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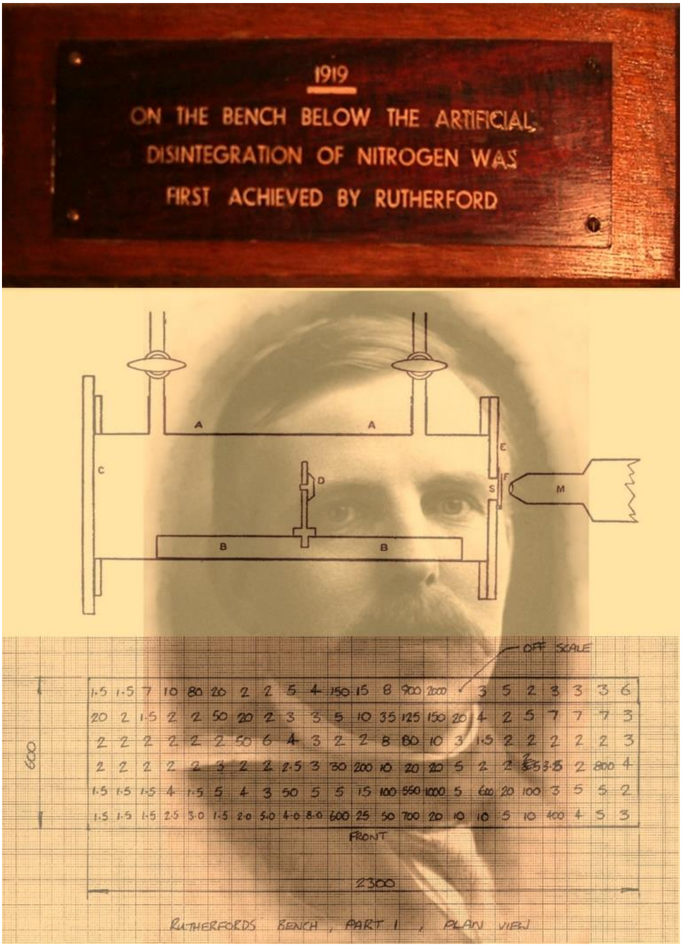

The Centenary of Transmutation

Special Issue October 2021

This special issue is dedicated to the memory of Professor John Pickstone and Dr Jeff Hughes of the Centre for the History of Science, Technology and Medicine (CHSTM) for their unstinting support for the preservation of Manchester's science heritage. Their lively, insightful and witty contributions to our meetings are much missed.

The front cover image illustrates a plaque (top) commemorating "1919. On the bench below the artificial disintegration of nitrogen was first achieved by Rutherford", erected in the old Schuster Laboratory likely during the 1950s before Physics evacuated to its new buildings. The apparatus described in part I of the 1919 tetralogy "Collision of alpha particles with light atoms" is also reproduced (middle). Rutherford can be seen staring in to the space where the nitrogen disintegrations occurred, between a radium C source of alpha particles and a zinc sulphide scintillation screen, giving rise to long-range H-particles observable through a microscope. The bench on which the experiment was conducted is extant, but was found to be quite radioactive (bottom). The pattern of radioactively likely indicates where on the bench the apparatus was located.

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Foreword

Welcome to this, the seventh special issue of the newsletter, being a record of talks given at the History of Physics Group meeting entitled:

'The Centenary of Transmutation'

which was held in Manchester, in June 2019. It was organised by Neil Todd and Peter Rowlands and as with other issues enables us to bring these presentations to those members who are unable to join us on the day. I should like to extend my thanks to all the speakers for devoting the time and effort necessary to produce written versions of their talks.

Malcolm Cooper
Newsletter editor

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About the speakers and organisers

Dr Neil Todd
University of New South Wales, Australia

Neil Todd received a BSc in Theoretical Physics from the University of Exeter before switching fields to Psychology, completing a PhD at Exeter on the topic of motor timing. After post-doctoral work he was appointed Lecturer in Psychology at the University of Manchester at a time when Psychology occupied the former Physics Buildings. During this period he became interested in the history of physics at Manchester, especially after the buildings were found in the late 1990s to be contaminated with radioactive substances dating from the Rutherford era. He has written several articles on the history of radium and proposed a new field of "radio-archaeology", which forms the topic of his forthcoming book *"Radioactive Ghosts"*. He is presently Senior Research Fellow in the Clinical School at the University of New South Wales, Australia.

Dr Peter Rowlands
University of Liverpool

Peter Rowlands is Honorary Research Fellow in the Physics Department, University of Liverpool. He is a theoretical physicist and historian of science, and author of many papers and books in both areas. His physics books include *Zero to Infinity* and *The Foundations of Physics*, while his historical works include a trilogy on the physics of Isaac Newton and two books on Oliver Lodge.

Dr. John Campbell
University of Canterbury, NZ.

John Campbell is a retired physicist at the University of Canterbury, Rutherford's old university. He is the author of *Rutherford Scientist Supreme*, *Rutherford's Ancestors,* and *www.rutherford.org.nz*; the organiser of the Rutherford Origin in Nelson, and the Rutherford Memorial at Havelock; and co-producer of the 3 hour documentary *Rutherford* which was based on his book. These projects involved him raising over one million dollars.

Professor Brian Cathcart
Kingston University London

Formerly a journalist at Reuters and the Independent newspapers, Brian Cathcart has for the past decade been a leading campaigner for measures to raise ethical standards in the UK press. He is the author of books on both current and historical themes, including two relating to nuclear history: *Test of Greatness: Britain's Struggle for the Atom Bomb* (1994) and *The Fly in the Cathedral: How a small group of Cambridge scientists won the race to split the atom* (2004).

Professor Robin Marshall
University of Manchester

Robin Marshall was appointed as "Professor of Experimental Physics" at Manchester University in 1992 to lead the Particle Physics Research Group. He was elected a Fellow of the Royal Society in 1995 and awarded the Max Born Medal and Prize by the German Physics Society in 1997. He now lives in the Rhone Valley near Avignon, writing, publishing and painting.

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Editorial

Neil Todd, Peter Rowlands and Malcolm Cooper

Ernest Rutherford was probably the most significant experimental physicist in the first half of the twentieth century, both for his own discoveries and for those made by others in the laboratories he directed. He took the newly discovered phenomenon of radioactivity and made it the instrument of the most penetrating investigation of the nature of matter before the advent of particle accelerators. Although he made major discoveries at all of the institutions where he worked, a very significant part of his most important work was accomplished during the twelve years when he was Langworthy Professor of Physics at Manchester, from 1907 to 1919, where his colleagues and students included Moseley, Bohr, Geiger, Marsden, Chadwick, Hevesy, Russell, Boltwood, Nuttall, Makower, Andrade, Lantsberry and Kay, to name only the most outstanding of many. This period culminated in the achievement of artificial nuclear transmutation, as revealed in a tetralogy of papers in 1919[1].

Rutherford's whole programme of work using radioactive materials was aimed at explaining and understanding the concept of how one chemical element transforms into another, which he saw as a key to understanding the ultimate nature of matter. Radioactivity was seen as involving the "disintegration" of that part of the atom which explained its chemical nature. His ultimate success in finding a way of doing this, using directed alpha particles, was a continuation of his discovery of disintegration as a natural process with Soddy in 1902[2].The identification of the nucleus as the seat of this activity meant that he could produce changes using alpha particles, and this was a programme he had conceived even before the experiments published in 1919. Part of this work involved trying to find structure in the nucleus, using a primitive form of shell model, which would help to explain how the composite nucleus disintegrated.

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[1] Rutherford E. (1919). "Collision of α-particles with light atoms*", Phil. Mag. VI*, 37: "I. Hydrogen", 537–561; "II. Velocity of the hydrogen atom", 562–571; "III. Nitrogen and oxygen atoms", 571–580; "IV. An anomalous effect in nitrogen", 581–587.

[2] Rutherford E, Soddy F. (1902). "The cause and nature of radioactivity, Part I", *Phil. Mag. IV*, 21, 370–396.; Rutherford E, Soddy F. (1902). "The cause and nature of radioactivity, Part II", *Phil. Mag. IV*, 23, 569–585.

At a later date he took transmutation in a new direction by effectively reversing the disintegration and performing the first fusion reaction with Oliphant and Harteck[3].

This special issue *"The Centenary of Transmutation"* is the second of two issues which have marked centenaries of several remarkable discoveries at the Physical Laboratories of Manchester during Lord Rutherford's tenure as Langworthy Professor. Previous meetings (held in the original buildings at the University of Manchester) marked the discovery of the atomic nucleus in 1911 and then the contributions of Niels Bohr and H G J Moseley to the quantum theory of the atom and concept of atomic number in 1913/4[4]. As before, the meeting was held in the original buildings at the University of Manchester and we were very pleased to have a set of speakers (authors) who are experts in the field of Rutherford history.

In the first of the articles Neil Todd[5] gives an account of the Physical Laboratories which opened in 1900 and the way in which Rutherford re-moulded them for his own purpose after his arrival in 1907. None of the great discoveries could have taken place without the extraordinary element radium, a large quantity of which Rutherford received in 1908, but given its nature it was inevitable that contamination occurred as a result of its use. As Todd has documented, however, the contamination should be considered a form of archaeological data and, in conjunction with other information, he has been able to piece together where much of the historic work was done, including the transmutation experiments. We are fortunate in that we have a precise record of the location and the bench on which Rutherford did the work is preserved. Sometime before the Department of Physics relocated in the 1960s a number of memorial plaques were erected at the historic sites and above Rutherford's bench, as it became known, was emplaced a plaque which noted:

"*1919. On the bench below the artificial disintegration of nitrogen was first achieved by Rutherford*".

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[3] Oliphant MLE, Harteck P, Rutherford E. (1934). "Transmutation effects observed with heavy hydrogen", *Proc. Roy. Soc. A*, 144, 692-703.
[4] M Cooper (Ed). (2012). *From Nucleus to Neutrons: 1911 – 1932,* Institute of Physics, London.; A video recording of the 2013 meeting can be found at http://www.ehphysg.eu/e11-p8v41.html.
[5] Todd NPM. (2021). "The Physical Laboratories of the University of Manchester: Historical and radio-archaeological perspectives" in M. Cooper, P. Rowlands, NP. Todd (Eds.) *The Centenary of Transmutation*, Institute of Physics, London.

John Campbell [6] in his article gives a description of the series of experiments and discoveries which culminated in the 1919 publications, noting from Rutherford's private letters that he clearly intended in advance of this work to attempt to induce disintegration artificially by the close collision of alpha particles with the nuclei of light atoms – to "break up atoms" as he wrote to Bohr in 1915. The popular phrase "splitting the atom" to describe disintegration probably arose from this kind of language and was enshrined in an unofficial coat of arms designed by his students in 1923. If Rutherford did not himself use the term transmutation in the 1919 tetralogy, it was widely understood by his contemporaries at the time that transmutation was exactly what it was. (He did, however, as we will show, use the term in 1914 in the *more popular context* of a lecture outlining the intended course of his future work[7].)

To give some examples, as Robin Marshall notes[8], Arthur Eddington at the 1920 British Association meeting seized on Rutherford's result to postulate stellar nuclear reactions declaring "What Rutherford can do in his laboratory . . . . should not be too difficult in the Sun.". Marshall further brings to our attention the proceedings of the 1921 Solway Conference where Rutherford's discovery was discussed. As Rutherford had carefully documented, the disintegration collisions did not conserve kinetic energy. The ejected proton (H-particle) had more energy than the incoming alpha-particle and the heavy recoil atom had a range close to that of oxygen. These results caused Jean Baptiste Perrin at the 1921 meeting to observe that the inelastic nature of induced disintegration reactions could only be explained if there was another explosive source of energy involved in a disintegration reaction which resulted in a nuclear reorganization and a "transmutation".

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[6] Campbell J. (2021). "Rutherford's road to 'splitting the atom'" in M. Cooper, P. Rowlands, NP. Todd (Eds.) *The Centenary of Transmutation*, Institute of Physics, London.

[7] Rutherford E. (1916). "The constitution of matter and the evolution of the elements. The William Ellery Hale Lecture given to the National Academy of Sciences, Washington, D.C., 1914" in *The Annual Report of the Smithsonian Institution for the year ending June 30, 1915*, pp. 167-202.

[8] Marshall R. (2021). "The nuclear force and transmutation" in M. Cooper, P. Rowlands, NP. Todd (Eds.) *The Centenary of Transmutation*, Institute of Physics, London.

If Rutherford's contemporaries were mostly clear about the significance and interpretation, that cannot be said of the reporting in the popular press, as Brian Cathcart[9] documents in his piece comparing public reactions to the 1919 discovery and the 1932 Cockcroft and Walton "atom splitting" headlines. Among the lurid headlines at the time the *Manchester Guardian* in June 1919 reported the discovery as "*Nitrogen a Compound? Sir Ernest Rutherford's latest discovery*". There were though some notable exceptions and Cathcart highlights an article in the *Yorkshire Post* from August 1919 which he suspects may have been authored by WH Bragg. Whoever the author was, it cleverly described the significance of Rutherford's discovery in terms that the alpha particle, itself a product of spontaneous transmutation ("disintegration"), may induce yet a further artificial transmutation ("disintegration") when colliding with another atom. Whether the *Yorkshire Post* article was related or not there was in fact a subsequent article in the *New York Times* in December 1919, as is illustrated by Campbell, where the term transmutation even made it to the headlines: "*Alchemist's goal reached by Briton? Paris Matin says Sir Ernest Rutherford has discovered Transmutation*".

The final article in this issue, by Todd and Rowlands[10], was not presented at the meeting, but addresses some of the unanswered questions that were raised on that occasion and in subsequent discussions. One issue which arose from the meeting was the origin and historical usage of the word "disintegration" in comparison with "transmutation". A second was origin and use of a chemical notation to describe nuclear reactions. Taken for granted today, it was used neither by Rutherford nor Blackett at the time of their publications, and only came in to use some time after. It is of interest, and is instructive to the history of the period, therefore, to trace when exactly the chemical notation was introduced and by whom. Todd and Rowland's investigation reveals the progenitor as nuclear chemist William Draper Harkins.

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[9] Cathcart B. (2021). "'Splitting Atoms': the news media and public perception of transmutation" in M. Cooper, P. Rowlands, NP. Todd (Eds.) *The Centenary of Transmutation*, Institute of Physics, London.

[10] Todd NPM, Rowlands P. (2021). "Transmutation, the concept of nuclear 'disintegration' and the origin of the nuclear chemical notation" in M. Cooper, P. Rowlands, NP. Todd (Eds.) *The Centenary of Transmutation*, Institute of Physics, London.

Opening address given to the meeting by Sean Freeman

Welcome to Manchester, to the University and to the Physics Department – well at least to our old premises vacated in the 1960's… We are here today to mark one hundred years since the publication of a series of four papers by Ernest Rutherford – then the Langworthy Chair of Physics at the Victoria University of Manchester. We have an interesting programme of expert speakers – I'm not an expert on the subject matter for today. But, as a way of introduction, I want to set the scene and make a few comments as a jobbing nuclear physicist.

Rutherford moved to Manchester in 1907, after performing work on radioactivity at McGill in Canada that won him the Nobel Prize for chemistry. It probably attests to Rutherford's genius that arguably his most famous work was done after the Nobel Prize whilst at Manchester. Between 1907 and the start of the First World War, he achieved a number of other important results that defined the start of the field of nuclear physics. He had sorted out the structure of the atom and discovered the atomic nucleus with his interpretation of the famous Geiger and Marsden gold foil scattering experiments. (This finding – along with football, cotton mills and Boddington's beer – is still used in marketing the city of Manchester, other Manchester beers are available!). He proved that alpha radiation is composed of helium nuclei; and with Geiger developed the first ionisation chambers to detect radiation. The work we discuss today is essentially the first initiation and observation of a nuclear reaction.

The work was done during World War I, sporadically by Rutherford when he could in between war work. It followed on from some initial experiments by Marsden who had earlier found the intriguing result that swift hydrogen nuclei were observed when investigating the passage of alpha particles in gases. Rutherford's work proved categorically that these particles were indeed protons (in the terminology soon to be adopted) and found that their incidence dramatically increased with the introduction of nitrogen gas – many more than could be explained by protons knocked on from any hydrogenous material in his apparatus. He very carefully and painstakingly eliminated all possibilities other than that it was the alphas interacting with nitrogen nuclei that produced the protons via a nuclear reaction.

Later experiments showed that what was true with nitrogen was true with other gases and metal foils – he saw protons liberated from nuclear reactions on many targets. This was the discovery that protons were therefore a universal constituent of all atomic nuclei – a fundamental constituent of atoms. Rutherford remained a bit bothered – he couldn't relieve himself of the worry that the apparatus wasn't completely hydrogen free and the protons were just being knocked out of some unrevealed hydrogenous material. But in 1921 he did careful experiments with James Chadwick which showed that protons knocked on from hydrogen gas had demonstrably less energy that those liberated from reactions on nitrogen nuclei. Later painstaking research done by Patrick Blackett, at Rutherford's suggestion, in Cambridge and published in 1925, successfully used a cloud chamber to find visible tracks of the disintegration that Rutherford had discovered at Manchester. Blackett thus became the first person to reveal the details of the process – i.e. of alpha particle capture with the ejection of a proton to leave a residual nucleus of oxygen. (Incidentally, Blackett moved to Manchester in 1937 as a professor and won the Nobel Prize in 1948 for later work on cosmic rays).

My esteemed colleagues will give you a much more detailed account of the context, the experiments, and the implications – and I hope they will forgive me for any historical inaccuracies in my account so far! I'm not a historian. I'm an experimental nuclear physicist when not running the School of Physics and Astronomy in Manchester. But perhaps I could sketch out some of the implications of this result in terms of scientific and societal impact and how the echoes of it still influence us today.

In my own field of curiosity-driven nuclear physics, we are still performing nuclear reactions. We use them to measure the shapes and sizes of atomic nuclei and to probe the quantum motion of protons and neutrons inside. For many years, the ingredients we used in these reactions were restricted to those we can find naturally in nature (stable or very long-lived isotopes) – which correspondingly means that we could only make a small subset of all the isotopes that are expected to exist. Indeed, we were missing out on many of the isotopes that only exist for mere fractions of a second, but which fleetingly play important roles in huge chains of nuclear reactions that occur naturally in extreme astrophysical sites that drive processes that manufacture the full range of chemical elements we see around us in nature out of the hydrogen and helium that were produced in the Big Bang. However, there are new research facilities being built around the Globe that use a primary nuclear reaction to produce a radioactive nucleus that is then itself used to initiate a second reaction. With these radioactive nuclear beam facilities, we are studying strange and exotic nuclear structures and understanding nucleosynthesis in the Universe. My own research team recently commissioned a spectrometer at CERN to measure the reactions induced by radioactive nuclear beams. Indeed, Rutherford's own reaction – alpha-in, proton-out, the so-called alpha-p reactions, turn out to be very important in processes that happen in heavy stars and in the accretion disks of certain binary systems. But Rutherford's reaction drove several avenues in nuclear physics in the early part of the 20th century.

During the 1920's, it became clear that using alpha particles from radioactive sources was a restricted approach. In order to initiate a nuclear reaction, two nuclei must be pushed together within the limited range of the nuclear forces between them – indeed, Rutherford's reaction was the first indication that nuclear forces exist. Energy is needed to overcome the electrostatic repulsion between the reacting nuclei and the energy available in radioactive sources is limited. This drove an international competition in the 30's to build the first particle accelerator – narrowly won by Cockcroft and Walton in Rutherford's laboratory in Cambridge. The development of accelerators with higher and higher energies in subsequent decades (supported by early cosmic-ray observations) gave birth to the field of elementary particle physics, now performed with some of the highest energy accelerators available, such as the LHC at CERN. But accelerators have found practical uses for society from cancer therapy and production of medical isotopes through to their use as sources of light and X-rays, and are used to probe the structures of materials and are used in security scanning.
Rutherford's work provoked a number of research groups in the late 1920's to survey the reactions of alphas on various targets looking for resulting protons and sometimes gamma-rays. Groups in Paris, Berlin and Cambridge found unusual and exciting results in the bombardment of beryllium targets, which led to the discovery of the neutron by Chadwick. On-going research into neutron-induced nuclear reactions led to the discovery of fission and the development of nuclear power stations and other, perhaps less positive, fission and fusion devices used as weaponry.

So, the impact of these results obtained in rudimentary labs in a northern industrial city, by a genius with a careful and painstaking approach, have therefore resonated down the decades – initiating whole new fields in physics and supporting other science and engineering disciplines along the way as well as helping to shape the society we live in today.

