in Cambridge. A year earlier, that wouldn’t have been possible: for the first quarter-century of its existence the Cavendish had only been allowed to accept students from inside the University of Cambridge. In 1895, though, the rules were changed, and graduates from other universities were allowed in for the first time. Rutherford was the first of these outside students to register for an advanced degree at the Cavendish – an important event for both student and laboratory [5].

He faced a good deal of anti-colonial prejudice in Cambridge, but coped by throwing himself into his research. At first, his work was a continuation of what he’d done at Canterbury: he invented a device for detecting wireless waves, and spent a lot of his time sending wireless waves across Cambridge. The Cavendish professor, J.J. Thomson, took a shine to this energetic young New Zealander, and helped him to settle in. J.J. became one of the great influences on Rutherford, and helped reshape his work and his career [6].

The mid-1890s were a remarkable and transformative few years in physical science. A series of discoveries opened up entirely new worlds for exploration. The ionic theory of matter then animating physical chemistry was less than a generation old [7]. In 1894, Ramsay and
Rayleigh discovered argon. Helium and the other rare gases quickly followed, and a new group had to be created in the periodic table, shaking the elemental foundations of the subject [8]. In 1895, Rontgen discovered X-rays. So sensational was this discovery that scientists and medics all over Europe rushed to repeat the experiments and make pictures of the bones inside the hand [9]. JJ invited Rutherford to work with him on the properties of X-rays, and for much of 1896 Rutherford worked on these delicate experiments, gaining experience of gas discharge techniques. It was these gas discharge experiments that led JJ to the discovery of the ‘corpuscle of negative electricity’ – what would later come to be called the electron – in 1897 [10]. Rutherford’s path lay in a different direction.

In 1896, Becquerel discovered radioactivity, a much weaker phenomenon than X-rays [11]. In 1897 Rutherford began to research on the rays emitted by uranium using sensitive electrical measurement techniques, and found they could be divided into two kinds: alpha and beta (gamma rays followed slightly later). Of course, Pierre and Marie Curie had also been researching radioactivity in Paris, and in 1898 their discovery of polonium and radium transformed the field [12]. Marie Curie was closely associated with the development of the radium industry in France, and took a strong proprietorial interest in the emerging radium market – driven by medical, as much as scientific, factors [13]. With these much more intense sources and possible personal and social benefits, radioactivity became a hot topic, exiting public interest and sensation [14]. The Curies were generous in sending samples of their new elements to scientific colleagues elsewhere – including Rutherford. And these samples were what made his work possible.

Montreal

In 1898, Rutherford was appointed Professor of Physics at McGill University, Montreal. At McGill, he researched, lectured and published on the radioactive elements and their radiations. He corresponded with anybody and everybody remotely interested in the subject, and as he began to build his career, he also built his reputation as the authority on radioactivity – partly because of his comprehensive 1904 treatise and textbook Radioactivity [15], and partly through his lively – almost evangelistic – lecturing style. One member of a Rutherford audience described him like this [16]:

We paid our visit to the Physical Society. Fortune favoured us beyond our deserts. We found that we had stumbled in upon one of Dr. Rutherford’s brilliant demonstrations of radium. It was an eye-opener. The lecturer himself seemed like a large piece of the expensive and marvellous substance he was describing. Radioactive is the one term sufficient to characterise the total impression made upon us by his personality. Emanations of light and energy, swift and penetrating, cathode rays strong enough to pierce a brick wall, or the head of a Professor of Literature, appeared to sparkle and coruscate from him all over in sheaves. Here was the rarest and most refreshing spectacle – the pure ardour of the chase, a man quite possessed by a noble work and altogether happy in it.
That came from a classics professor at McGill who usually described scientists as “plumbers” and “destroyers of art”!

So what was Rutherford so happy about? What was his reputation built on? Much of his work in Canada was on the ‘emanations’ (gases) given off by radioactive substances. He became interested in the properties of the radiations emitted by the different elements and the relationships between them. In 1902, in collaboration with the English chemist Frederick Soddy, then also working at McGill, he elaborated the disintegration theory of radioactive decay [17]. Soddy later recalled the experiments, and “standing there transfixed as though stunned by the colossal import of the thing”; he blurted out, “Rutherford, this is transmutation: the thorium is disintegrating and transmuting itself into an argon gas.” With professional reputations at stake, Rutherford shot back: “For Mike’s sake Soddy don’t call it transmutation – they’ll have our heads off as alchemists” [18]. In print, they called it “spontaneous transformation.”