We have an exciting programme today – and it will be interesting to hear the details, context and implications of those four papers published in the summer of 1919 from a series of experts in the scientific history and historical context

Before we start, I want to sincerely thank the organisers - Neil Todd and Peter Rowlands - for all their efforts in making this meeting happen, to the speakers that we are just about to hear, and also for your participation in our event today.

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The Physical Laboratories of the University of Manchester – historical and radio-archaeological perspectives

Neil Todd, University of Exeter, UK

It is fitting that a meeting in June 2019 to celebrate the centenary of Rutherford's 1919 discovery of a new physical process, that of artificial transmutation, took place within the buildings in which that discovery occurred. Although designed at the end of the 19th century by Arthur Schuster and architect JW Beaumont for the purpose of research in and teaching of topics of classical physics, the erection of Physical Laboratories of the University of Manchester coincided with an earlier series of discoveries, X-rays 1895, radioactivity 1896, the electron 1897 and radium in 1898, the same year as the foundation stone of the Laboratories, which were to spark off the remarkable transformation in physical science referred to by some historians as the second scientific revolution. By the time Rutherford arrived in 1907 the revolution was well underway, not least thanks to Rutherford and Soddy's 1902 "disintegration" theory of successive transformations (spontaneous transmutations) to explain radioactivity. However, it was surely the further series of discoveries which occurred here between 1907 and 1919, the atomic nucleus 1911, the Bohr-Rutherford quantum atom and the firm establishment by Moseley of the concept of atomic number 1913, to name only the most outstanding, culminating in the 1919 publications, which justifies the epithet of the birthplace of modern physics for the Manchester Physical Laboratories.

These discoveries, almost without exception, could not have taken place without the element radium which, along with its daughter elements, provided sources of energetic particles. Radium, perhaps unique among the radioactive elements for its potency and half-life, also has a very high propensity to give rise to the contamination of everything it comes into contact with, and this was a problem which was to plague Rutherford throughout most of his career (until radium was made redundant by the invention of machines which could do the same). Manchester was not spared the contamination problem and traces of it were to remain until recently only after several cycles of remediation. Although potentially a health issue, the contamination is also a unique kind of archaeological data which can provide information about the human activities which caused it. In this paper I will give an account based on a study of the patterns of contamination, in conjunction with historical data, which has allowed a reconstruction of how Rutherford moulded the Physical Laboratories for his own purposes. The paper is in three parts covering the history of the building before, during and after Rutherford.

I: Before Rutherford, 1898 - 1907

The New Physical Laboratory of the University of Manchester

Towards the end of the 19th century the Department of Physics was outgrowing the space available to it in the basement and 1st floor of the original 1873 Owen's College building[1],[2]. Arthur Schuster was instrumental in persuading the University to agree to the establishment of a new Physical Institute, to be located on Coupland Street, and in soliciting a number of large donations towards the cost of its construction and in equipping it. The design of the new building was based on careful study of the leading physical laboratories of Europe in collaboration with the Manchester architect J.W. Beaumont[3].

Figure 1. The architect's drawing of the New Physical Laboratories

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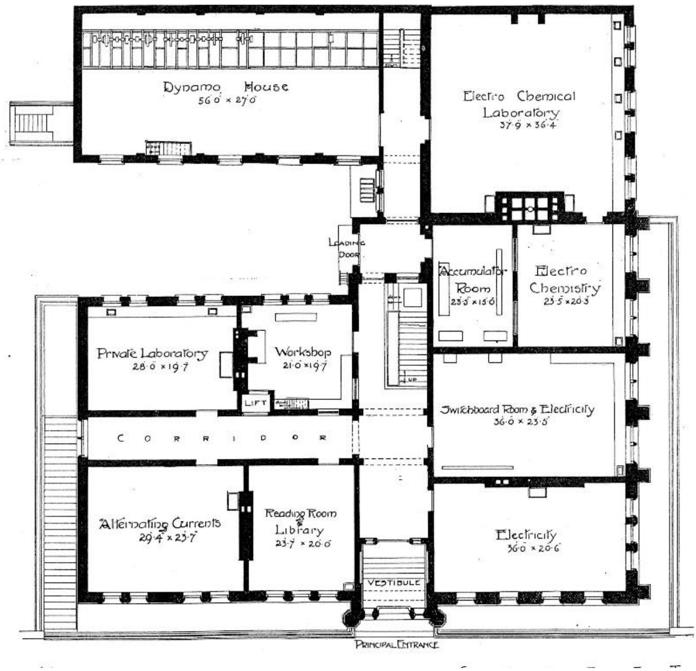
[1] Thomson J. (1886). *The Owens College, its Foundation and Growth*, Waterlow and Sons, London.

[2] Hartog PJ. (1900). *The Owens College, Manchester: A Brief History of the College and Description of its Various Departments*, Waterlow and Sons, London.

[3] Schuster A., Hutton J. (1906). *The Physical Laboratories of the University of Manchester: A Record of 25 Years' Work*, Manchester University Press, Manchester.

The official opening of the new Physical Laboratories of the University of Manchester was conducted by Lord Rayleigh in June 1900 during a conversazione to which the public were invited. Figure 1 illustrates the first page from a pamphlet which was given to visitors at the opening ceremony illustrating the architects drawing of the building and the details of the exhibition. The importance of this event was highlighted by the University awarding of honorary degrees to a number of senior Fellows of the Royal Society including James Dewar and J.J. Thomson. There were a number of inaugural lectures that year including one by Sir Oliver Lodge.

Organised on four levels the new Institute was shared between Physics and Electro-Technics (later to become Electrical Engineering). The ground floor (Figure 2) included a large private laboratory (now called the Rutherford Room), a workshop and rooms devoted to experimentation in electricity and magnetism. Attached to the main part of the building was the John Hopkinson Electro-Technical Laboratory (now part of the Coupland Building occupied by Psychology), which featured a dynamo-house (now a student common room), a gas turbine engine-room (occupied by the Museum), an electro-chemical laboratory (now demolished) and a switchboard room to control the flow of electricity throughout the building.
The first floor (Figure 3) included the Professor’s private room but was primarily set aside for undergraduate teaching in sound and light and contained the main elementary laboratory. The second floor (Figure 4) featured a magnificent large lecture theatre and associated apparatus and preparation rooms. (I believe that I was the very last physicist to give a lecture in the Large Lecture Theatre before it was destroyed in the early 2000s after refurbishment). Also on the top floor were two rooms were set aside for spectroscopic and astronomic transit research. Features of these can be seen from the outside of the building, including ledges for mounting a heliostat and the bay window which housed a transit instrument (now on display in the new Schuster Building). Figure 5 illustrates a plan of the lower ground floor or basement. This level was primarily devoted to research, including in spectroscopy, photometry, photography and low-temperatures (now occupied by the Manchester Museum).



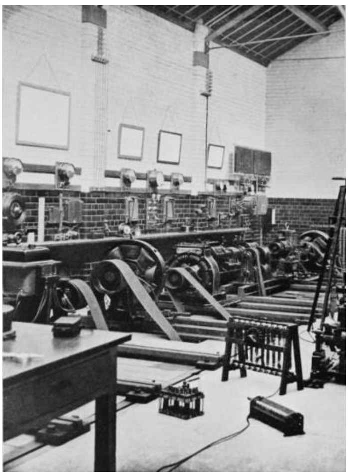


Figure 2. The ground floor plan and images of the dynamo hall (left) and electro-chemical laboratory (right).

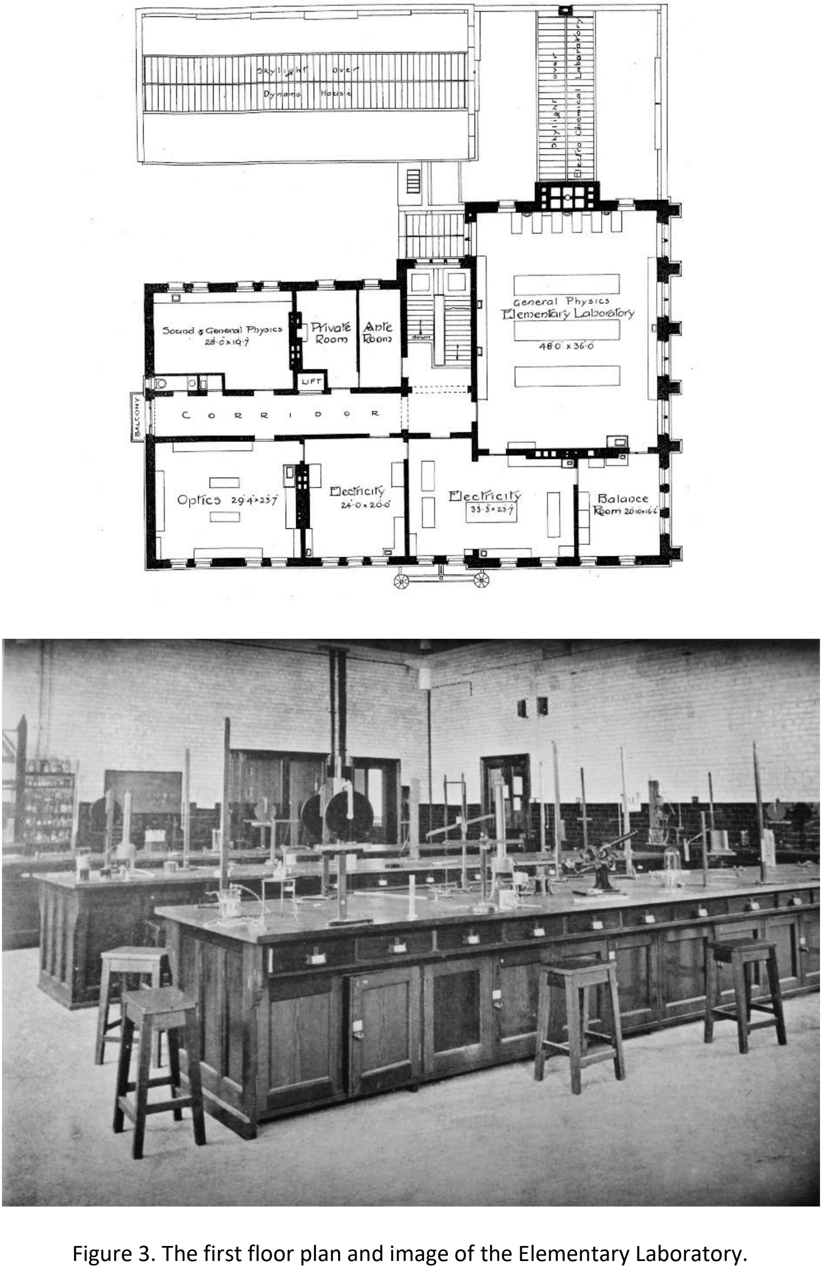


Figure 3. The first floor plan and image of the Elementary Laboratory.

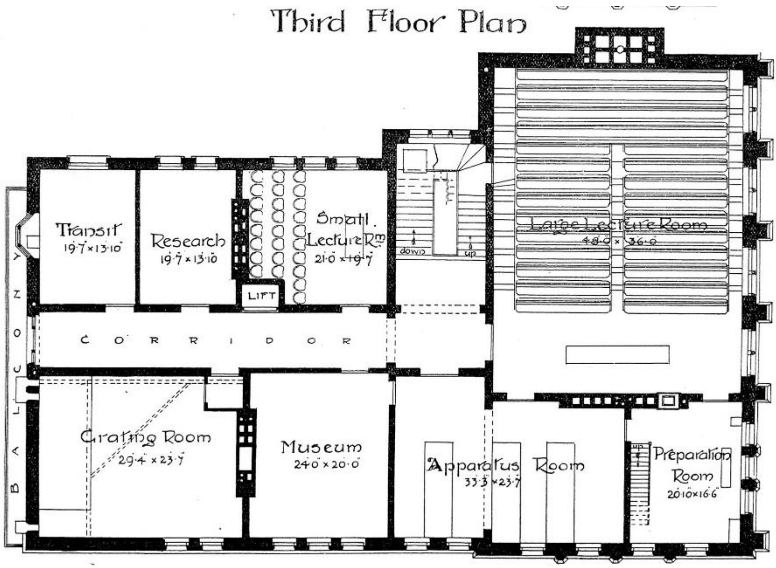


Figure 4. The 2nd floor plan and image of the Large Lecture Theatre. (Note - at that time the basement was regarded as the 1st floor.)

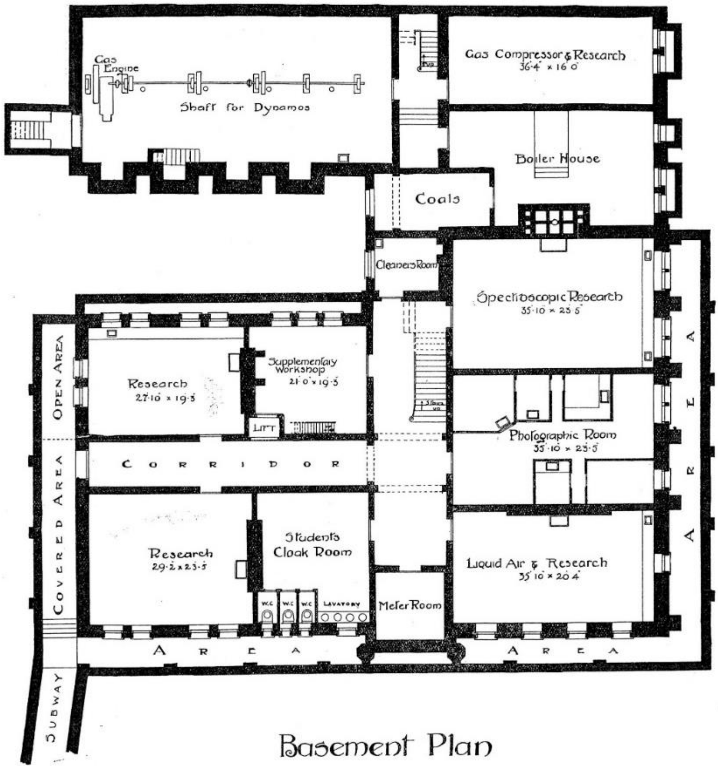


Figure 5. Basement (lower ground) plan of the Physical Laboratories of Manchester.

Discovery of X-rays, radioactivity and radium - A revolution in science begins

Although the 1900 Building was designed and devoted to topics of 19th classical physics it had been commissioned and constructed at a time of rapid discovery, heralding the start of a revolution in physics and chemistry. The discovery of X-rays in 1895 by Wilhelm Rontgen[4], was followed in close succession by radioactivity in 1896 by Henri Becquerel[5] and the

[4] Crowther J. (1945). “Rontgen Centenary and Fifty Years of X-rays” *Nature* 155, 351.

[5] Badash L. (1965). “Radioactivity before the Curies” *Am. J.Phys.* 33, 128-135.

electron in 1897 by JJ Thomson[6]. These fundamental discoveries triggered a period of frenetic research activity in which many other major discoveries were made. At the time that Thomson carried out his work leading to the electron he was being assisted by a young Ernest Rutherford, then a student at the Cavendish Laboratories, who investigated the ionising effects of X-rays on gasses by means of changes in their conductivity. He was subsequently then able to employ such methods to investigate the effects of the rays given off by uranium and in his very first paper on the subject of radioactivity, submitted September 1898, showed that the rays were made up of at least two types, which he labelled, α and β rays[7]. In parallel the Curies in Paris discovered in 1898 in certain active ores of uranium two new radioactive elements, polonium, which separated out with bismuth[8], and radium, which separated out with barium[9]. In that same year thorium was shown independently by Schmidt and Curie to be a fourth member of the family of radioactive elements. The following year Debierne working with the Curies in 1899 found a third active element in the pitchblende residues which he called actinium[10]. By end of 1899 it was shown by a number of workers including Becquerel that the radium also gave off β-rays and shortly after that they could be deviated by a magnetic field similarly to the cathode rays with an e/m similar to that of the electron but with a speed much closer to that of light.

By the time Rutherford's paper was published in January 1899 he had already been appointed MacDonald Professor of Physics at McGill University in Montreal. Working rapidly alone and with a number of colleagues, including his first doctoral student they discovered that certain radioactive substances, initially thorium and then radium, gave off a radioactive gas which they called "emanation" (radon), adding yet another to the rapidly growing group of radioactive substances. In 1901 he teamed up with chemist Frederick Soddy, then demonstrator in Chemistry at McGill, who in a remarkable collaboration together published a series of major

[6] Thomson JJ. (1897). "Cathode rays" *Phil.Mag. V,* 44, 293-316.
[7] Rutherford E. (1899). "Uranium radiation and the electrical conduction produced by it" *Phil.Mag. V,* 47, 109-163.
[8] Curie P, Curie S. (1898). "Sur un substance nouvelle radioactive, continue dans la pitchblende" *Comptes Rendus* 127, 175-178.
[9] Curie P et al. (1898). "Sur un substance nouvelle fortement radioactive, continue dans la pitchblende" *Comptes Rendus* 127, 1215-1217.
[10] Debierne A. (1899). "Sur un nouvelle matiere radio-active" *Comptes Rendus* 127, 906-908.

papers in rapid succession in 1902 and 1903[11]. They confirmed that the thorium emanation was a member of the noble gas family and that there must exist another substance mediating the production of the emanation from thorium, which they termed thorium-X by analogy to William Crookes' uranium-X[12]. It became clear to them that radioactivity must involve a form of sub-atomic chemical change or in other words it was a form of transmutation, or alternatively "transformation" or "disintegration" as they conservatively termed it to avoid the charge of "alchemy". The outcome of this work was the articulation of a radical theory of radioactive change, including both thorium and radium, which became known as the *theory of successive transformations*, alternatively referred to as the "disintegration theory" of radioactivity, where every radioactive element could be characterised by its half-life. At each stage in the series of transformations or "disintegrations" a chemical change took place whereby a parent atom would give rise to a daughter atom of distinct chemical species. It was radical because it challenged the established wisdom that Dalton's chemical atom was immutable, and hence their nervousness in using the term "transmutation" and choice of alternative terms such as "transformation" or "disintegration".

Figure 6. Frederick Soddy (back 2nd from right), Arthur Schuster (middle), and Ludwig Boltzmann (front 2nd from right) in the Dynamo Hall in 1903.

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[11] Rutherford E, Soddy F. (1902). "The cause and nature of radioactivity I, II." *Phil. Mag*. ***IV*, 21,** 370–96, 569–85; (1903). "Radioactive change" *Phil. Mag*. *V*, 29, 576-591; Rutherford E. (1903). "Radio-activity of ordinary materials" *Nature* 67**,** 511-2.

[12] Crookes W. (1900). "Radio-activity of uranium" *Proc. Roy. Soc.* 66, 409-423.

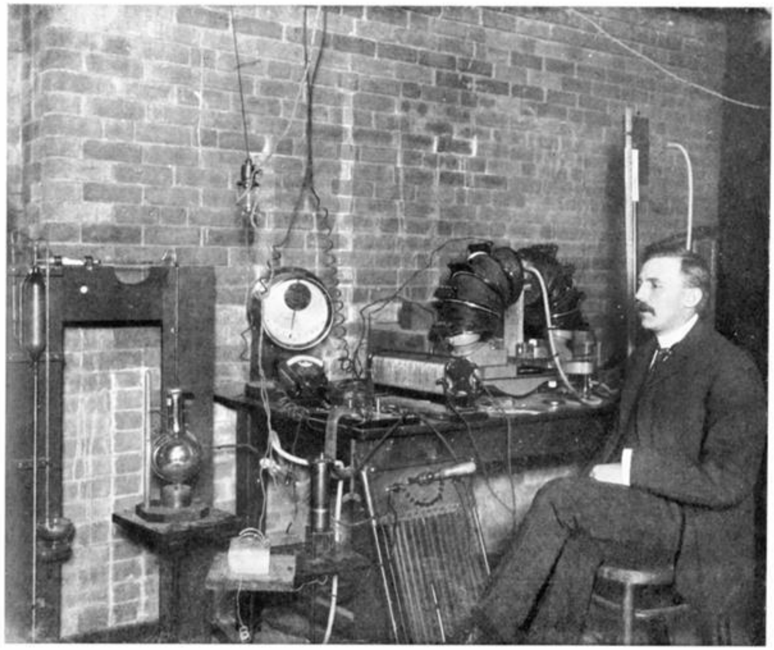

Figure 7. Rutherford in his basement laboratory in the McGill Physics Building in 1903.

A photograph (Figure 6) from 1903 taken inside the Dynamo Hall records a visit to Manchester by Soddy along with several important figures of 19th century physical science, including Ludwig Boltzmann. This was taken at about the time of the 1903 British Association Meeting in Southport at which the heating effect of radium and the origin of atomic energy were famously discussed. Contributions had been made by Lord Kelvin and by Rutherford. Soddy had at the time of the photograph had just completed a set of experiments with chemist William Ramsay at UCL proving the evolution of helium from radium, thus providing powerful evidence to support the disintegration theory[13]. That they were able to do this they owed to the German chemist Friederich Geisel who had developed a more efficient method for extraction of radium thus facilitating manufacture and commercial available at around that time.

[13] Ramsay W, Soddy F. (1903). “Experiments in radioactivity and the production of helium from radium” *Nature* 68, 354-355.

Figure 8. Attendees at the Schuster Jubilee Fest of 1906. Arthur Schuster is sitting at middle front next to the chemist Henry Roscoe. Squatting on the right is Walter Makower and in the back rows are also Thomas Royds and Sidney Russ who would all go on to work with Rutherford.

Rutherford, then also obtained Giesel radium from London at about the same time in 1903 after visiting Soddy at UCL. In fact Rutherford had initially loaned this to Soddy and Ramsay for their helium experiments. Figure 7 illustrates Rutherford in his McGill basement laboratory with radium apparatus which was shipped from London by Soddy in 1903. The radium itself was not practical for use in experiments, in part because of the contamination it caused. For that reason it was kept sealed in solution attached to a mercury pump to extract the evolved gases over mercury.

Schuster, in Manchester, also obtained radium, shortly following Soddy's visit, and commissioned radioactivity research prior to Rutherford's arrival, including work by Walter Makower[14] and Sidney Russ[15], who can be seen together in the Physics and Electrotechnics Departmental photograph from 1906 (Figure 8).

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[14] Makower W. (1905). "On the method of transmission of the excited activity of radium to the cathode" *Phil. Mag. 10,* 59, 526-532.

[15] Makower W, Russ S. (1907). "On the effect of high temperature on radium emanation and its products" *Proc. Roy. Soc.* 79, 158-166.

II: Rutherford in Manchester 1907 – 1919

1907 – 1909: Acquiring and using radioactive substances - The Radium Room.

In 1906 Schuster was planning to retire but was successful in persuading Rutherford to succeed him as Director of the Physical Laboratories at Manchester and Langworthy Professor. When Rutherford arrived in Manchester in 1907 he was already famous for his work in radioactivity, and especially the revolutionary disintegration theory for which he was awarded the Nobel Prize in chemistry in 1908. Rutherford soon set about moulding Schuster's laboratory for his own purpose. An important event early on in Rutherford's period at Manchester was the arrival of a large quantity of radium salt in February 1908 from Austria which enabled him to initiate a series of experiments which he had been planning (Figure 9)[16].

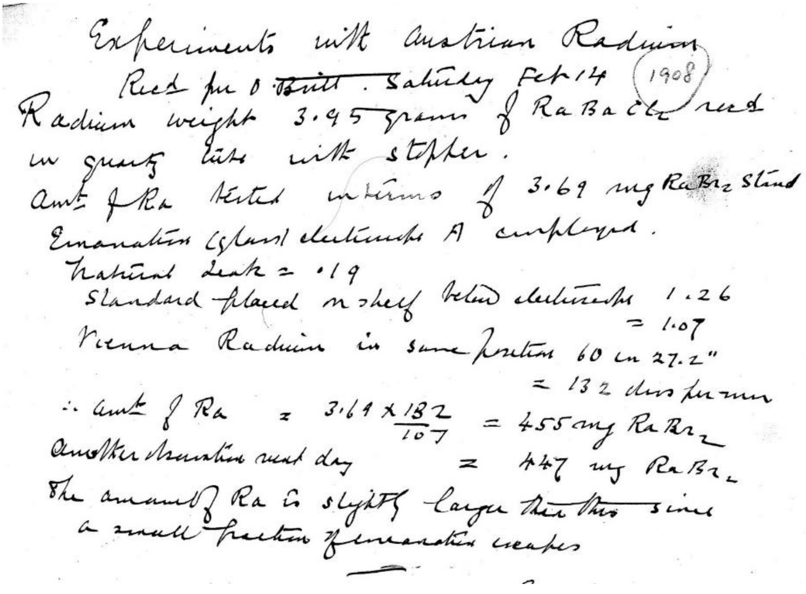
Experiments with Austrian Radium
Recd per ~~Britt~~. Saturday Feb 14 (1908)
Radium weight 3.95 grams of $RaBaCl_2$ recd
in quartz tube with stopper.
Amt of Ra tested in terms of 3.69 mg $RaBr_2$ Stand
Emanation (glass) electroscope A employed.
Natural leak = .19
Standard placed on shelf below electroscope 1.26
= 1.07
Vienna Radium in same position 60 in 27.2"
= 132 divs per min
∴ Amt of Ra $= 3.69 \times \frac{182}{107}$ = 455 mg $RaBr_2$
Another determination next day = 447 mg $RaBr_2$
The amount of Ra is slightly larger than this since
a small fraction of emanation escapes

Figure 9. Rutherford's laboratory notes recording the arrival of the Austrian radium in February 1908. (Reproduced from AD 7653/PA 182, by courtesy of the Syndics of Cambridge University Library.

[16] AD 7653/PA 182 from the Rutherford Papers at Cambridge University Library.

As was by then standard, a special room at the top of the building was set aside in which to keep the radium, so that any escaping radium emanation (radon) could be vented out of the windows to avoid contamination of the whole laboratory (Figure 11). This was after hard lessons at Montreal where radium was kept in the basement (Figure 7) resulting in the entire laboratory becoming contaminated from the emanation diffusing through the building, as is clearly described by two of Rutherford's senior workers in their 1912 textbook on radioactivity[17].

"*When working with large quantities of radium a special room should be set aside for carrying out the manipulations, in order to avoid contaminating measuring instruments with emanation the escape of which can scarcely be avoided."* [p74]

"It is advisable to set aside a special room, preferably at the top of the building, for the purpose of separating the emanation from the radium. In case of accidental escape of emanation, the windows should at once be opened." [p132]"

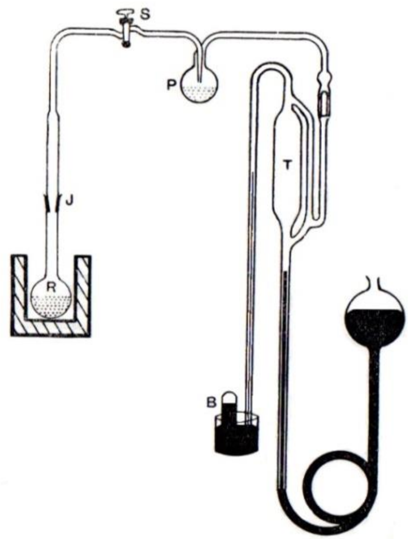

Figure 10. The Toepler pump apparatus for keeping radium in acid solution and for drawing emanation, adapted from Fig. 107 of *Radioactive Substances and their Radiation*[18].

[17] Makower W, Geiger H. (1912). *Practical Measurements in Radioactivity,* Longmans, Green & Co., London.

[18] Rutherford E. (1913). *Radioactive Substances and their Radiations,* Cambridge University Press, Cambridge.

Rutherford was also clear that every precaution should be taken to avoid contamination.

"In a laboratory in which radio-active experiments are constantly made, it is desirable that all sources of active matter should be kept in sealed vessels, in order to avoid possible radio-active contamination due to the distribution of radio-active material. This is especially important with a substance of a high activity like radium. The presence in a closed room of an unsealed capsule containing a few milligrams of radium salt, on account of the escape of the emanation, is sufficient in the course of a day to increase greatly the spontaneous leak of neighboring electrometers and electroscopes...... In many laboratories, the radium emanation is now used in the place of radium itself for many experiments. It is important that this emanation should be kept in sealed vessels, and the work of transference should be done in some part of the laboratory where any accident involving the escape of emanation shall not lead to the contamination of the main part of the building." [pp112-113] [19]

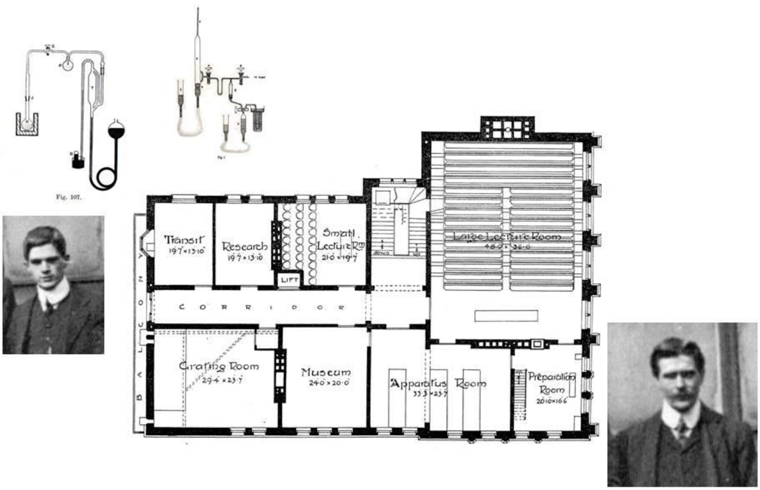

Figure 11. A reconstruction of the organisation of the top floor of the Physical Laboratories by Rutherford. The transit room was designated as the "radium room" where Walter Lantsberry worked as a radium technician. At the other end of the floor the Preparation Room was occupied by the Laboratory Steward William Kay who did much of the radioactive source preparation for Rutherford during WWI.

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[19] Rutherford, *op. cit.* (note 17).

Schuster's transit room with its large bay window was considered to be ideal and from then until 1919 this was designated as the "radium room" where the radium was kept and where radioactive sources were prepared for experiments in the rest of the building. As noted above radium as a salt (in this case radium barium chloride) was useless for experiments and the standard practice was to dissolve the salt in mild hydrochloric acid in a glass bulb attached to a mercury pump so that the radium emanation could be milked off (Figure 10), purified in a separate glass apparatus and compressed into small glass tubes to make radioactive sources for experiments. The radium room, containing the precious substance, was the inner sanctum of the laboratory making possible all of the experiments which Rutherford and his school carried out during his time at Manchester and where Manchester graduate Walter Lantsberry worked as a radium technician. Lantsberry later died aged 32 in 1922 likely due to his contact with radium. Both this room and William Kay's room (the Preparation Room) remained contaminated with radium and mercury until remediation conducted in the 1990s and 2000s[20].

One of the most important early experiments which Rutherford conducted at Manchester was done in 1908 with a young Manchester graduate Thomas Royds in the radium room[21]. Using incredibly delicate glass tubes, thin enough for the radioactive decay products to penetrate, but strong enough to contain emanation at atmospheric pressure, they showed that alpha-particles, one of the products of decay, were in fact ionised atoms of helium, thus complementing the 1903 work by Soddy and Ramsay. After accumulating them in an outer glass tube and compressing them into another tube the element helium could be detected spectroscopically from the colour of the light it gave off after passing a current. The apparatus for this experiment has been preserved and is now on display at the Cavendish Museum at Cambridge.

1909 – 1911: Nuclear discovery - The basement laboratories.

Having set up the radium room, research workers could be supplied with radioactive sources in the rest of the laboratory. Schuster's basement research rooms were soon occupied by Rutherford's young team of

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[20] Todd NPM. (2008). *Historical and Radio-archaeological Perspectives on the use of Radioactive Substances by Ernest Rutherford*, unpublished report. A copy can be obtained at www.manchester.ac.uk/rutherfordreview/background-documentation/.

[21] Rutherford E, Royds T. (1909). "The nature of the α-particles from radioactive substances" *Phil. Mag. VI,* 21, 281-286.

assistants and students, not least Hans Geiger, who had been hired in 1906 by Arthur Schuster. Geiger's basement room was the one originally designated for low-temperature work and is located at the museum end on the corner (where the 1898 foundation stone in laid). This was the room where the famous photograph of Rutherford and Geiger was taken in 1912 (Figure 12). One of the most important early developments which came out of this work in about 1909 was the invention of an electrical method for counting radioactive decays which eventually led to the famous "Geiger Counter"[22].

The basement laboratories which Schuster had designated for photography were suited for another method Rutherford developed, i.e. that of "scintillation counting". When the electrical method was not suitable, counting of alpha-particles was literally done by eye, which involved peering through a microscope at a small patch of fluorescent material (sodium iodide). In order to do this it was necessary for the observer to become adapted to the dark, for which purpose photographic dark rooms were ideal. These were located in the room next door to Geiger's. Using such methods in 1909 -10 the young Ernest Marsden, under the guidance of Hans Geiger, carried out the experiments which led Rutherford in 1911 to the discovery of the atomic nucleus[23].

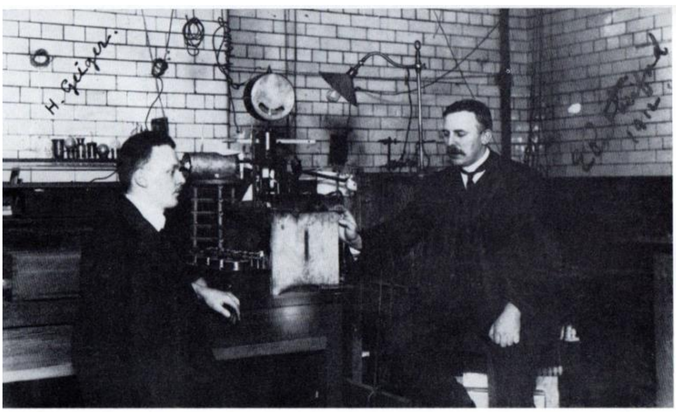

Figure 12. Rutherford and Geiger in the basement with their apparatus for counting α-particles.

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[22] Rutherford E, Geiger H. (1908). "An electrical method of counting the number of α-particles from radioactive substances" *P. Roy. Soc.* A81, 141–161.

[23] Geiger H, Marsden E. (1909). "On a diffuse reflection of the α-particles" *P. Roy. Soc.* A82, 495–500.

Another young Manchester student, John Nuttall, working alongside Geiger in the basement, carried out a series of experiments which led to the enunciation in 1912 of a law, known as the Geiger-Nuttall law, which related the energy of emitted alpha-particles to the half-life of the emitting radioactive substance[24]. The significance of this law was not fully appreciated until later. Nuttall himself was one of the few Rutherford era staff who stayed on at Manchester, retiring only in 1955.

Perhaps the most fundamental work undertaken in the old Schuster basement was that of H.G.J. Moseley. A graduate of Oxford, Moseley came to Manchester to work in with Rutherford in 1909. Prior to the X-ray work during the period when Rutherford developed his nuclear model of the atom, Moseley worked in the basement close to Geiger's room on radioactivity experiments. His letters give a vivid impression of what it was like working in the laboratory at that time. I quote two in particular[25]. In this first quote from November 1910 he is referring to work which would lead to his 1912 publication in on "The number of β-particles emitted in the transformation of radium"[26]. This letter highlights just how precarious radioactive research work was.

Nov 13, 1910. "*My work is going through much tribulation. On Thursday I at last induced my apparatus to stay at a pressure of 1/400 mm. that is a three-hundred-thousandth of an atmosphere, after plastering with a red sticky stuff which resembles butter. Then I started my experiment, but a glass tube of thickness much less than tissue paper filled with Radium Emanation chose to break off its stalk inside, and everything had to come to pieces to get it out. Fishing for a thing which breaks at a touch was too risky to be tried, for to let Emanation loose upon the Laboratory is a capital offense*."[27]

The next letter written from within his basement lab about a year later is referring to the same experiment and in it he gives a graphic description of the elaborate procedures which were required to prepare radioactive sources and transport them to the basement laboratory room where he worked.

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[24] Geiger H, Nuttall JM. (1911). "The ranges of the α-particles from various radioactive substances and a relation between range and period of transformation" *Phil. Mag. VI,* 22, 613-621.

[25] Heilbron JL. (1974). *H.G.J. Moseley: The Life and Letters of an English Physicist, 1887-1915*, University of California Press, Berkeley.

[26] Moseley HGJ. (1912). "The number of β-particles emitted in the transformation of radium" *P. Roy. Soc. 87,* 230-255.

[27] Letter 45 in Heilbron *op. cit.* (note 25) 177-178.

Dec 7, 1911. "I am writing in a Laboratory so steam heated that even with coat off it is hardly bearable, and at the same time I am waiting for an experiment to prepare itself....At present beta-ray experiments which must be got through while my supply of emanation lasts.... The experiment is now clamouring for attention, and I must go to it. I have to do many things in a minimum of time that it seems more like a conjuring trick than anything else. The experiment begins in the attic and continues in my room on the ground floor, so that I have to race down three flights of stairs in the middle, to the great astonishment of the occasional student."[28]

1912 – 1914: The 1912 building extension

As can be easily imagined, with such experiments the risk of accidents and hence contamination was high, despite the strictest rules laid down by Rutherford. It was inevitable with an ever growing army of researchers in the Rutherford lab that the problem of contamination would become critical and it became necessary to find new space free from contamination. An important development in March 1912 at the Physical Laboratories was the completion and opening of a new extension (Figure 13). As with the opening of the 1900 building this was marked by a public ceremony, a conversazione and an exhibition of experiments. Among the exhibits was one "counting atoms" by Hans Geiger in the basement.

Figure 13. Southern view from Coupland Street of the 1912 extension to the Physical Laboratories.

[28] Letter 53 in Heilbron *op. cit.* (note 27) 183-184.

The following quote is a description of the extension by Schuster in a University document to accompany the new extension, "The Physical and Electrotechnical Laboratories of the University of Manchester"[29].

"With the steady increase in the number of research students, it became more and more difficult to provide sufficient space... This difficulty was emphasised by the nature of many of the investigations... In these researches it was necessary to employ large quantities of radium and radioactive substances. As is well known, these remarkable bodies emit a very penetrating radiation, known as γ-rays, which is able to traverse the walls and floors of the Laboratories, and to disturb electrical measurements of workers, not only in the immediate vicinity but in the neighbouring rooms. During the last few years this problem has become very acute, and in order to isolate the workers as far as possible from one another it has been found necessary to encroach to some extent on the space intended for laboratory instruction...."

However, we can also be sure that a critical factor in the decision to expand was the need to find laboratory space which was free from the permanent radioactive contamination which had become widely distributed in the four years since Rutherford acquired a large source of radium in 1908.

"*In addition to the difficulty of avoiding disturbances due to penetrating radiations, a Laboratory in which large quantities of radioactive substances are in continual use gradually becomes contaminated by the distribution of active matter. For example, an invisible trace of radium on a finger suffices to make permanently radioactive every object that is touched. Although precautions have been taken to reduce this infection to a minimum, it has proved sufficiently serious to render difficult, if not impossible, some of the more delicate measurements required in researches on radioactivity ..."*

[29] Schuster A, Hutton J. (1912). *An account of the Physical and Electrotechnical Laboratories and of the New Extensions,* The Manchester Courier Ltd, Manchester.

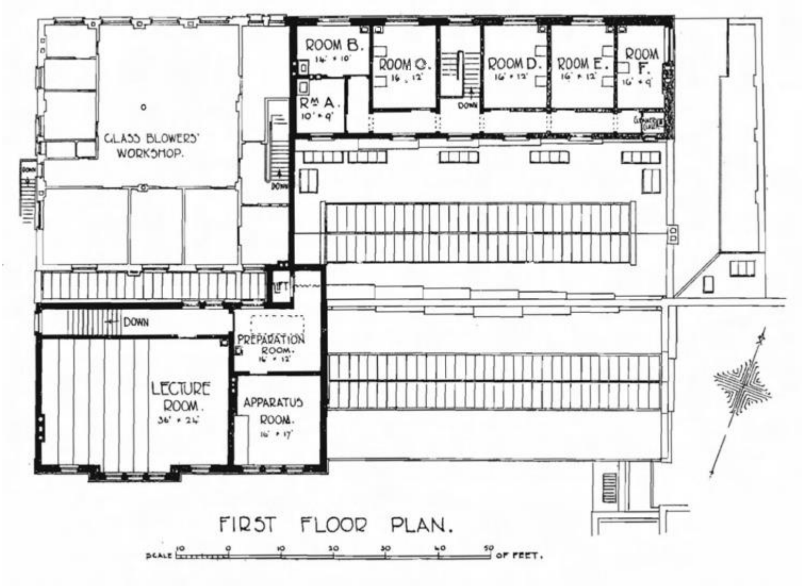

Figure 14. Plan of the first floor of the 1912 extension to the Physical Laboratories.

As well as creating more space for physics in the main building, by allowing Electrotechnics to move into the new building and Physics to take over the vacated rooms previously occupied by Electrotechnics, the extension would provide additional space for certain experiments involving “delicate measurements” which would not be possible in the contaminated part of the building. This additional space was made available in the form of six rooms on the north side of the new building. A description of these new rooms is given by Schuster in the same document as above (see Figure 14).