This combination of physics and chemistry was to characterise much of the work in the “Tom Tiddler’s ground” of radioactivity. Rutherford and Soddy were members of a very small circle of people working in this esoteric field, a tiny patch of ground sitting between physics and chemistry (and medicine, for that matter): but they were ranged against the established big battalions of chemistry and physics, where some people still didn’t believe in the existence of atoms, still less their mutability.

Rutherford started to expand the circle by building a research school in Montreal, attracting students from all over the world, training them up and sending them back to teach and train students of their own. One of these students, the German chemist Otto Hahn, would go back to Berlin and, more than thirty years later, be the co-discoverer of nuclear fission.

Visiting Britain for a British Association meeting in 1903, Rutherford rubbed shoulders with the great and the good. He was elected FRS, and was generally lionised. He began to realise what he was missing, and when in 1907 he was invited to succeed Arthur Schuster as Professor of Physics at Manchester University, he jumped at the chance. He’d spent nine extremely productive years at McGill: his time there was recognised by the award of the 1908 Nobel Prize for Chemistry, “for his investigations into the disintegration of the elements, and the chemistry of radioactive substances” [19]. He joked about his “instantaneous transformation” from physicist to chemist, but enjoyed sharing the prize money with his family and buying a new car. His time in Canada had indeed been profitable in more ways than one.
Manchester

Within three weeks of his arrival in Manchester, Rutherford had experiments up and running, and was beginning to fire his new colleagues with his enthusiasm for radioactivity. He began to mix with the social and intellectual elite of Manchester and the London scientific world – membership of the Athenaeum, Council of the Royal Society and so on – and became a man of scientific affairs [20]. He built up his research group, which included a number of women at various times, radioactivity being a field unusually open to them [21]. He also changed the curriculum at Manchester to direct students towards research projects in radioactivity. Publications on the properties of radioactive materials and their radiations began to pour out of the Manchester lab [22].

But it wasn’t all sweetness and light. Rutherford became involved in an acrimonious controversy with the eminent London chemist William Ramsay. Ramsay was also doing work in radioactivity, and the dispute was partly to do with the possession of some radium lent to the Royal Society by the Vienna Academy of Sciences: larger quantities of radium allowed one to produce effects and do experiments no-one else could do, so offered a good way of pushing the field (and one’s career) forward. But it was also to do with Ramsay’s claims to have used radiation to break down copper into lighter elements such as lithium – claims which Rutherford and the other cognoscenti of radioactivity dismissed out of hand [23].

Ramsay was a thorn in his side for several years, but Rutherford pushed on with his own research, helped by a separate loan of radioactive material from Vienna, where a new Radium Institute headed by Stefan Meyer added another node (and a potential and well-resourced competitor) to the growing international network of radioactivity research [24]. With his own students he made significant advances. With Thomas Royds he produced the first spectrum of radium emanation; and with Royds and assistance from the Manchester glassblower Otto Baumbach, he proved in a very elegant experiment that alpha particles are essentially helium atoms [25].

The alpha particle became Rutherford’s favourite tool as he began now to focus on the structure of the atom. With Hans Geiger he used alpha particles as projectiles to explore the forces in the atom through scattering experiments. To detect scattered particles, they developed the scintillation technique, which involved counting tiny flashes of light through a microscope as individual particles hit a fluorescent screen. The experiments were difficult, having in fact to be performed under taxing conditions in a darkened room. One observer described them like this [26]:

There must be two rooms and two workers. One of the rooms must be kept a good deal darker than a photographic dark room, and in it there is one of the men who is to act as the observer ... In this room there is a microscope and scintillation screen, and also whatever may be the set up of radium appropriate to the experiment. In the neighbouring room the other man sits and keeps the record of the count of the scintillations. Thus it may be that what is to be
counted is the total number of scintillations made on the screen in two minutes and at the end of it he will write down the number told him by the observer. When the experimental set-up is to be changed, the [observer] must first blindfold himself, and then the light is put on in the dark room and the other man comes in and resets the instrument. He must turn out the light and go out and shut the door before the observer can uncover his eyes. Altogether it is a laborious business.

Laborious indeed; so much so that Geiger tried to develop an electrical technique for counting the alphas. But a viable Geiger counter would only come later, as we shall see. It was the scintillation technique, with all its difficulties, that formed the basis for much of the rest of Rutherford’s life’s work [27].