“The Physics Research Rooms marked A to F on the plans, are situated on the first floor of the north wing facing Bridge St. In this position they are well outside the range of penetrating radiations from active material in the main building, which is some 30 yards further south. Primarily intended for experiments in connection with radioactivity, they are nevertheless equally well adapted for other branches of Physical work. ... If necessary, several of the rooms can be darkened for photographic or special radioactive work.” [30]

[30] Shuster and Hutton, op. cit. (note 29).

Rutherford also comments on the problem of contamination and gives a description of the new physics rooms and in his annual reports to Council. In the 1910-1911 report:

"In the course of the year the Council of the University decided to build an extension of the Physical Laboratory, partly to provide room for the Department of Electrotechnics, at present housed in the Physical Laboratory, and partly to give extra accommodation for research in Physics. The building is now in the course of erection and will probably be completed early in 1912. This extension will prove very advantageous, and will unify the work of the Department of Electrotechnics and will afford very necessary facilities for special work in the Physics Department. It has been a matter of great difficulty in recent years to find places for the research students in order to avoid disturbances due to the radiations from the active matter employed. It is intended to use the new floor almost entirely for accurate work in radioactivity and the conduction of electricity through gases. The distance of the new rooms from the main laboratory is of great importance in preventing the possibility of contamination by radioactive matter, which is very difficult to avoid in the main laboratory." [31]

In the 1911-1912 report:

"A part of the new extension was set aside for the use of the Physics Department. The rooms so provided have already proved of great service in research work. The new laboratory has the great advantage of being free from all radioactive contamination, and it has thus been possible to carry out refined experiments, which would have been very difficult in the main laboratory." [32]

Among the growing army of researchers was Niels Bohr who arrived in Manchester in March of 1912 shortly after the 1912 extension opening. Remarkably, within just four months Bohr had already introduced Planck's constant to the Rutherford nuclear atomic model, as is testified by the Rutherford memorandum of July 2012, some early sketches which Bohr

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[31] Rutherford E. (1911). "I Reports on the Physical Department Session 1910-11" in *Reports of the Council of the University of Manchester. Appendix XI. Reports on Departments,* University of Manchester Press, Manchester.

[32] Rutherford E. (1912). "I Reports on the Physical Department Session 1911-12" in *Reports of the Council of the University of Manchester. Appendix XI. Reports on Departments*, University of Manchester Press, Manchester.

sent to Rutherford in July 1912 before he returned to Denmark[33]. At around this time Moseley became interested in X-ray diffraction and published with Charles Darwin on this subject[34]. Inspired by Bohr's revolutionary new theory[35] this work led Mosely to conduct a series of experiments in 1913/14 which proved that every element can be classified by the number of positive charges in the nucleus, the atomic number[36].

Figure 15. Radio-chemist A.S. Russell at work in a small Chemical Laboratory.

In parallel with this theoretical and physical research, the 1912 extension also allowed radio-chemical research to continue without high risk of contamination. Notable in this regard at Manchester was that of A.S.

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33 Bohr N. (1912). "I. The Rutherford Memorandum (1912)" in L Rosenfeld, U Hoyer (Eds.) *Niels Bohr Collected Works II, Work on Atomic Physics (1912-1917)*, North Holland, 136-158, 1981.

34 Moseley HGJ, Darwin CG. (1913). "The reflection of the X-rays" *Phil. Mag. VI*, 26, 210-232.

35 Bohr N. (1913). "On the constitution of atoms and molecules" *Phil. Mag. VI*, 26, 1-15,

36 Moseley HGJ. (1913). "The high-frequency spectra of the elements" *Phil. Mag. VI*, 26, 1024-1034.

Russell whose image was captured working in a small chemical laboratory, possibly on the ground floor of the 1912 extension (Figure 15). Russell was credited with first stating the β-ray displacement law[37], that when a β-ray disintegration takes place an atom changes in chemical nature so as to move one period higher in the periodic table. The β-ray law complements an α-ray displacement law articulated by Soddy in which an element moves two periods lower in the periodic table. Russell was also one of the only chemists to have worked successfully with both Rutherford and Soddy and it was during the same period that Bohr and Moseley were making their contributions that the concept of the "isotope" crystalized[38] thus finalizing the modern conception of the periodic table governed by atomic number and not weight.

9. The Manchester University Physical and Electro-Technical Laboratories staff and research students, 1912. L to R: front row: R. Rossi, H. G. J. Moseley, J. N. Pring, H. Gerrard, E. Marsden; row 2: H. Geiger, W. Makower, A. Schuster, E. Rutherford, R. Beattie, H. Stansfield, E. J. Evans; row 3: C. G. Darwin, J. A. Gray, D. C. H. Florance, Margaret White, May Leslie, H. R. Robinson, A. S. Russell, H. Schrader, Y. Tuomikoski; row 4: J. M. Nuttall, W. Kay, H. P. Walmsley, J. Chadwick. Courtesy of Kasimir Fajans.

Figure 16. The 1912 Physics Departmental photograph.

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37 Russell A.S. (1913). *Chem. News,* 107, 49,

38 Soddy F. (1921). "Origins of the conceptions of isotopes" in *Nobel Lectures, Chemistry 1901-1921,* Elsevier Publishing Company, Amsterdam, 1966.

The 1912 departmental photo (Figure 16) was taken in front of the 1912 extension where most of the key workers described in the above pages are gathered, including Moseley, Geiger, Marsden, Schuster, Rutherford, Darwin, Russell, Kay and Nuttall.

1915 – 1919: Transmutation – The Professor's ground floor laboratory.

Tragically for Manchester, and for humanity in general, the great debacle of World War I broke out in 1914 and the productive Manchester team was broken up, with many of the young workers and students enlisting on both sides, including Geiger, Marsden and Moseley. Perhaps most tragically, Moseley was killed by a sniper's bullet to the head at Gallipoli in 1915, thus ending the career of one of the most brilliant of his generation. It is generally agreed that had he survived he would have been awarded the Nobel Prize.

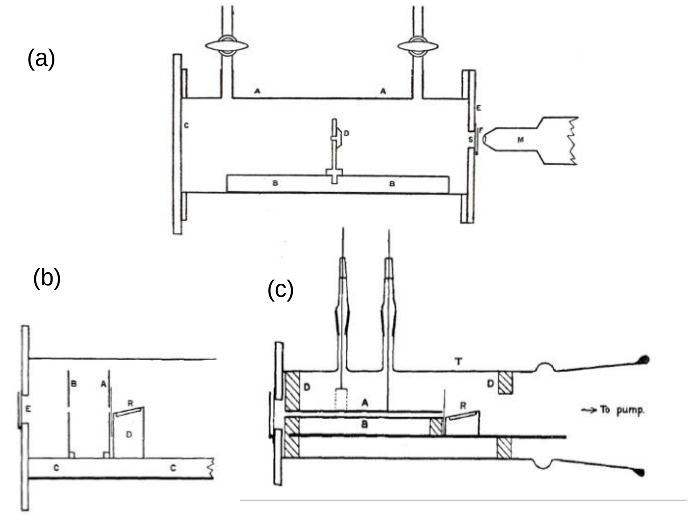

Figure 17. Apparatus used by Rutherford to investigate collision of *α*-particles with light atoms: (a) a rectangular brass box, (b) and (c) variants used to determine the velocity and range of H-particles and recoil atoms.[39]

[39] Rutherford E. (1919). "Collision of α-particles with light atoms" *Phil. Mag. VI*, 37: "I. Hydrogen", 537–561; "II. Velocity of the hydrogen atom", 562–571; "III. Nitrogen and oxygen atoms", 571–580; "IV. An anomalous effect in nitrogen", 581–587.

Rutherford himself was diverted into war work on submarine detection by sonar, which he carried out in the basement with the aid of a large tank of water. However, despite the depletion of workers and the distraction of war work, he was able with help of his Laboratory Steward William Kay to continue work on his own research, which he did in the private laboratory on the ground floor (now the "Rutherford Room").

The outcome of this research, which had originated in another aspect of Marsden's later work on scattering of alpha-particles from light gases, resulted in a quartet of papers published in 1919 which this special issue commemorates (Figure 17), details of which are described in the other articles in this issue.

Shortly after the end of WWI Rutherford was offered the Cavendish Chair at Cambridge to succeed JJ Thomson. When he left Manchester in 1919 he took with him a small number of key people, including James Chadwick (the later discoverer of the neutron) who had been interned in Berlin, along with his radium, the solution of which he had evaporated, and much of the glass-ware occupying the radium room. Thus ended the Rutherford era at Manchester, although, as we shall see traces of his occupancy remained in the form of radioactive contamination and contamination from the mercury which was employed in the pumps and apparatus to manipulate radium emanation.

III: After Rutherford 1919 - 2019

The buildings after Rutherford

Rutherford was succeeded at Manchester by WL Bragg, whose primary interest was in X-ray crystallography[40]. During his Manchester period (1919 – 1937) a number of building extensions were carried out. An extension had already been made to the Physical Laboratories in 1912 during Rutherford's time due to overcrowding (and the fact that the original 1900 building had become extensively contaminated) and at this time Electro-technics (later Electrical Engineering) separated from Physics. However, at the end of WWI there was a massive influx of former soldier students and space was limited. The original 1900 quadrangle was developed in 1920. In 1931 a physics extension adjoining the 1909 Engineering block was completed

[40] Phillips D. (1979). "WL Bragg 1890-1971" *Biographical Memoirs of the Royal Society* 25, 75-143.

(later called the Bragg Building). This was officially opened by Rutherford on a visit to Manchester in 1932. Rutherford had earlier returned to Manchester in the early 1920s to dedicate a plaque to Moseley. This was originally located on the landing of the 1900 building, but was relocated in 1967 to the Moseley Lecture Theatre in the new Schuster Building.

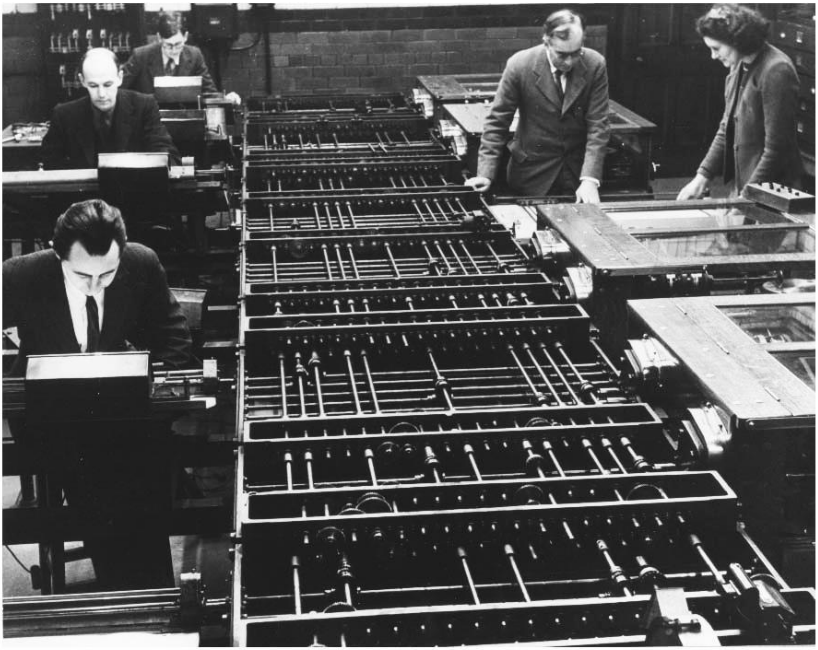

Figure 18. Douglas Hartree's differential analyser was constructed in Geiger's old basement room.

During the Bragg period the original Schuster research rooms were adapted for different purposes, other than X-ray crystallography, which involved photography and would have been susceptible to fogging from the radioactive contamination. A differential analyser was erected in 1935 in the old Geiger room by Douglas Hartree (Figure 18), who later became the first Chair of Theoretical Physics in 1938. Moseley's room was occupied by Samuel Tolansky, a spectroscopist. Other rooms were adapted as rooms for Third year Honours students. The radium room on the top floor was by then being used as a departmental tea room. It was at this time that a young Bernard Lovell arrived in 1936 at Manchester, working initially with

Hartree in the basement, and then with Blackett. Lovell recalled[41], before WWII and his move to Jodrell Bank, that in his early days working with Blackett when he had to make his own Geiger counters, he had found a number of rooms to be contaminated, including the tearoom. He well remembered William Kay who at that time still occupied the Preparation Room.

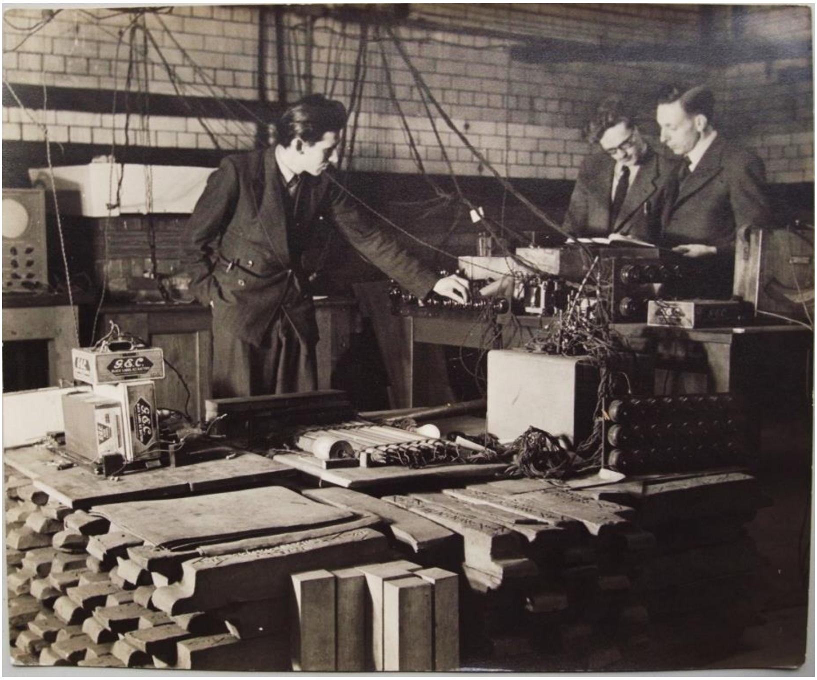

Figure 19**.** The old Electrochemistry Laboratory was used by Blackett's team for cosmic ray research.

Bragg left Manchester in 1937 to take up a position at the National Laboratory, and then went shortly after to the Cavendish to succeed Rutherford who died in October 1937. Bragg was in turn succeeded at Manchester by Patrick Blackett[42], whose primary interest was in cosmic rays, for which purpose he commandeered the old electrochemical

[41] Sir Bernard Lovell was interviewed by me in 2009.

[42] Lovell B. (1975). "PMS Blackett 1897-1974" *Biographical Memoirs of the Royal Society* 21, 1-115.

laboratory. Dramatically, William Kay was evicted from his top floor room and moved to the old workshop on the ground floor. During Blackett's occupancy (1937 – 1952) there was a major reorganisation of the laboratory and several further Departmental segregations, between Theoretical and Experimental Physics in 1938 and from Astronomy in 1952.

There was also some further extension work in this area of campus over the Blackett period. Electrical Engineering in 1949 developed the area between the 1912 Electro-Technics extension and the 1909 Engineering Building on Bridgeford Street. Sometime in the 1950s another Physics extension (now occupied by Psychology) was erected between the 1932 and 1900 buildings. On the museum end of the 1900 building a block (now demolished) was constructed in which the Theoretical Physics group was based. Among the important discoveries and developments during the Blackett period was the discovery of strange particles by Rochester and Butler in 1947 in the old electrochemical room (Figure 19) and, in a room a few yards away in the 1912 building, the successful operation of the first stored programme computer in 1948 by Williams and Kilburn (a plaque commemorating this can be seen on Bridgeford Street).

Figure 20**.** Samuel Devons, the last of Rutherford's students, with one of the van de Graaff accelerators.

After Blackett's departure in 1952 and a short interim, he was succeeded in the Langworthy Chair by Samuel Devons (Figure 20), one of the last of Rutherford's students at the Cavendish. During Devons' short occupancy (1955 – 1960) Manchester's nuclear renaissance took place, manifest in the construction of a small (2 MeV) and a large (6 MeV) van de Graaff accelerator, one of which (the small) was housed next to the Theoretical Physics block on Coupland Street, and the other (the large) on Ackers Street. Also constructed during this period was the Manchester heavy ion linear accelerator (LINAC) on Oxford Road. By this time the old Schuster basement was mostly turned over to Third year undergraduate teaching. The old ground floor lab had become an electronics workshop. The old transit/radium room at the top of the building continued as the tearoom. In 1954 Electrical Engineering vacated the Coupland Street site and moved to a new building on Dover Street (now the Zochonis Building and occupied by Psychology)[43]. From 1960 until 1967 when Physics moved to the new Schuster Building a succession of interim heads reported to Council. These included Brian Flowers, Henry Hall, Eric Paul and John Willmott.

After Physics and Electrical Engineering had vacated, their old buildings were reoccupied partly by the Manchester Museum and partly by the Department of Psychology, after a short occupancy by Physiology. The Museum took over the old Schuster basement and some parts of ground, and 1st floor, on the Museum side. The part occupied by Psychology, which included most of the top 3 floors of the 1900 building, the 1912 and the 1950s extension, was renamed the Coupland I Building. This included the large lecture theatre which was renamed the Cohen Lecture Theatre. In 1999, following what was supposed to be a temporary move to the Zochonis Building to allow refurbishment, that part of Psychology occupying the 1900 building was moved permanently. In 2005 after remediation and refurbishment this area was renamed the Rutherford Building and reoccupied by the University administration. Psychology remains in the 1912 and the 1950s physics extension areas, which continues to be called the Coupland I Building.

[43] Broadbent TE. (1998). *Electrical Engineering at Manchester University. The Story of 125 Years' Achievement*, Campus Print Ltd, Manchester.

Historical and radio-archaeological perspectives

Sometime between Rutherford's departure in 1919 and the Physics move to the new Schuster in 1967 a number of plaques were erected to commemorate what were considered to be the most important discoveries of the Rutherford era. It is likely that these were erected in the 1950s or 1960s and quite possibly during the end of the Blackett era or later during Samuel Devons' tenure in the run up to the Rutherford Jubilee in 1961. During Manchester's nuclear renaissance Rutherford's significance would have come to the fore and Devons had a particular interest in the history of science. This included an interview with William Kay, the former laboratory steward, which was republished by Jeff Hughes[44]. Although Kay had retired at the end of WWII he still occasionally came into the Department and during these interactions in the late 1950s the interview was carried out. John Nuttall, the last of the Rutherford era staff retired in 1955, the year of Devons' arrival and would have been able to pass on his knowledge.

The Rutherford Jubilee of 1961 to celebrate 50 years since the nuclear discovery was an extraordinary event when the last of Rutherford's "boys" returned to Manchester, especially for a commemorative session held in the Whitworth Hall[45]. These were Ernest Marsden, James Chadwick, Niels Bohr, Charles Darwin and E Andrade (Figure 21). Brian Flowers, the Jubilee organising committee chair, recalled that there would have been tours of the old laboratory[46]. I also understand from former Departmental Historian David Sandiford that Marsden checked or corrected some of the locations on this occasion. David Sandiford was also a sources of a typed document "Historic work in the Schuster Building", passed on to me by Rutherford's biographer John Campbell, which he had been given in the 1980s by Sandiford.

[44] Hughes J. (2008). "William Kay, Samuel Devons and memories of practice in Rutherford's Manchester laboratory" *Notes Rec. R. Soc.* 62, 97–121.

[45] Birks J. (1962). *Rutherford at Manchester*, Heywood and Company, London.

[46] Lord Brian Flowers was interviewed by me in 2010.

Figure 21. Rutherford's "old boys", left to right: James Chadwick, Charles Darwin, Ernest Marsden, E Andrade and Niels Bohr reunited on the occasion of the Rutherford Jubilee in 1961.

This document is invaluable in its record of the historic locations and appears to be correlated with independent information we have concerning the location and content of the plaques. I know of five plaques definitely and there was almost certainly a sixth. Two of these were located in the ground and upper floor of the 1900 building and still mounted in 1999 when Psychology was evicted. These two appear to have been disposed of during the refurbishments in early 2000s but I have a photographic record of them. Three, which were originally mounted in the basement, came to my attention later and until last year were kept in a box in one of the basement rooms occupied by the Museum. On the basis of all of this evidence I can state that the plaques, their locations and significance were as follows. There was one plaque located on the upper floor (old D-floor), four in the basement (old A-floor) and one on the ground floor (old B-floor).

Plaque located in the old Transit Room/Room D9/Room 2.62.

Figure 22. The plaque commemorating the Rutherford and Royds 1908 experiment.

Originally designated as a Transit Room in 1900, sometime after Rutherford had used it for his radium room during his occupancy from 1907 to 1919, it became used as the Departmental Tea Room, and was labelled Room D9. As noted above, Lovell remembered it from late 1930s when he found it to be very contaminated. During Psychology's occupation from the early 1970s until eviction in 1999 it was used a staff room. I was the last member of Psychology to use it when it was Room 2.62 and so it became of particular interest to me. Throughout the occupation by Psychology there was a plaque mounted on the wall to the right as you enter commemorating the experiment by Rutherford and Royds in 1908 (Figure 22). According to the 1980 document: "*1908 - in this room Rutherford and Royds first collected helium from alpha particles and photographed the spectrum*". The plaque was removed in the early 2000s during remediation and refurbishment, and was presumably disposed of.

Figure 23. The old “Transit Room” before and after remediation. When used as the radium room by Rutherford the Toepler pump apparatus was likely kept in the bay window. Evidence of the wooden bracket which held the pump is still evident to the right of the window.

From a radio-archaeological perspective this room was one of the most contaminated both radioactively and with mercury[47]. It required several rounds of remediation for the cleaning to be done to an acceptable level, including having the floor dropped in 2010 (Figure 23). Figure 24 indicates a reconstruction based on the location of radioactive and mercury contamination of where the pieces of apparatus may have been located. The radium apparatus was likely kept in the bay window and secondary apparatus for purification of the radium emanation with a second mercury pump was likely kept by the other window. The next door room was also highly contaminated with mercury and may well have been where Bertram Boltwood worked during his year visit to Manchester in 1910. William Kay’s interview by Devons in 1958 gives details of the location of the Radium Room and that Boltwood worked there.

[47] Todd, *op. cit.* (note 20).

"Well, the radium room was right at the top at the far end. That's where we kept the radium. That's where he did all his production of emanation-rays, in there with Boltwood. That's where all the glass apparatus was,..." [Hughes, 2008, p102][48]

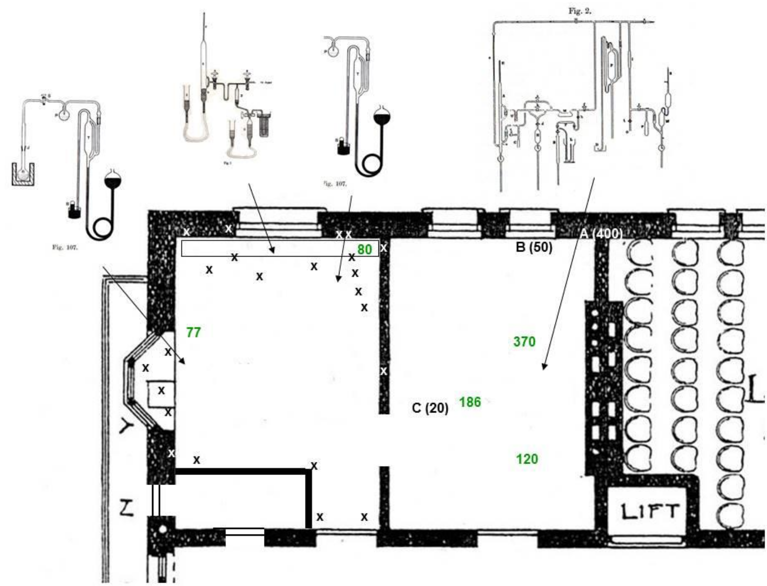

Figure 24. A reconstruction of where various pieces of apparatus may have been located in the old "Transit Room" and adjacent "Research Room". Patches of radioactive contamination are marked by an X and areas of mercury contamination in green numbers.

Plaques located in the old Liquid Air Room/Room A1/Room CB04/05/06/07

Originally this was designated for Liquid Air Research in the original 1900 Shuster Laboratory. During Rutherford's occupation it was the room occupied by Hans Geiger and where the famous 1912 photograph was taken. In the 1960s this room was used as an undergraduate Third Year Laboratory and was numbered Room A1. At some point it had been partitioned and during the remediation in early 2000s it had several numbers

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[48] Hughes, *op. cit.* (note 37).

CB04/05/06/07. It is now occupied by the Museum and used for storage. According to Sandiford’s document one plaque noted “*1909 - Here alpha-particles were first counted by an electrical method by Geiger and Rutherford”.* This plaque was probably located in the wall on the left as you enter the room. A second noted: “*1912 - Here also Geiger and Nuttall measured the range of alpha-particles and established the Geiger-Nuttall Law*”. This was probably located on the wall to the right as you enter.

Plaques located in old Photographic Room/Room A18/A19/Room CB 01

Originally the room was partitioned up into smaller dark rooms for photography. In the 1960s it was still used as a dark room and was still probably partitioned. To reach A19 it was necessary to pass through Room A18. During the remediation it had a single label CB 01 and the partitioning had been removed. It is now occupied by the Museum and used for storage. According to Sandiford’s document *“1909 - Geiger and Marsden discovered large angle scattering of alpha-particles here, and later made the accurate measurements which verified Rutherford’s scattering law”*. The plaque would have been located in one of these.

Plaque located in old Research Room/Room A8/Room CB 09

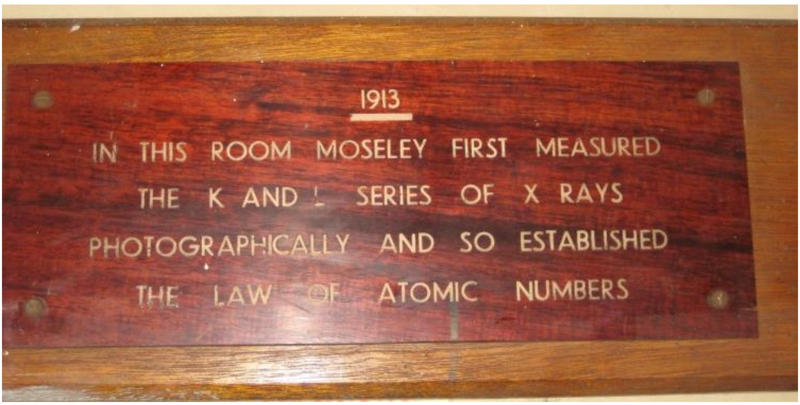

Figure 25. The plaque commemorating Moseley’s X-ray work establishing the law of atomic number.

Originally designated as a Research Room, in the 1960s it was also used as a Third Year Laboratory and was numbered Room A8. During the 2000s it was labelled as CB 09. It is presently used by the Museum for storage. According to Sandiford's document:

"*1913. In this room Moseley first measured the K and L series of X-rays photographically and so established the law of atomic numbers*". This was probably located on the wall to the right as you enter.

<u>Plaque located in old Private Research Room/Room B5/Room G54/55</u>

This room was originally designated as a private Research Room. In the 1960s it was used as an electronics workshop and labelled as Room B5. According to the Sandiford document:

"*1919 - From 1907 – 1919 Rutherford carried out many of his important researches in this room; notably the determination of e/m for alpha-particles in 1912 and the first successful experiments on the disintegration of light nuclei in 1919*".

Figure 26. The plaque commemorating Rutherford's artificial disintegration/transmutation of nitrogen.

During the occupation by Psychology it was partitioned into two rooms G54/G55, part of which was used as an MSc Computer Room. Throughout this period Rutherford's bench was located within it at the southern end. There was a plaque mounted above it on the wall (Figure 26 and 27) which commemorated:

"*1919. On the bench below the artificial disintegration of nitrogen was first achieved by Rutherford*".

Figure 27. Rutherford's bench and commemorative plaque before remediation.

During refurbishment in the early 2000s the plaque was removed, and presumably disposed of. Nearly 1000 kg of material was removed from the room in the decontamination, and the bench was also cleaned by sand blasting, being highly contaminated (Figure 28)[49]. The patterns of contamination on the bench tell us where the apparatus illustrated in Figure 17 was probably located and where Rutherford and Kay would have spent many hours in the dark counting scintillations. It is likely that the apparatus was oriented perpendicular to the bench on the hotspot (centre right) so that the observers would have sat at the bench front staring into the microscope.

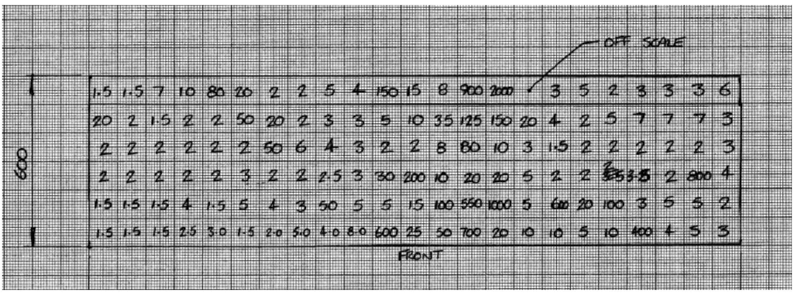

Figure 28. A map of the radioactive contamination on the surface of Rutherford's bench before remediation.

[49] Todd, *op. cit.* (note 20).

The room has now been restored and a set of general commemorative plaques have been relocated on the wall where the original was placed (Figure 29). Despite the remediation there are still a couple of hot spots which are fun to demonstrate with a modern Geiger counter when conducting tours of the building. During such a tour on the occasion of the Centenary of Transmutation meeting in June 2019 the meeting a video clip of Rutherford speaking in 1935 was played, probably the first time that his voice was heard booming around the corridors of the Physical Laboratories of Manchester since he had departed 100 years earlier.

Figure 29. Rutherford's bench and commemorative plaque after remediation.

Concluding remarks

It is extraordinary to consider the history of the building which since its foundation stone was laid in 1898 was a witness to such a remarkable period in the history of science from the discovery of radioactivity, the articulation of the disintegration theory of radioactivity as a form of spontaneous transmutation, the discovery of the nucleus, the quantum theory, atomic number, the isotope and the discovery of artificial disintegration/transmutation of light nuclei. As Rutherford himself noted on a return visit in the 1930s to open a new building (now called the Bragg Building).

I owe a great debt to Manchester for the opportunities it gave me for carrying out my studies. I do not know whether the University is really aware that during the few years from 1911 onwards the whole foundation of the modern physical movement came from the physical department of Manchester University. [50]

It is also remarkable to consider that this was achieved with such simple methods using radioactive materials, well before the invention of particle accelerators in 1932. Even 100 years on, traces of these materials could still be found within the buildings as a kind of radioactive ghostly call from the past occupants. Among the oldest of the radioactive ghosts inhabiting the buildings is that of Frederick Soddy who during his 1903 visit brought news of Geisel's radium which Schuster eagerly pursued with a purchase shortly thereafter, and undoubtedly contributed to the contamination of the building well before Rutherford arrived in 1907. Considering these tiny traces from the past Soddy's description of the spinthariscope comes to mind.

"This minute insignificant trace of radium is positively belching forth α-particles. It seems incredible that the incessant bombardment of the screen can be caused by such an infinitesimal amount of radium. Yet so it is, and in a month's time, if the instrument is re-examined, it will be found that the scintillations are as numerous and as brilliant as formerly. After a time, perhaps a year, the phosphorescent screen itself will be worn out by the incessant bombardment, will become insensitive and need renewal. But replace it by a new one and the radium will be found to be as energetic as ever. The owner of the instrument will pass away, his heirs and successors, and even his race will probably have been forgotten before the radium shows any appreciable sign of exhaustion." [51]

Finally we should note that when Rutherford and Soddy articulated the disintegration theory of radioactivity in 1902 it was absolutely clear to them that an atomic disintegration was invariably accompanied by a chemical

[50] Eve AS. (1939). *Rutherford, Being the Life and Letters of the Rt. Hon. Lord Rutherford, O.M.*, Cambridge University Press, Cambridge, p350.

[51] Soddy F. (1909). *The Interpretation of Radium: Being the Substance of Six Free Popular Experimental Lectures Delivered at the University of Glasgow, 1908*, John Murray, London.

change, i.e. it was a form of spontaneous transmutation. To quote from Rutherford's 1908 Chemistry Nobel Prize lecture:

"Consider for a moment the explanation of the changes in radium. A minute fraction of the radium atoms is supposed each second to become unstable, breaking up with explosive violence. A fragment of the atom – an α-particle – is ejected at a high speed, and the residue of the atom, which has a lighter weight than before, becomes an atom of a new substance, the radium emanation. The atoms of this substance are far more unstable than those of radium and explode again with the expulsion of an α-particle. As a result the atom of radium A makes its appearance and the process of disintegration thus started continues through a long series of stages."[52]

It was completely natural then for Rutherford a decade later to extend the term "disintegration" to induced or artificial transmutation. Not only had he determined in 1919 that the bombardment of nitrogen by α-particles yields H-particles, he had also determined in the part III paper that the heavy recoil atom following the induced disintegration of nitrogen had a range of that of oxygen and that these reactions were, therefore, inelastic (they conserved momentum but not energy). The term "disintegration" was accepted and used by his contemporaries and students, including the successor occupants of the Old Schuster Laboratory after 1919, variously under the Langworthy Professorships of Bragg, Blackett, Devons and Flowers, right up to the 1960s when physics moved out. So when they had in the 1950s erected the plaque above the bench where Rutherford conducted the work leading to the 1919 publications to acknowledge his achievement with the words "*On the bench below the artificial disintegration of nitrogen was first achieved by Rutherford*" there can be no doubt that they also were clear that it was induced or artificial transmutation. It is absolutely fitting that we commemorate and celebrate the centenary of Rutherford's great discovery.

[52] Rutherford E. (1908). "The chemical nature of alpha particles from radioactive substances" in *Nobel Lectures, Chemistry 1901-1921,* Elsevier Publishing Company, Amsterdam, 1966.

Rutherford's path to "splitting the atom"

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In 1891 the students of Canterbury College in New Zealand formed a science society, to meet fortnightly during term time. They printed a programme and, being students, the then naughty word of science (evolution) was in four titles: "The Evolution of the Elements", "Evolution of Biology", "Evolution in Psychology", and even "Evolution in Morality and Religion". This caused the Bishop of Christchurch to thunder from the pulpit that "the students of Canterbury College were saturated with agnosticism." A letter writer to the local newspaper had the solution. "Science must be banished from the College curriculum."[1] Luckily it wasn't, because one of the early joiners of the society that year was a second year physics student called Ernest Rutherford. Rutherford left Canterbury College in 1895, with three degrees from the University of New Zealand (B.A, M.A.(Hons), and B.Sc.) and two years of original research work at the forefront of the electrical technology of the day, the magnetisation of iron in the megahertz frequency range.

Cambridge 1895-1898

He had an Exhibition of 1851 Scholarship to go anywhere in the world to study a topic of interest to New Zealand industry. On-board the ship to England, he learned the German language as Germany was a centre of physics research. When his ship arrived in England he visited the Cavendish Laboratory of Cambridge University and decided to take his scholarship there, because its director, J.J. Thomson, had written one of the text books Rutherford had used in his researches. Besides, on first meeting they liked each other.[2]

Rutherford spent his first months at Cambridge using his little "inventions" from New Zealand to measure the dielectric constant of dielectrics in the megahertz range and then his little magnetic detector of very fast current pulses to set a world record over which electromagnetic waves had been

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[1] Fuller details of most of the events in this article may be found in Campbell J A (1999). *Rutherford Scientist Supreme*, AAS Publications.

[2] Rutherford E., *Letter to Mary Newton*, 3rd Oct 1895, Rutherford Family.

detected (half a mile). This work so impressed Thomson that he invited Rutherford to work with him on his current project, how a perfectly good electrical insulator (a gas) could be turned into a perfectly good electrical conductor (a gas discharge). What were the entities conducting electricity? Rutherford used gaseous diffusion as a method to investigate these objects.

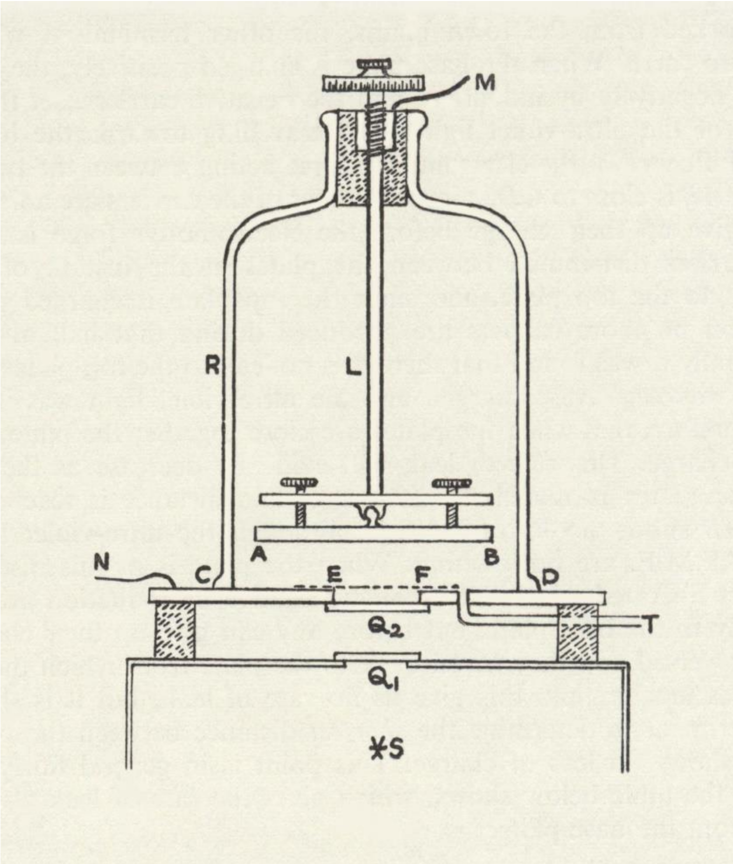

Fig. 1. Rutherford's apparatus for determining the diffusion speed of the negative charges involved in electrical conduction in ionized gases[3].

[3] Rutherford E. (1898). "The discharge of electrification by ultra-violet light", *Proc. Cam. Phil. Soc. 9,* 401-416.

One of his experiments involved the apparatus in Fig. 1. The bell jar allowed different gases and pressures to be utilized. A metal plate (AB) had UV light (S) shone on it through quartz windows (Q) and a metal gauze (EF) so that the gas near it became conducting. AB and CEFD were parallel and connected to the Cambridge town electricity supply. The electrical conductors from the gas were known to be negative entities. When the plates were close together the objects conducting the electricity were repelled during the half-cycle when EF was negatively charged but could reach EF when it was positively charged, so a current flowed between them. As the two plates were shifted apart there was a point where the conducting entities didn't have time, via gaseous diffusion, to reach EF on the positive half-cycle so that no conduction took place. Rutherford was getting a handle on the size and mass of the conducting entities.

But it was Thomson himself who carried out the definitive experiment[4]. He took a beam of cathode rays (same entity), deflected it to one side using an electric field and to the other using a magnetic field. By balancing these two forces he showed that the conducting entities had to be about 1000 times lighter that the smallest know atom (hydrogen). Thomson had discovered the electron, the first object smaller than an atom. Rutherford, who had worked on this problem alongside Thomson for more than a year, was an immediate convert to the fact that there were objects smaller than the atom.

Just a month before Rutherford had been invited to join Thomson on this problem an amazing accidental discovery was announced: X-rays. A month later, X-rays led to the accidental discovery of radioactivity. Thomson initially continued with gaseous conduction but Rutherford, who used both of these new methods to ionize his gases, was more intrigued by what was radioactivity. Before he left Cambridge in 1898 he had shown that radioactivity seemed to consist of two types of rays, one easily stopped (a piece of paper will do) and one more penetrating. From his classical background he named these alpha and beta rays.

[4] Thomson JJ. (1897). "Cathode rays", *Phil. Mag. V,* 44, 293-316

Canada 1898 - 1907

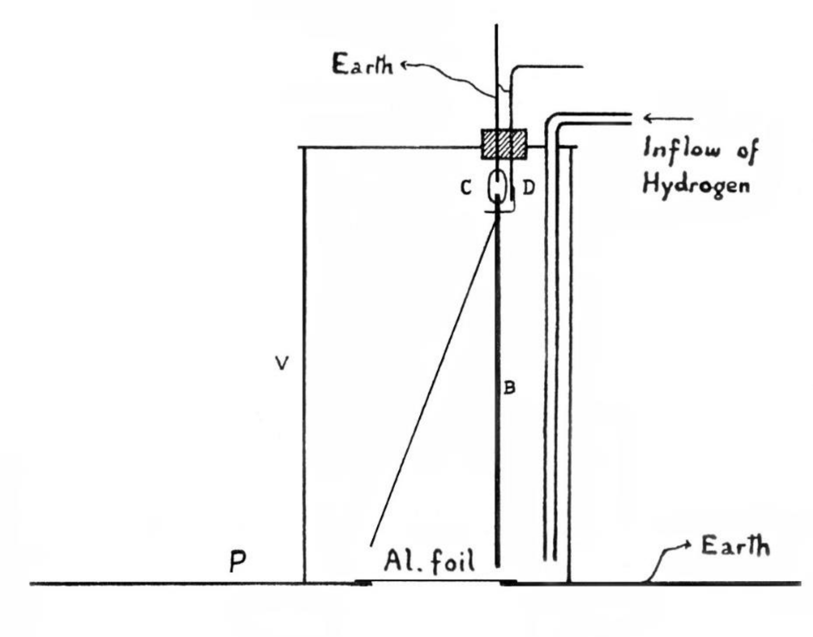

Fig. 2. The Electroscope. Rutherford's 1898 detector of alpha radiation[5].