By about 1905 physicists were beginning to take an interest in atomic structure and electrical theories of matter, and Rutherford’s former supervisor J.J. Thomson led the field with his model of electrons distributed in a diffuse positive charge – what came to be called the ‘plum pudding’ model (though with Thomson’s Wrangler mathematics it was naturally rather more sophisticated than that) [28]. Experiments on the scattering of alpha- and beta-particles now came to play an important role in framing ideas about atomic structure. In this context, Rutherford and Geiger showed in the scattering experiments that the atom was the seat of intense electrical forces. In 1909 Geiger assigned a young research student from Blackburn, Ernest Marsden, the task of seeing if there was any large-angle scattering. To his (and everyone’s) amazement, Marsden found that a small percentage of alpha particles projected at gold foil were scattered through an angle greater than 90°. It was, as Rutherford later famously put it, “as though you had fired a fifteen-inch shell at a piece of tissue paper and it had bounced back at you” [29]. He concluded, of course, that the alpha particle back-scattering must be the result of collision with an intense electrical force within a single atom. In December 1910 and the month or two that followed, he came up with and refined the idea of the nuclear atom to explain the anomalous scattering – Geiger recalled that “One day in 1911 Rutherford, obviously in the best of spirits, came into my room and told me that he knew now what the atom looked like” [30].

On 7 March 1911 Rutherford presented his first paper on the nuclear atom to the Manchester Literary and Philosophical Society, and so we celebrate the public arrival of the nuclear theory of the atom this year (though Rutherford himself didn’t start using the term ‘nucleus’ or decide on its positive charge until about August 1912) [31]. A fuller paper followed in the *Philosophical Magazine* in May [32], and in the autumn, he attended the first Solvay Congress in Brussels, where one might have expected the hypothesis to be discussed by this elite international scientific audience – including Marie Curie, a few months before winning her Nobel Chemistry Prize. But it was barely mentioned, and clearly did not make much of a mark. Nor was it widely discussed in the literature. In fact, its reception was lacklustre at best. Far from sweeping all before it, the nuclear theory of the atom seemed a bit of a damp squib – at least outside Manchester [33].
That changed two years later. Collaboration was clearly as important for Rutherford in Manchester as it had been in Montreal. In particular, as an experimentalist, he relied in particular on mathematical physicists to calculate the consequences his atomic models. At Manchester Charles Galton Darwin (grandson of Charles Darwin) was his first ‘house theoretician’; from 1911, the young Dane Niels Bohr came to play that role, and others would later [34]. In 1913, Bohr integrated the Rutherford nuclear atom with the quantum theory to try and explain atomic spectra, giving us the Rutherford-Bohr atom that we’re now familiar with. With its wider applicability – its relevance to spectroscopy, for example – Bohr’s reworking of the Rutherford atom created rather more of a splash. It also came at a time of other exciting new work – including Moseley’s work on nuclear charge and atomic number, and the discovery of the displacement laws and isotopy in the radioelements by Soddy and others. This work was in a mutually corroborating relationship with the nuclear atom – each, as it were, both helped explain and justify the other [35].

Radioactivity research at Manchester – and Rutherford very much thought of his discipline as radioactivity, not nuclear physics [36] – now turned to unpack the structure of the atom and to probe the nuclear hypothesis in detail. But the work was interrupted by the outbreak of war, and while many of his young protégés were enlisted, Rutherford worked for the Admiralty on underwater sound detection (for tracking the new menace of submarines) – and, incidentally, took out a patent on the work with William Bragg [37]. During the odd day when he wasn’t travelling to military research establishments or attending meetings in Whitehall offices, he did find time to carry on his scattering experiments, sitting in his little dark room in Manchester counting tiny flashes of light with William Kay, the lab steward [38]. Out of alpha-particle bombardment experiments with nitrogen in 1917 came the startling result that in some cases, particles of hydrogen – what he soon called protons – were released, signifying that the nucleus itself had been disintegrated: he’d ‘split’ the atom. Apologising for his absence from a committee meeting, he wrote “If, as I have reason to believe, I have disintegrated the nucleus of the atom, this is of greater significance than the war” [39].