When Rutherford was appointed to lead physics research at McGill University (Canada) in 1898 his methods of detection of radioactivity were primitive as in Fig. 2. An electroscope consisted of a metal plate (B) to which was attached a flexible foil of metal to its left. On charging, the foil moved away from the plate (like charges repel) with the angle giving a measure of the charge on the electroscope. A good electroscope could hold its charge for at least a day. However, if an alpha emitter was placed below the thin aluminium foil it could enter and discharge the electroscope quickly, the rate of discharge being a measure of the strength of the source. With the electroscope charged and an alpha source in place, Rutherford blew tobacco smoke into the electroscope and greatly diminished the rate of discharge. He had demonstrated the principle on which the modern radioactive smoke detector works.

[5] Rutherford E. (1905). *Radioactivity*, CUP, Cambridge.

Typically electroscopes were placed in a metal can because even small draughts could blow around the light metal foil. Rutherford and his co-worker Owens (the new Professor of Electrical Engineering) had also noticed the thorium alpha source also seemed to give off a radioactive gas, he called thorium emanation. Rutherford, with the assistance of Harriet Brooks, his first research student, and Owens had discovered what was later called radon. Interestingly, Brooks used gaseous diffusion to get a handle on the size of the “emanation”.

In March 1901, the McGill Physical Society called a meeting on “The existence of bodies smaller than an atom”, in order to demolish the chemists who, in the main, hadn’t accepted this idea. Rutherford was opposed by a young Oxford chemist, Frederick Soddy. He had arrived from England hoping to get a chair at Toronto but settled for a temporary demonstratorship at McGill. Soddy, whose talk was entitled “Chemical Evidence for the Indivisibility of the Atom”, attacked Rutherford and Thomson who “had been known to give expressions to opinions on chemistry in general and the atomic theory in particular which call for strong protest.” Neither was moved. Rutherford, a B.Sc. graduate in chemistry and geology needed a chemist more knowledgeable than he to do the chemical side. He had asked the professor of chemistry, (Walker) who joined McGill when he did, to work with him. Walker declined on the grounds that he was an organic chemist. So after the meeting Rutherford invited Soddy to join him after the summer break to work on the chemical side. Within three months Soddy was accepting phrases such as “radioactivity is a manifestation of sub-atomic chemical change.” In 1903 Soddy returned to England to work with William Ramsay on inert gases, of which radon was one.

Beta particles are easily deflected by electric and magnetic fields but no one had been able to deflect the much heavier alpha particles. Rutherford did, using in one of these many experiments the apparatus in Fig. 3. An alpha emitter (W) produced a narrow fan of alpha particles between two metal plates (A and B). This beam was detected using a photographic plate (P). Just like in Becquerel’s first experiments, the plate slowly fogged where alpha particles struck. An electric field across the plates could deflect the alpha beam one way or the other over a small distance that could be easily measured.

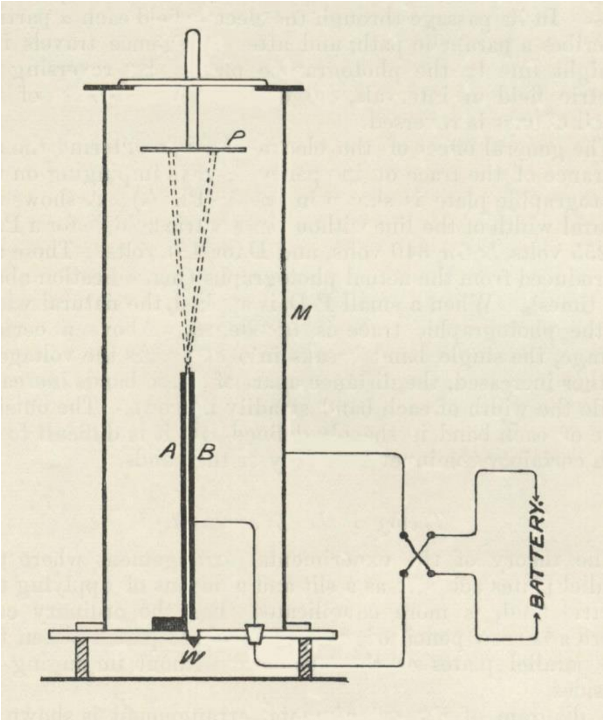

Fig.3. Rutherford’s 1906 Apparatus for Deflecting Alpha Particles by an Electric Field[6].

Rutherford, being sure alpha particles were just helium atoms minus two electrons, heated radioactive minerals and captured the helium gas expelled. Using this method he was then able to develop the novel method of radioactive dating to estimate the age of the Earth. He extended the small age obtained by Kelvin (based on classical cooling) to be closer to the much longer times that geologists needed to explain, for example, salination of rivers and oceans and deposition of the Earth’s silt layers. With the help of the American chemist Bertram Boltwood, they expanded the few radioactive transformations that he and Soddy had elucidated until they had shown how uranium radioactively decayed through a long series of steps to become stable lead. Subsequently U/Pb measurements allowed accurate geological dating.

[6] Rutherford E. (1906). “The mass and velocity of the α-particles expelled from radium and actinium*” Phil. Mag. VI*, 12, 348-371

Alpha scattering

Rutherford moved to Manchester in 1907 to be nearer the centre of physics. This was a pity for in 1908 he received the Nobel Prize in Chemistry "for his investigations into the disintegration of the elements, and the chemistry of radioactive substances." It was the first Nobel Prize for work carried out in Canada. Manchester proudly accepted the credit. In his alpha deflection experiments in Canada Rutherford had had to work in a vacuum because when his beam went through air, or a thin slice of mica, it became fuzzy. The alpha particles were scattered through a few degrees according to the very poor photographic plate detector. This had caused him to comment that "the atoms of matter must be the seat of very intense electrical forces."[7] He had the nub of the idea for the "nuclear" model of the atom.

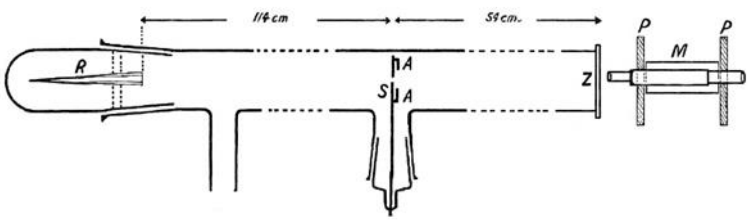

Fig. 4. Geiger's 1908 small angle alpha scattering apparatus.

At Manchester he inherited an assistant, Hans Geiger, so immediately put him to make accurate measurements of the number of alpha particles scattered by a thin foil as a function of angle over a few degrees[8]. The apparatus could be evacuated of air. Alpha particles from R were collimated into a narrow beam by a small slit S and struck a thin foil placed in AA. The alpha particles, scattered over small angles of up to two degrees, were observed using a scintillation screen Z. For the foils used, gold scattered strongly and aluminium less so. A study was underway for all substances from which it was possible to easily make thin films.

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[7] Rutherford E. (1906). "Retardation of the α-particle from radium in passing through matter", *Phil.Mag. VI,* 12, 134-146.

[8] Geiger H. (1908). "On the scattering of the α-particles by matter*", Proc. Roy. Soc. A81***,** 174-177.

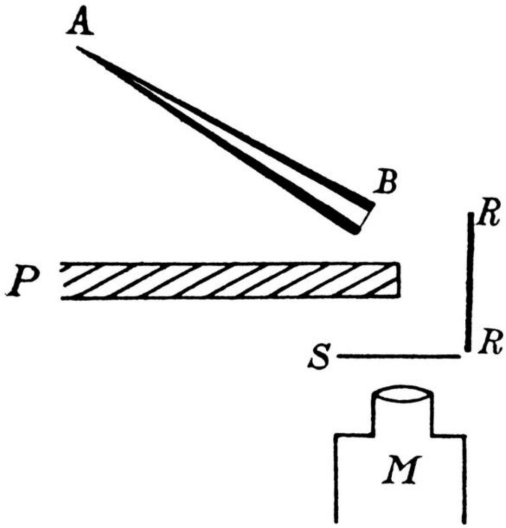

Fig. 5. Marsden's 1909 large angle alpha scattering apparatus.

As assistant, Geiger fulfilled many roles in Rutherford's laboratory. One involved running a training laboratory in radioactive techniques which Rutherford set up because he believed senior undergraduates should be involved in forefront research. Geiger reported to Rutherford that a senior undergraduate from Lancashire, Ernest Marsden, was ready for a research of his own. Everyone knew that beta particles could be scattered off a block of metal but no one thought that alpha particles would be so scattered. So Rutherford asked Marsden to see if there were any alpha particles scattered off of a block of metal[9]. Alpha particles emitted from B impinged on a block of metal RR and, if any were scattered, were detected by a scintillation screen S and viewed by a microscope M. A lead plate P prevented any alpha particles taking the direct path to the scintillation screen. Marsden quickly found there were, even if the block of metal was replaced by Geiger's thin metal foils. This was entirely unexpected. It was, as Rutherford later declared, as if you fired a fifteen-inch naval shell at a piece of tissue paper and it came back and hit you.

[9] Geiger H, Marsden E. (1909). "On a diffuse reflection of the α-particles", *Proc. Roy. Soc.* A82, 495–500.

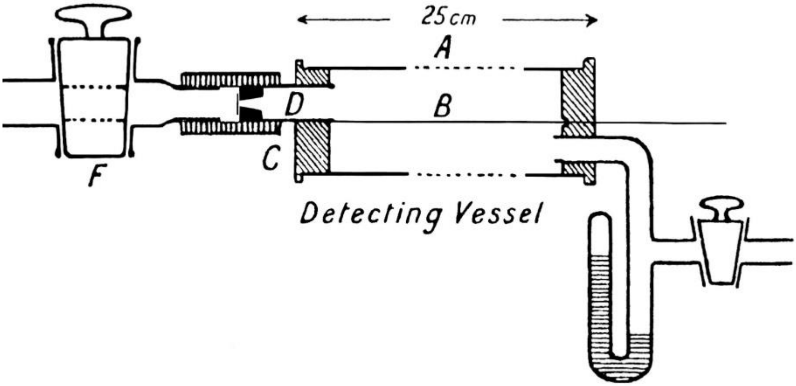

Fig. 6. The 1908 Rutherford-Geiger tube.

There followed a hiatus of eighteen months, which is surprising given Rutherford's statement back in Canada that the atom must be the seat of intense electric fields. But the answer is that he had so much work going on in the laboratory this was just one of many very interesting results. To give just one example, he needed a detector of individual alpha particles so developed the Rutherford-Geiger tube[10]. A metal tube (A) had a central wire (B) of uniform thickness at its centre. Insulating plugs (C) allowed the gas type and pressure inside to be adjusted. A high DC voltage was established between tube and wire that was not quite sufficient to produce a gas discharge between them. But the system was primed ready to go. An alpha source could be allowed to send alpha particles individually into the tube. Each alpha particle left a trail of ionised gas and this was sufficient to allow momentarily a gas discharge between wire and tube. An electrometer between wire and tube showed a momentary conduction pulse. Later, this electrometer output was shone on a slowly moving photographic paper, giving a permanent recording and allowing tireless recording of alpha particles. (There have been seven Nobel Prizes for detectors of individual nuclear particles but never one for the first, the Rutherford-Geiger tube. Not

[10] Rutherford E, Geiger H. (1908). "A method of counting the number of α-particles from radioactive matter", *Mems. Man. Lit. and Phil. Soc. IV*, 52, 1-3. The diagram is from Rutherford E, Geiger H. (1908). "An electrical method of counting the number of α-particles from radio-active substances", *Proc. Roy. Soc.* A81, 141-161.

surprisingly, as Rutherford won the Nobel Prize that year for his earlier works.) With this they were able to confirm that the scintillation screen gave one scintillation per alpha particle, allowing them to accurately measure the strength of radioactive sources (the first unit of radioactivity was called the "Rutherford") and their half-lives, the charge on the electron, the heating effect of radium, and several other fundamental properties.

So it was that one day in the winter of 1910 Rutherford exclaimed to Geiger that he "knew what the atom looked like". Most of the mass, and all of only +ve charge, was concentrated in a tiny volume (later named the "nucleus") only a thousandth the size of an atom. Geiger immediately started more accurate measurements of large angle scattering to confirm Rutherford's theory.

"Splitting the atom"

With heavier nuclei, a near head-on alpha particle scattered before it got anywhere near the nucleus but Rutherford thought that for light atoms, the alpha particles could get much nearer, possibly even colliding with the nucleus. In 1913 Rutherford therefore asked Marsden to fire alpha particles at light nuclei such as hydrogen. Classical physics showed that, in a head-on collision, the hydrogen ion (H^+, i.e. the nucleus of the hydrogen atom) would recoil at a speed 1.6 times that of an alpha particle and thus travel in air some four times further. Any single-charged ion up to oxygen should recoil further than the incident alpha particle travelled, accordingly to its mass. Rutherford and Marsden duly observed the weak flashes of recoiling ions, in particular H^+, on their scintillation screens. In 1914 Marsden accepted a chair in New Zealand, which Rutherford had recommended him for. So Marsden wrote up his work to date[11], explaining that the long-range recoil particles (H^+) were observed in hydrogen gas and thin films of materials rich in hydrogen, such as paraffin wax and India rubber. They were sometimes observed in air and other materials but that may be because of water vapour impurities in the air or the sample, or condensed on the sample, or occasional higher energy alpha particles emitted from the source.

World War 1 intervened. Rutherford turned his mind to one of the most pressing war problems the Admiralty had, how to detect submarines when submerged. When America entered the war in October of 1917, he led the French/English delegation to the USA to convey submarine detection

[11] Marsden E. (1914). "The passage of α-particles through hydrogen", *Phil. Mag. VI,* 27, 824–830.

techniques to the Americans. He fruitlessly encouraged them to utilize their scientific men on problems associated with the war, and not to waste them in the trenches. His directional hydrophone was to be fitted to fleet ships, so by 1917 Rutherford could return to his scientific researches, specifically the alpha particle scattering from light atoms.

By Dec 1917 he could report to Niels Bohr that "I am also trying to break up the atom by this method. --- Regard this as private."[12] He bombarded gases such as hydrogen, carbon dioxide, nitrogen, and oxygen with alpha particles, paying particular attention to avoiding water vapour impurities. The recoil speed (and hence range in air) of the different nuclei depended on their mass. Sometime in 1918 he observed a curiosity. When he bombarded dry nitrogen with alpha particles he also observed the long range H^+ nuclei, longer than a mere head-on collision for the relevant nuclei could produce. Clearly the hydrogen nuclei were a component part of the nitrogen nuclei.


ALCHEMISTS' GOAL REACHED BY BRITON?

Paris Matin Says Sir Ernest Rutherford Has Discovered Transmutation.

Fig 7. A headline from the New York Times 9th Dec 1919

He delayed publishing this work until the war ended and did so the following spring, after he had accepted a new position in Cambridge as head the prestigious Cavendish Laboratory. Cambridge later cheerfully accepted the glory of Rutherford "splitting the atom". Around the time that he was in the process of moving, in April 1919 he sent off four papers under the overall title of "Collision of α Particles with Light Atoms". The fourth

[12] Rutherford E., *Letter to Niels Bohr*, 9th Dec 1917, Bohr Institute Archives.

was subtitled "IV. An Anomalous Effect in Nitrogen."[13] He concluded that in the disintegration of nitrogen by alpha bombardment "the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus." Furthermore, "the range of the (recoiling) nitrogen atoms is about the same as the oxygen atoms, although we would expect a difference of about 19 per cent. If in collisions which give rise to swift hydrogen atoms, the nitrogen is at the same time disrupted, such a difference might be accounted for, for the energy is then shared between two systems."[13] He had "split" or "disintegrated" the atom using artificial means (by using naturally occurring alpha particles from radioactive atoms), and so discovered artificial transmutation, thus becoming the world's first successful "alchemist" (he had produced hydrogen from nitrogen) (see Fig 7).

The following year, during in his 1920 Bakerian lecture to the Royal Institution, Rutherford proposed that a neutral particle (the "neutron"), with a similar mass to the proton, had to exist to account for isotopes[14]. (The neutron was not discovered until 1932, in his laboratory.) That same year he first suggested the name "proton" or "prouton" for the hydrogen nucleus[15]. In order to further investigate the disintegration of nitrogen at around this time he set a Cambridge visitor, Takeo Shimizu, to build an automatic Wilson Cloud Chamber to take thousands of photos of recoil tracks produced from firing alpha particles into nitrogen. When Shimizu returned to Japan in 1921 he patented his device[16] and wrote up his results to date[17]. Shimizu was replaced by Patrick Blackett who, in 1925, showed that the disintegration of nitrogen by alpha particles occurred by alpha capture and proposed that what was left behind after the ejection of a proton was a rare isotope of oxygen (O^{17})[18].

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[13] Rutherford E. (1919). "Collision of α-particles with light atoms IV. An anomalous effect in nitrogen", *Phil. Mag. VI*, 37, 581-587.

[14] Rutherford E. (1920). "Nuclear constitution of atoms", *Proc. Roy. Soc.* A97**,** 374-400.

[15] Correspondents report on the BAAS meeting at Cardiff covering Rutherford E. (1920) paper. "Building-up of atoms", *Engineering* 110, 382.

[16] Shimizu T. (1921). "A reciprocating expansion apparatus for detecting ionising rays", *Proc. Roy. Soc.* A99**,** 425-431

[17] Shimizu T. (1921). "A preliminary note on branched α-ray tracks", *Proc. Roy. Soc.* A99, 432-435.

[18] Blackett P MS. (1925). "The ejection of protons from nitrogen nuclei, Photographed by the Wilson method", *Proc. Roy. Soc.* A107**,** 349-360.

Fig. 8. The unofficial Coat of Arms the students made for Rutherford as President of the 1923 BAAS meeting in Liverpool.

There have been twelve Nobel Prizes awarded for particles but never one for the second nuclear particle discovered, the “proton”. He was nominated for 1922 but the examining committee concluded, “Notwithstanding the importance of Rutherford's recent research, the committee nevertheless finds that the question of an award should be deferred until greater experience has been gained about these remarkable phenomena.” Also in 1922, Rutherford was appointed the President of the British Association for the Advancement of Science for its August 1923 meeting in Liverpool. The BAAS made up a President’s pennant for the occasion, incorporating the Liverpool Coat of Arms and, at the bottom, RUTHERFORD, LIVERPOOL, 1923. Either side of the lettering “RUTHERFORD” were four stars (the Southern Cross, representing New Zealand) and the Maple leaf of Canada. The students designed their own “unofficial” banner (Fig 8). Its motto “*Atom Virumque*” is the student’s reworking of the first line of Vergil's "Aeneid" (*arma virumque cano* = I sing of arms and a man) to be “an atom and a man”). Thus the popular notion of “splitting the atom” to describe nuclear reactions was established before this 1923 event.

Fig. 9. The 1971 New Zealand stamp celebrating the centennial of Rutherford's birth.

Many years after Rutherford's death in 1937 the nuclear equation which describes the process which Rutherford discovered in 1918 was depicted on a New Zealand stamp of 1971, one of two to celebrate the centennial of Rutherford's birthdate. It was released in December, well after Rutherford's birthdate on August 30th. New Zealand had been shamed into having a stamp by the Russians, who had released their Rutherford stamp on the correct date[19]. England, sadly, never commemorated the event in this manner.

[19] For the full story, see www.rutherford.org.nz under Honouring Rutherford – 1971 New Zealand 7c.

The nuclear force and transmutation

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Introduction

The focus of this article is a retrospective review of the experiments in Manchester a hundred and more years ago, to see at what stage, if at all, the effects of the nuclear force can clearly be identified in the data. The actual discovery of the nucleus itself, as a consequence of Geiger and Marsden's experiments and Rutherford's interpretation relied entirely on the electric force, whose strength varies like the inverse square of the separation between the electric charges on the bombarding alpha particle and the target nucleus. The strength of this force therefore increases with closer and closer encounters and there is no reason why *a priori* this would not be enough to disrupt the nucleus in Rutherford's transmutation experiments.

At the time of the historic discoveries in 1919, two forces of Nature were known: gravity and electromagnetism. History assigns the theory of gravity to Newton and the theory of the electric part of electromagnetism to Coulomb. Both these assignments are unfair to others. Robert Hooke wrote to Newton telling him that the force of gravity varied like the inverse square (although Newton had already tested a version of an inverse square at an earlier date). Edmond Halley returned from a visit to St Helena, where he had set up an observatory to observe the transit of Venus and told both Hooke and Newton that his clock ran slow when he took it up a mountain and he had been required to shorten the pendulum. Newton knew that the period of a pendulum varied like the square root of the length of the pendulum divided by the acceleration due to gravity, *g*, and was able to extrapolate to planetary distances. A consequence of Newton's mathematics was that there could be no field inside a hollow body if, and only if, the law was an inverse square. Joseph Priestley used this fact to deduce that the electric force was also an inverse square, by noting that there was no field inside a charged hollow sphere. He did this 18 years before Coulomb's direct measurement and indeed, the precision tests of the validity of the inverse square, currently better than one part in 10^{16} are done by Priestley's method, since Coulomb's direct method is inadequate.

Gravity had an input to electricity and we shall also consider here, to what extent these two forces had an input into the understanding of the nuclear force.

Portents of the nuclear force

By the end of the 19th Century, the understanding of the physical universe was in desperate need of both the nuclear force and transmutation and its consequences. There were several observed phenomena that defied explanation in terms of what soon became known as “classical physics”. All this changed as nuclear physics and quantum mechanics forced their way into the tapestry of known physics, albeit in the face of some reluctance by the old guard.

Two phenomena are noteworthy and give an indication of the wider malaise afflicting the subject of physics. On the 18th of August 1898, an article appeared in Nature[1] containing some of Arthur Schuster’s holiday dreams. Schuster was the Director of the Physical Laboratories at Manchester and most of the article was spent pondering the novel concept of anti-matter. Of relevance to the discussion here was a paragraph where he disputed the possibility that gravitational or electric forces could be responsible for the enormous power observed in solar prominences. Something new was needed. By this time, Schuster was a veteran of numerous eclipses and he was moved to mention a special one: “Is the cause of coronal streamers known? And can anyone look at a picture of the great prominence of the 1885 eclipse, and still believe that gravitational attraction or electric repulsion is sufficient to account for its extravagant shape?” Such a statement would have anyone, not just an expert on the history of eclipses, wondering what was special about the one in 1885. In fact Schuster’s memory was awry. There was nothing special about the 1885 eclipse, visible in New Zealand, which Schuster did not observe. It was the 1886 eclipse, which he saw from the West Indies that showed solar protuberances rising to more than a million miles, more than the solar diameter, above the surface.

The other phenomenon that had vexed and perplexed physicists during the 19th Century was the age of the earth and the sun. The age of the sun is currently held to be 4.603 billion years, although this particular value depends on computer models of stellar evolution and the use of

[1] Schuster A. (1898). “Potential matter – A holiday dream“ *Nature* 58, 367.

nucleocosmochronology. Also of relevance to our discussion is the currently accepted age of the earth: 4.543 billion years. At the end of the 19th Century, the contemporary conception of the value of these ages by physicists meant that they were at odds with evolutionists, palaeontologists, geologists and botanists, who all held the view, correct at the time, that physics had nothing to offer regarding the ages of the sun and earth. Physics was irrelevant and out in the cold. Lord Kelvin had done his best, calculating how long it would take to cool to its present temperature, but as he applied his almost unparalleled brain to the available knowledge, he could only make matters worse.

Germany's 19th Century physics colossus, Hermann von Helmholtz, arguably at least the intellectual equivalent of Kelvin, had calculated the sun's age on the basis of it being a coal fire and came up with 5,000 years. Archbishop Usher, counting generations since Adam, said that the earth was created on the 22nd of October, 4004 BC.

Kelvin then proposed that the source of the sun's energy was derived from relentless gravitational collapse and this was enough to keep the sun glowing brightly for 40 million years. Charles Darwin objected that evolution needed more time. From the outset, Kelvin was sufficiently hostile to the intrusion of nuclear physics into any theory of the source of heat of the sun and earth. As late as 1906, he did not believe that radium was an element. Any residual doubts about the role of nuclear physics in stellar evolution were extinguished by Rutherford's transmutation work in Manchester in the years from 1914 to 1919.

The discovery of natural transmutation, the conversion of one element into another by virtue of radioactive decay, had already taken place in the Macdonald Physics Building at McGill University in Montreal during the first few years of the 20th Century, although Kelvin dismissed it as speculation. Rutherford himself is on the record before and after his Manchester research that it was only natural to investigate whether he could induce transmutation himself. On arrival in Manchester in 1907, he set about further investigations into the radio-activity of atoms and over the subsequent 12 years, transformed the view of the physical world, solving several niggling problems like those above, along the way. His Department in 1910 is shown in Figure 1 and several of the people in the photograph appear in this article.

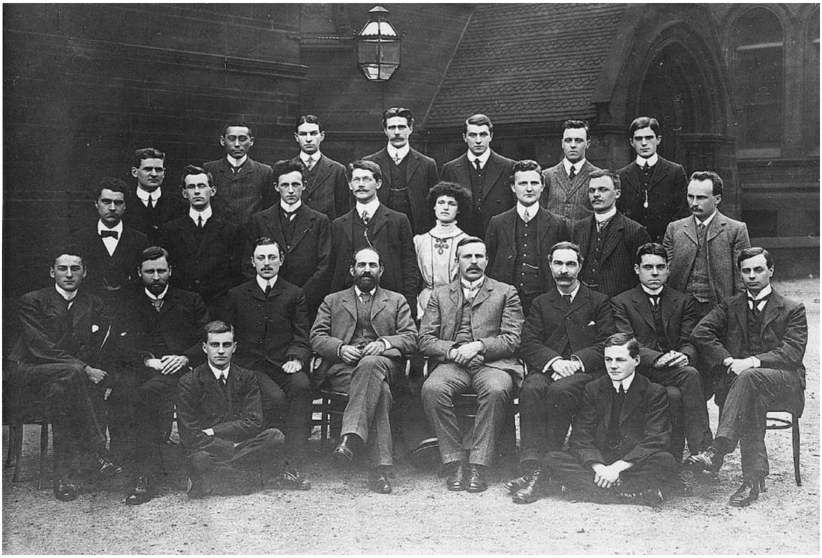

Figure 1: Manchester Physics Department staff and students in 1910.

Slightly forward of the back row on the left: William H Eccles. Back row standing, L to R: Suekichi Kinoshita, Roberto Rossi, William Kay, George N Antonoff, Ernest Marsden, Walter Lantsberry. Middle row standing, L to R: Frank Whaley, Harold Greenwood, William Wilson, W Borodowsky, Margaret White, Evan Evans, Johannes Wilhelm Geiger, Yrjo Tuomikoski. Front row seated, L to R: Sidney Russ, Herbert Stansfield, Harry Bateman, Arthur Schuster, Ernest Rutherford, Robert Beattie, Norman Pring, Walter Makower. Seated on the ground: Roland Slade, William Harwood.

The Geiger-Marsden experiments

The first of the Geiger-Marsden experiments[2], where alpha particles were fired at a gold target, is renowned for the first experimental demonstration of the existence of the atomic nucleus. However, due to the large electric charge on the gold nucleus, the distance of closest approach between the two particles was never less than about 40 10^{-13} cm and the nuclear fields did not overlap. Any manifestation of the nuclear force can thus be discounted in this experiment.

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[2] Geiger H, Marsden E. (1902). “On a diffuse reflection of the α-particles” *Proc. Roy. Soc.* A82, 495–500.

The observation that one in 8,000 of Rutherford's swift alpha particles was deflected by more than 90 degrees was enough to provoke further investigations because on the basis of the plum pudding model of the atom, proposed by J J Thomson, there should have been none deflected by such a large amount. That single statistic "1 in 8,000" was enough to provoke Rutherford to change the perceived view of the physical world.

Geiger and Marsden were then instructed to carry out a systematic study of large angle scattering, and especially to extend the range of targets down to carbon in order to test the new theory that Rutherford had devised. The crucial ingredient of this work[3], was that the distance of closest approach between the alpha particle and a carbon nucleus was a mere 2 10^{-13} cm, for head on collisions, less than what we now know to be the carbon nuclear radius of 2.6 10^{-13} cm. In principle, the door was now open to observe the effect of the nuclear force. A careful examination of the data, however, shows no such visible effect. It should be noted that when Geiger and Marsden presented their results and compared them to the predictions of Rutherford's formula, they used an approximation for the atomic number, Z, which was assumed to be one half of the atomic weight. Given that atomic numbers entered as the square, this had a significant effect for heavy nuclei. Another factor was that the equation did not take into account the recoil of the scattering nucleus and so the reduced mass should have been used. These two effects worked in opposite directions and cancelled to some extent, although overall the reduced mass effect was bigger and led to an overall correction, which was of the order of 15% for light nuclei. Such an error was regarded as reasonable by Rutherford and did not raise any suspicions. In any case it is easy to re-analyse Geiger and Marsden's data to see the consequences of correcting the approximations. They presented data which were essentially the ratio of data to theory for seven elements: gold, platinum, tin, silver, copper, aluminium and carbon. The standard deviation of the published 12 data points around the mean was 14% of the central value. When these corrections are now made, the standard deviation reduces significantly to 9% and within this accuracy, no deviation from electric scattering can be perceived. Rutherford would have been pleased to know this.

The reason why the nuclear force still was not observed, even though the distance of closest approach meant that it could have been present, was that

[3] Geiger H, Marsden E. (1913). "The laws of deflexion of α-particles through large angles" *Phil. Mag. VI*, 25, 604–623.

the scattering of alpha particles by these nuclei was dominated by small angle scatters with large separations between the two nuclei. This was determined by the geometrical configuration of the experiment, where small angle scattering prevailed. Even so, the validity of the inverse square law of electricity had been pushed down to an unprecedented distance scale. In 1911, the inverse square law for gravity was known to hold for distances of 4.5 10^{14} cm (Neptune) down to the height of an apple tree. Now the inverse square law for electricity was seen to be valid over a further 13 orders of magnitude to the nuclear scale.

What more natural thing to do, than to use hydrogen as a target and get the particles even closer? Geiger had now returned to Germany, so Marsden was assigned the task.

Fast H-particles

After the realisation by Rutherford that virtually all of the mass of an atom was concentrated in the nucleus, Charles Galton Darwin, Rutherford's mathematician at Manchester, worked out[4], in close conjunction with Rutherford, the kinematics of collisions between alpha particles and light nuclei, especially as a function of the mass of the nucleus. They found that in the case of a hydrogen nucleus, which they called an "H-particle", the velocity of the recoiling hydrogen nucleus would be 60% greater than the incoming alpha, for head on collisions. The aim of the first experiment on these "fast H-particles", carried out by Marsden and published[5] in 1914 was simply to test this kinematic prediction.

The apparatus for the initial studies was simple: a glass vessel, 1 metre long and 9 cm in diameter was filled with hydrogen and a source of alpha particles mounted on an iron tray which could be slid along the length of the tube using a magnet. With the source placed sufficiently far enough away from a zinc sulphide screen, so that any alphas were stopped by the hydrogen, clear scintillations were observed, corresponding to knock on H-particles. When the hydrogen was replaced by air, no such H-particles were observed. From this experiment, it was learnt that Darwin's kinematic

[4] Darwin CG. (1914). "Collision of α-particles with light atoms" *Phil. Mag. VI*, 27, 499–506.

[5] Marsden E. (1914). "The passage of α-particles through hydrogen" *Phil. Mag. VI*, 27, 824–830.

calculations were correct and as an added bonus, the slightly different characteristics of H-particle scintillations were noted – they were less intense than those caused by alpha particles.
With the benefit of future knowledge and hindsight, it is possible to consider what Marsden might have observed, but did not, especially with regard to the nuclear force. For nearly head-on collisions, the spatial extents of the alpha particle and the hydrogen nucleus overlapped (see Figure 2), with potentially profound consequences. The scattering of the two particles would no longer follow that of two particles with all of their charges located at their centres of gravity. This was a consequence of Newton's calculations for gravity, using calculus. But Marsden did not measure the angular distribution and would have been unaware. More profoundly, especially when the hydrogen was replaced by air, the nuclear force would have come into play and albeit with low probability, the process eventually observed by Rutherford and published in 1919 would have taken place – artificial transmutation of nitrogen, with the emission of H-particles. In this particular experiment, Marsden observed a few extra H-particles when air was used instead of hydrogen but relegated them to the effect of background radiation. With hindsight, they were almost certainly coming from induced transmutation of the nitrogen in the air and this is the first indication, although not appreciated by the experimenters, when the nuclear force made itself known in the laboratory.

At the end of his paper, Marsden begged to express his indebtedness to Mr W C Lantsberry for his efficient help. Lantsberry became a co-author of the second paper on this topic. Lantsberry, who had graduated in the department in 1914, was Rutherford's radium factotum, in charge of half a gramme of radium in the radium room, preparing and carrying samples to the research benches for Rutherford and his men and women to work with. This experience led to a job as a radiologist at Baltimore Hospital, where he was put in charge of an even larger amount of radium, preparing implants and radon capsules. He tragically died at the age of 34, his symptoms of anaemia and jaw atrophy, corresponding to those of classic radium poisoning.
In-between the publication of the two papers on fast H-particles, Marsden was appointed to the Chair of Physics at Victoria University College, Wellington. There was no interview; he was appointed at the age of 26 on the word of Rutherford. The second paper[6] was written up in Wellington and it came with a statement that it had not been possible to complete the

[6] Marsden E, Lantsberry W.C. (1915). "The passage of α-particles through hydrogen" *Phil. Mag. VI*, 30, 240–243.

experiments, but given that certain points of interest had arisen, it seemed advisable to publish them. Indeed, Marsden never returned to the subject again and it was left to Rutherford to continue the work with spectacular and unexpected results.
Before his new job in New Zealand and then the war put a premature end to Marsden's research in Manchester, he and Lantsberry had done enough to arouse Rutherford's curiosity. Scintillations were clearly observed, of the characteristic sort that Marsden had observed when bombarding hydrogen gas and sending its nuclei to the zinc sulphide screen. The yield of observed H-particles was far more than the formula predicted and the authors set about trying to find out where the excess came from. They failed. But as we shall soon relate, the excess was of epoch-making magnitude.

Marsden and Lantsberry's logic concerning the outcome of the experiment, which they clearly laid out in their paper, almost certainly guided by the hand of Rutherford, is a classic example of what is now known as a "Holmesian fallacy". They anticipated Sherlock's algorithm by 14 years and in words close to his, proceeded to eliminate all that was impossible, so that whatever remained, however improbable, must be the truth. But they failed to rule out an alternative explanation, because the alternative was completely unknown to them. All known possible sources of the anomalous extra yield were considered, such as hydrogen occluded onto glass surfaces or present in the air, and all these were correctly disproved and eliminated. Their conclusion was almost, but not completely assertive: "Thus there seems a strong suspicion that H-particles are emitted from the radioactive atoms themselves, though not with uniform velocity."

Alas, they did not know everything, and so the truth lay still unknown when all the impossibilities had been eliminated. As it happens, it is now known that there are no naturally occurring isotopes that emit protons, so not only was the Holmesian fallacy proved, but Rutherford was guaranteed to discover a new process during the course of his experiments, carried out in Manchester where he and his reliable laboratory steward, William Kay (see Figure 1), were among the few members of staff left during the war.

What Marsden, Lantsberry and Rutherford did not know, and had no means to guess in 1914, was that the alpha particles were interacting with the nitrogen nuclei in the air to transmute the nitrogen into an isotope of oxygen and a hydrogen nucleus, whereby the fast H-particle was emitted at high speed as part of the alchemical process. The alert reader might well ask why oxygen did not participate in this new phenomenon? The answer to this question lies in the nuclear shell model and the relative higher stability of nuclei with an even number of protons and neutrons, something unimaginable at the time.

The effect of the nuclear force was clearly visible in this second experiment on fast H-particles, but just as clearly, was not appreciated at the time.

The four famous papers of 1919

The original motivation for these continued studies with hydrogen, nitrogen and oxygen was the possibility, mooted by Marsden and Lantsberry, possibly suggested by Rutherford himself, although he quickly disassociated himself from the notion, that the fast H-particles were coming from the source itself. Rutherford did have transmutation in mind, but kept quiet about it in public until these papers appeared in 1919. He had mentioned it in a personal letter to Bohr in December 1917 that he was trying to do it and asked Bohr to regard it as private.

Rutherford started this sequence of experiments towards the end of 1914 as soon as Marsden left for New Zealand, continuing them for four years as his other war duties (e.g. sonar detection of submarines) permitted. He accepted the Cavendish Chair at Cambridge early in 1919 and stayed in Manchester until June 1919, the month that his four papers appeared in the Philosophical Magazine. The papers were signed in Manchester in April 1919.

In the first sentence of the first of his four epoch-making papers[7], Rutherford explained why light atoms were of interest. On the nucleus theory of atomic structure, it was to be anticipated that the nuclei of light atoms should be set in swift motion by intimate collisions with alpha particles.

The earlier work of Marsden and Lantsberry was mentioned, preceded by a clear statement by Rutherford that it was Marsden himself who had concluded that there was strong evidence that hydrogen nuclei were coming from the radioactive source itself. By now of course, Rutherford knew the

[7] Rutherford E. (1919). “Collision of α-particles with light atoms” *Phil. Mag. VI*, 37: “I. Hydrogen”, 537–561; “II. Velocity of the hydrogen atom”, 562–571; “III. Nitrogen and oxygen atoms”, 571–580; “IV. An anomalous effect in nitrogen”, 581–587.

origin of the H-particles and he spent the four contiguous papers, spanning 51 pages, gently leading the reader along the path to the climactic discovery.

This first paper concentrated on the nature of the H-particles produced in collisions between alpha particles (helium) and hydrogen. The scientific avarice of a historian can sometimes lead the reader into the temptation of racing through the first two or three papers of this quartet, almost as a duty, before feasting on the artificial transmutation of the fourth. But Rutherford made profound observations in the first of his four papers, based on his measurements and it is clear from the numbers that he quoted, with a measure of hindsight, that he clearly and unambiguously observed for the first time, the effect of the nuclear force in a man made experiment. This statement, made by none, or at most a few until now, naturally requires justification.

Due to the limited knowledge at the time, Rutherford could not say it was a new force of nature, but he did say that new interactions not varying with the inverse square had come into play. He declared his belief that the inverse square law of force between two electric charges, which was valid at separations of 10^{-12} cm, surely did not suddenly become invalid at 10^{-13}, and in this he was absolutely right. It was a sheer numerical coincidence that led him to believe that the electron was the culprit. At the time of this experiment, it was believed that the relatively recently discovered electron had a size which was determined by its mass and electric charge. Rutherford also believed that the electron was a constituent of the nucleus, in order to reconcile atomic mass with atomic number.

Let us now follow Rutherford’s sequential arguments.

• He calculated that the distance of closest approach between the two particles was 3 10^{-13} cm (see Figure 2). This number has stood the test of time and is correct.

• He observed by counting scintillations that the yield of “swift H atoms” (*i.e.* fast protons) was a prodigious 30 times greater than the theoretical number, calculated using the Rutherford scattering formula.

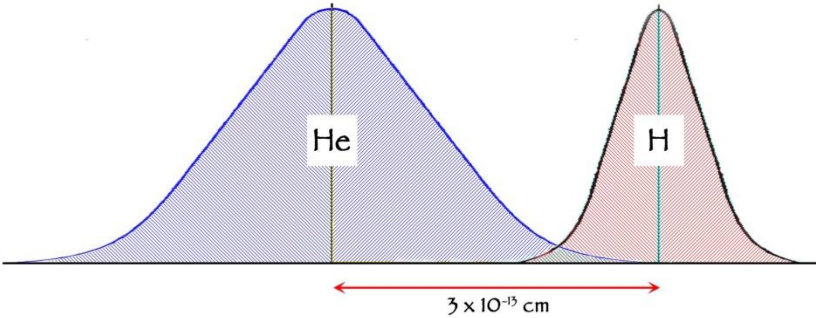

Figure 2: An alpha particle (helium nucleus) and a proton (hydrogen nucleus) at their closest distance of approach. The shapes are taken from Hofstadter's Nobel lecture.

• He noted that the distance of closest approach of the alpha and hydrogen: $3\ 10^{-13}$ cm, was "about the same as the accepted value of the diameter of the negative electron, viz. $3.6\ 10^{-13}$ cm".