**Cambridge & Conclusion**

After the war, Rutherford succeeded J.J. Thomson as Professor of Physics at Cambridge, and he returned to Cambridge where he spent the rest of his life working out the consequences of this discovery; if the nucleus could be disintegrated, it must presumably have some kind of structure. In the 1920s and 1930s Rutherford’s Cavendish was a powerful centre both for radioactivity and for imperial physics – an enormous number of PhD students from the various outposts of the Empire passed through, and returned to their home countries to establish modern physics there, contributing to the gradual globalisation of the subject. The nuclear programme also drew heavily on new experimental resources. The delicate photographic traces from the mass-spectrograph developed by J.J.’s former assistant Francis Aston demonstrated the ubiquity of isotopes across the periodic table [40]. In the hands of a tyro like Patrick Blackett (himself later Professor of Physics at Manchester), C.T.R. Wilson’s
cloud chamber offered compelling (if sometimes confusing or contradictory) visual evidence of nuclear disintegrations [41]. And Rutherford brought with him from Manchester James Chadwick, who became his lieutenant, taking charge of the scintillation-counting work and day-to-day oversight of the Cavendish [42].

Again, it wasn’t plain sailing. Rutherford’s programme to explore the nucleus using multiple forms of attack was thrown into turmoil in the mid-20s when researchers at the Vienna Radium Institute led by Hans Pettersson contested the results of the Cavendish in nuclear disintegration experiments, mirroring Rutherford’s experimental programme in an increasingly public and embarrassing controversy. The problem was with the scintillation counting technique, which turned out to be too subjective to be replicated successfully across laboratories [43]. The way out of the impasse was the development of new forms of electrical detectors by a new young breed of wireless-minded researchers adept at the use of valves and circuitry. Though it took time for the new electrical counting technology to stabilise and to be made to give readily reproducible results, it soon changed the field in significant ways [44]. It was out of these technical developments, for example, that James Chadwick’s discovery of the neutron came in 1932, opening up entirely new ways of thinking about and experimenting on the nucleus. The huge importance of wireless technique in the Cavendish in the 1930s also explains, by the way, why many of Rutherford’s “boys” worked on radar, rather than the atomic bomb, during the Second World War.

A second response to the Cambridge-Vienna controversy was much closer engagement between experimentalists and an international cast of theoretical physicists, including Heisenberg, Pauli and Bohr. After the elaboration of quantum mechanics from the mid-1920s, theoreticians vied to apply the new mathematical techniques to the contested arena of the nucleus, and the embattled experimentalists began to listen. In 1932 Cockcroft and Walton used artificially accelerated protons and Gamow’s suggestion of quantum tunnelling to disintegrate a nucleus, ushering in a new age of machine physics [45]. Coupled with the development of linear accelerators and cyclotrons in America (where Tuve and Lawrence explicitly entered the field to try and shed light on the contested area of nuclear disintegration), machine physics – the origins of CERN and other particle physics labs – radically changed the scale and scope of nuclear science [46]. As the machines grew in size and power in the 1930s, Rutherford said that a large new accelerator being built at Cambridge and the vast hall housing it reminded him of a scene from Alexander Korda’s 1936 film of H.G. Wells’ modernist utopia The Shape of Things to Come [47].

And there was another significant change. Those who had entered the field of nuclear disintegration in the wake of the Cambridge-Vienna controversy in the late 20s and early 30s – the wireless enthusiasts, theoretical tyros and machine-builders – were younger researchers, and they lacked the disciplinary identification with the field of Radioactivity that characterised Rutherford and his first generation of students. These newer entrants needed a new disciplinary label for their subject: and they called it Nuclear Physics. This is where the field as we now understand it achieved a sense of professional self-identity, quickly expressed and reproduced through textbooks, conferences and so on.
With these changes in technique, organisation, scale and scope, work on the atom was moving out of Rutherford’s hands into those of his younger colleagues and students. Nuclear physics had grown beyond its begetter. In the mid-1930s he called work on neutron-induced nuclear transformations “The Newer Alchemy” [48] – this was the work that would lead to fission in 1938 and the bomb in 1945 [49]. But Rutherford remained the figurehead of the field, and was in great demand as a public scientific and political figure (he became Lord Rutherford of Nelson in 1931) and as a public lecturer.

When he died unexpectedly in October 1937, the sadness at his loss was mitigated by the enormous legacy of work and students he left behind. With events in 1945 and after, many may feel that to be a mixed legacy: but for Rutherford, the joy of the research and the disinterest in applications shone through. A colleague once said to Rutherford that he always seemed to be on the crest of the wave. He replied "Well! I made the wave, didn't I?" Then, after a moment's reflection, he added, "At least to some extent" [50]. As we mark the centenary of a discovery which – for better or worse – has changed the world, who could disagree with that?

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