The attribution of "negative" to the charge of the electron was highly significant. Given his statement in the paper that "We have every reason to believe that the alpha particle has a complex structure consisting probably of four hydrogen nuclei and two negative electrons", it was then no surprise that he estimated that a helium nucleus "consisted of a charged disk of radius about $3\ 10^{-13}$ cm, with its plane perpendicular to the direction of motion." Why the nucleus should be a disk and not a sphere was not immediately explained, but soon would be. By a sheer fluke, he got the size of the helium correct. The shapes of the distributions of helium and hydrogen in Figure 2 have been taken from Robert Hofstadter's Nobel Prize lecture[8] of 1961, thus with the benefit of absolute hindsight. Helium does indeed have a radius of $3\ 10^{-13}$ cm, but this is a pure coincidence with the classical radius of the electron and is essentially determined by the size of protons (which Rutherford thought were point-like) and neutrons (about which he had contemplated).

We are now in a position to compare what Rutherford said was happening, with current knowledge of what actually was happening and consider if the nuclear force was visible. Let us first consider the effect on the Rutherford

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[8] Hofstadter R. (1961). "The electron-scattering method and its application to the structure of nuclei and nucleons" *Nobel Lecture*, December 11, 1961.

scattering equation if both nuclei consisted purely of electric charges with a distribution as determined by Hofstadter, who measured only the electric charge distribution and not the distribution of nuclear force centres.

Figure 2 shows that the charge distributions overlap slightly. Newton’s Principia equations and arguments concerning forces that follow the inverse square law showed that inside a body that produces force, the actual force is less than the force outside the body. It is clear from Figure 2 that the overlap is rather small. Hence it is a reasonable consequence that the impact on the scattering process will also be small and will reduce the yield by a small amount. It is implausible that this overlap, given all that is known about the electric inverse square law force, could increase the probability of an interaction by a factor of 30. Rutherford was faced with this huge factor and for once, he floundered. Ignoring the possible size of the hydrogen nuclei constituents in the helium nucleus, indeed, all accounts suggest Rutherford deemed them to be point-like, he suggested that the anomaly was due to an excessive distortion of the electron.

Of course, Figure 2 is an idealistic representation of the two nuclei in the case where only electric forces come into play. When subsequent and modern knowledge is added, the fact that the charges overlap means that the protons and neutrons in the two nuclei overlap and hence there was an interaction by virtue of the strong force. The strong force is attractive, hugely attractive even, and it massively outweighs the repulsive force between two positively charged nuclei and so when the kinematics of the collision brought the two nuclei together, they were brought into a strong force interaction that made an alpha particle 30 times more likely to be sucked into a collision with a hydrogen nucleus. If the strong nuclear force be added to make a new version of Figure 2, it is enough to say that the two nuclei would be thereby attracted to overlap completely.

There is no explanation for the yield of swift hydrogen nuclei, 30 times more prolific than predicted by the scattering of point electric charges, except than by the influence of the nuclear force under the experimental conditions set up by Rutherford. But he dared not call it out loud.

It is therefore essentially an irrefutable fact that the effect of the nuclear force was observed in this experiment and indeed, since Marsden had first noted the excess, that the nuclear force was already seen, but not appreciated by Marsden in Manchester in 1914. Rutherford disposed of this lingering notion that the H-particles were probably emitted by the radioactive source, early in this first paper, asserting that it seemed probable that the large number of scintillations observed by Marsden were mainly due to high velocity nitrogen and oxygen nuclei, knocked forward when struck by an alpha particle.

The magnitude of the forces that were now apparent was noted by Rutherford. He calculated that the electrostatic repulsive force between two positively charged nuclei was equivalent to the weight of about five kilograms and yet despite the enormity of this force, and the expectation that the helium nucleus itself might break up, no such disintegration was observed, indicating that the helium nucleus must be a very stable structure.

The second paper of the quadrilogy concentrated on the nature of the supposed H-particle, or “H atom” as Rutherford now called it. Given the enormity of the forces endured during the collision process, the possibility of some kind of disruption of the structure of the nuclei involved meant that it became desirable to measure the mass and the velocity of the “flying atoms” and to compare the results with the values deduced from Darwin’s collision theory, assuming that the collisions were elastic. He therefore carried out a repeat of J J Thomson’s *e* and *m* measurements on the electron, but this time using magnetic and electrostatic deflexion of the positively charged H atoms.

His result that *e/m* for the H-particles was 10,000 e.m. units compared favourably with the contemporary value of 9570 for hydrogen obtained by the electrolysis of water and he made the firm deduction that the long-range (swift) scintillations produced by firing alpha particles into hydrogen, were caused by hydrogen atoms carrying a unit of positive charge. This was essentially the discovery of the proton.

The third and fourth papers in the quadrilogy focussed on the results when alpha particles were fired into air and then oxygen and nitrogen separately, which showed that the nitrogen nucleus was being disrupted. The initial state consisted of the elements helium and nitrogen and the final state consisted of the element hydrogen and something which careful reading of the two papers shows, behaved more like oxygen than nitrogen. Six years later, when Blackett published his cloud chamber work, supervised by Rutherford, the element that accompanied hydrogen was not definitively identified as an oxygen isotope (^{17}O), indeed Blackett said: “Of the nature of the integrated nucleus little can be said without further data. It must however have a mass 17, and provided no other nuclear electrons are gained or lost in the process, an atomic number 8. It ought therefore to be an isotope of oxygen."[9] The problem was that Aston's spectrographic work at Cambridge, which Rutherford much admired, indicated within the accuracy of the measurements that oxygen did not have any isotopes. Two years after Blackett's paper, Aston assured the world that oxygen only had one isotope, ^{17}O and it was not detected in the atmosphere until 1929.

Without a doubt however, the presence of the nuclear force was clearly demonstrated by the fact that two elements were converted into two different ones by a re-arrangement and transfer of nuclear constituents, held together by the attractive nuclear force.

The impact

From the outset, when he and Soddy observed natural transmutation in Montreal, Rutherford was reluctant to use that word and carefully called it "disintegration" for many years to avoid being called an alchemist. He was equally reluctant to introduce the concept of a new force although he want as far as to say that the inverse square law had broken down and there were new forces that differed in magnitude and direction from the value expected by extrapolating the electric inverse square law.

Others were less hesitant and two examples suffice. Arthur Stanley Eddington demonstrated that whilst Rutherford himself might be coy in using the word "transmutation", others, especially himself, were not. He seized Rutherford's transmutation results and combined them with Einstein's famous equation, $E = mc^2$ to forge a theory for stellar evolution and in particular to solve the perplexity of the age of the sun. Giving his presidential address to the British Association in 1920, he declared: "What Rutherford can do in his laboratory . . . . should not be too difficult in the Sun." Rutherford had shown that two elements when brought together could form a new element. The combined masses of four protons were measured to be greater than the mass of helium. Therefore, if four hydrogen nuclei were to fuse to create helium via the transmutation process, which has been proved by Rutherford to exist, then the mass defect would be converted to energy via Einstein's equation.

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[9] Blackett PMS. (1925). "The ejection of protons from nitrogen nuclei, photographed by the Wilson method" *Proc. Roy. Soc.* A107, 349-360.

Rutherford presented a paper[10] at the 1921 Solvay Conference entitled: "La structure de l'atome". After his talk, several luminaries present stood up and asked questions which the passage of time has relegated to showing merely that they were all present: Millikan, de Broglie, Langevin, Lorentz, Ehrenfest and Mme Curie. But Jean Baptiste Perrin spoke and brought a special insight to the new phenomenon, derived from his military experience during the First World War, when he had been in the French Army Engineering Corp.

Jean Baptiste Perrin made the profound observation that the notion of a simple collision must be given up, because the proton emitted had more kinetic energy than the incoming alpha particle. This could not happen, for example, if a cannon ball knocked a brick out of a building. Some extra energy was needed, such as an explosive shell or an exploding target.

At the moment of the collision, Perrin asserted, a "transmutation" occurs, probably consisting of an intra-nuclear rearrangement, with the possible capture of the incident alpha by the nucleus, the emission of the hydrogen nucleus which forms the observed H-particle, and perhaps even with other, less important emissions.

Eddington and Perrin thus immediately embraced transmutation and the existence of a new force and source of energy.

Follow up experiments in Cambridge

The work did not end here. Rutherford moved to Cambridge and continued the investigations with barely a hesitation. He took on James Chadwick, whom he knew from Manchester and fresh faces in the name of Étienne Samuel Biéler, Takeo Shimizu and Patrick Blackett. The story of the consolidation of transmutation and the nuclear force, together with an expanded, comprehensive version of this article can be found in the author's recent book[11]: "Transmutation: The Inside Story", published in 2019.

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[10] Rutherford E. (1923). "La Structure de l'Atome" in HA Lorentz (Ed.) *Atomes et électrons. Rapports et Discussions du Conseil de Physique, du l'Institut International de Physique Solvay, du 1er au 6 Avril 1921*, Gauthier-Villars et cie, Paris, pp36–78.

[11] Marshall R. (2019). *Transmutation: The Inside Story*, Champagne Cat, Marlborough.

"Splitting atoms": the news media and public perception of transmutation

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In his later life, when he was a prominent public figure, Ernest Rutherford was a doughty champion of the popularisation of science; that is to say, he encouraged the idea that scientific developments should be explained to the public in terms the public might understand, and he was ready to set the example in this himself. When did this determination first show itself in his activities?

It might be possible to detect an inkling as early as 1911, when, after his breakthrough formulation of the theory of the atomic nucleus, and even before he published his ideas in the *Philosophical Magazine*, he read a short paper about them to a public audience at the Manchester Literary and Philosophical Society. If this was an attempt to reach the public, however, it can be counted at best a limited success. No evidence survives of anyone taking particular notice of what he said, and not a single newspaper reported it.

The approach is more clearly evident in Rutherford's conduct eight years later, when he was ready to reveal that in his bombardment experiments he had penetrated and broken up the atomic nucleus. Again he chose to deliver a public lecture alongside the publication of the relevant journal papers, and this time it was at a more conspicuous venue, the Royal Institution in London. Moreover, his lecture was advertised in advance in the London *Times* on at least three occasions under the title: 'Atomic Projectiles and their Collisions with Light Atoms'. And it is clear that Rutherford took a significant step farther in what might today be called the promotion of his discovery. On the morning of the lecture, the *Manchester Guardian* was able to publish this double headline on page six:

'NITROGEN A COMPOUND?
SIR ERNEST RUTHERFORD'S LATEST DISCOVERY'.[1]

[1] "Nitrogen A Compound?" *Manchester Guardian*, 6 June 1919, p6

The text beneath began:

> *'Manchester is to lose Sir Ernest Rutherford, but he has allowed Manchester the honour of announcing his latest discovery.'*

That opening point was old news, referring to Rutherford's decision to take up the directorship of the Cavendish Laboratory in Cambridge, which had been announced two months earlier. But the rest of the sentence is revealing. It is clear from the wording – 'he has allowed' – that Rutherford had taken the personal initiative of forewarning the paper of this important scientific announcement, probably by sending it the text of his London lecture. There can be no doubt from this that he was keen that the world beyond the physics community should know what he had achieved.

Alas, the report itself shows that the paper was not really capable of doing justice to his gesture. It contained a good deal of waffle, but this was the meat of it:

> *'Nitrogen . . . is now suspected to be, not an element at all, but a compound of hydrogen and helium: the helium forming the central sun or nucleus of the system, the hydrogen nuclei appearing as satellites. The combining weight of 14 is explained as due to a central nucleus of three helium nuclei, each of mass 4, the remaining two being accounted for by the helium satellites.'*

Thus, for the *Manchester Guardian*'s writer, who gave the initials F.A.B., the news angle here was that nitrogen was a compound and not an element, and this message would be amplified in the days that followed as, in a manner common at the time, a few other regional papers reprinted the *Manchester Guardian* report. Most adopted that headline:

'IS NITROGEN A COMPOUND?'

Rutherford's friend and first biographer A.S. Eve would later describe this interpretation as 'missing the whole idea of Rutherford's discovery', and it is easy to imagine that Rutherford himself felt exasperation when he saw the result of his initiative.[2] In fairness to F.A.B. there is no sign that he had

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[2] Eve, A.S., *Rutherford, being the Life and letters of the Rt. Hon. Lord Rutherford, O.M.,* Cambridge University Press, 1919, p. 272.

any relevant knowledge. His identity is not clear, but those initials are found elsewhere in the *Manchester Guardian* at the foot of literary reviews and articles about archaeology. And one can see how a reader without the benefit either of a physics education or of a proper expert briefing might have come to the conclusion he reached. In reality, however, nitrogen remained an element and Rutherford never suggested otherwise. What F.A.B. missed was that Rutherford had succeeded in breaking up atomic nuclei and that this opened the door to a better understanding of the fundamental nature of matter. The real story, as a journalist might put it, was less what the experiment revealed than that the experiment produced results at all.

Perhaps conscious of the honour done it by Rutherford, and perhaps aware of the insufficiency of its report, the *Manchester Guardian* had a reporter from its London office ask around. The result was a brief follow-up, beginning:

> *'I had a talk today with a high scientific authority about Sir Ernest Rutherford's latest discovery, as announced in our columns this morning. It is very deep water for a layman, but I will try not to distort the scientific opinion.'*[3]

And this was the writer's attempt to put the matter in context:

> *'The measure of the importance of the discovery is that it is only the second time that an acknowledged element has been proved to be no element. Sir William Ramsay proved that the element radium was, in fact, two elements – helium and a thing not understood called radium emanation. That was the first demonstration of the kind. Now Sir Ernest Rutherford has dissolved the element nitrogen into two other known elements, helium and hydrogen. It is not a revolution in chemistry and physics, but it is a very big thing.*'

This did not advance matters for *Manchester Guardian* readers in any helpful way, and it is likely have annoyed Rutherford, whose personal dislike for Ramsay is well documented and who cannot have enjoyed seeing him given precedence in this inappropriate way. (Sadly there is no way of knowing whether Ramsay himself was the 'high scientific authority' consulted by the journalist.)

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[3] "Our London Correspondence", *Manchester Guardian*, 7 June 1919, p8.

Besides the fumblings of the *Manchester Guardian*, one other interpretation of the discovery circulated in the press that week. Several regional papers, among them the *Nottingham Evening Post*, carried a short article written by someone who attended the Royal Institution lecture, possibly a representative of the Press Association, the national news agency. The *Post* gave it the headlines:

**'RADIUM BOMBARDMENT
REMARKABLE EXPERIMENT.'**[4]

It began:

> *'Lecturing yesterday at the Royal Institution, London, Sir Ernest Rutherford said he thought he had obtained some evidence of the disruption of atoms by the impact of the swift alpha particles shot out by radium C.'*

Bombardment experiments on nitrogen, the report explained, showed the apparent emergence of hydrogen atoms, and it concluded:

> *'The lecturer was therefore led to the speculation that the nucleus of the nitrogen atom is made up of three atoms of helium and two of hydrogen and that the hydrogen which made its appearance in his experiments was sent off the nucleus of the nitrogen atom by the impact of the alpha-particle.'*

This was considerably more faithful to Rutherford's own account of his work than the other reports, but it hardly made the matter clear for the lay reader, nor did it convey any idea of the momentousness of what had been achieved. No one reading this report, for example, would imagine that the events involved would eventually provide grounds for centenary celebrations and a blue plaque.

And so far as news reporting was concerned that was all there was: those three articles, seen in perhaps a dozen regional and local newspapers. The *Times*, which had advertised the Royal Institution lecture, did not report it at all, or comment on it. Neither did the *Daily Telegraph*, the *Daily Express* or the *Daily Mirror*. If, as seems to have been the case, Rutherford had nursed

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[4] "Radium Bombardment: Remarkable Experiment", *Nottingham Evening Post,* 7 June 1919, p2.

some hope of 'popularising' his 1919 breakthrough, the effort cannot be rated successful.

Two months later, however, an article appeared in the *Yorkshire Post* under this headings:

'SIR ERNEST RUTHERFORD'S LAST DISCOVERY IN MANCHESTER. THE MARVELS OF RADIUM AND HELIUM.'[5]

Credited simply to 'a correspondent', it began:

> *'I wonder if it is possible to give the average intelligent non-scientific reader an idea of the latest discovery made by Sir Ernest Rutherford, who has just left Manchester University for Cambridge. I should like to try.'*

What followed was an exemplary piece of popular science writing that took full advantage of its generous 1,700 words of space. It began with Dalton and included now-familiar discussions and illustrations of atomic matters, including for example how many atoms might fit side by side in one inch. It reached Rutherford and Ramsay by way of J.J. Thomson and then dwelt at some length on the speed and power of the particles emanating from radium. At this point it turned to what was new:

> *'And now we can say what Sir Ernest Rutherford's latest achievement really is. By pursuing a magnificent course of investigation, by experiments of extraordinary ingenuity, and by the reasoning of a mastermind, he has satisfied himself, and there is little doubt he will have satisfied others, that the new-born atoms of helium can and do smash up the atoms of certain other elements. The conclusion on reading this story seems irresistible, that when a new-born atom of helium strikes an atom of nitrogen (the most abundant component of air) fair and square, the cluster of particles constituting each atom of nitrogen is knocked into pieces, and that two of the fragmentary clusters are atoms of hydrogen.*

[5] "Sir Ernest Rutherford's last discovery in Manchester", *Yorkshire Post,* 16 August 1919, p8.

> *'The change of the element radium that goes on spontaneously is a transmutation. It is not quite the kind of transmutation dreamed of by the alchemists, because it is a thing that is beyond human control. But the transmutation which Sir Ernest Rutherford now brings to light is of the alchemist's kind, for we can at will either keep our nitrogen intact, or we can have it transmuted. The new-born helium atoms are thus grains of a Philosopher's Stone.'*

The article ended:

> *'Manchester, without, it is to be feared, being very conscious of the fact, has had new and imperishable lustre added to its name as the scene of epoch-making discoveries in natural science.'*

Who wrote this? It was clearly someone well informed about the work described, and there are hints in the tone adopted, notably in the sentence referring to ingenuity and 'the reasoning of a mastermind', that this was no junior scientist but someone of comparable public standing to Rutherford, indeed probably a friend of his. The name of W.H. Bragg suggests itself, not least because Bragg, besides being Rutherford's friend and correspondent and a very good explainer of physics, also had connections in Leeds, the home of the *Yorkshire Post*, having held a chair there from 1909 to 1915. But this is no more than speculation.

The content of the article is striking. Not only are Rutherford's experiments ably set in historical context and described, but the significance of the breakthrough is also explained with remarkable clarity, and in terms of *transmutation* – a term Rutherford did not use in his *Philosophical Magazine* papers, preferring *disinitegration*. *Yorkshire Post* readers were fortunate indeed to be able to read so clear-sighted and authoritative an account, and one worthy of the events it described. And we should bear in mind that, like a dozen or so other regional papers, the *Post* enjoyed in 1919 a rather higher standing in national affairs and in national journalism that it has in recent years. For all that, however, its engagement with this subject was not sufficient to stir any national newspaper into noticing Rutherford's latest achievement.

There is no hiding the fact: apart from among the more dedicated and thoughtful readers of the *Yorkshire Post*, there simply was nothing that could reasonably be described as a contemporaneous public perception of the great 1919 breakthrough. The practical reason for this was that neither editors nor readers were yet awake to the possibilities of a kind of journalism capable of interpreting and communicating such matters. Once in a while an editor would commission a piece from a leading scientist explaining some recent development, but the general assumption appears to have been that it was scarcely possible for lay people, including journalists themselves, to form any understanding of what scientists were up to, especially in the world of physics. This attitude was well illustrated in some lines from a *Sunday Times* article of 1922 which purported to give an account of a Rutherford lecture on radioactivity at the Royal Institution. It began:

> *'It is difficult for the laity to keep up with the men of science. The pace of the search for knowledge is now grown so hot that all but those in strict training toil some long way behind the leaders.'*[6]

The writer continued:

> *'Much of the lecture was scarcely for the lay mind, but Sir Ernest made it as non-technical as possible, even in the midst of somewhat complicated diagrams and equations.'*

When one considers the trouble that Rutherford took to make his public lectures accessible, this swooning helplessness seems all the more preposterous, but it was common, even the norm. Science broke into the news pages either when it was not science at all – Rutherford's appointment to head the Cavendish laboratory was widely reported – or when it could be reduced to an eye-catching nugget of the kind that might make it into conversation at the hearth or the bar. Thus the most widely reproduced science story of 1919 was a line from a speech by Sir Oliver Lodge, reported under the headline 'THE MIGHTY ATOM'. It ran as follows:

> *'The possibilities of atomic energy were described by Sir Oliver Lodge at the continued Watts* [meaning James Watt] *centenary commemoration in Birmingham yesterday. Sufficient energy, said Sir Oliver, was stored in an ounce of matter to raise the German fleet and pile it on top of a Scottish mountain.'*[7]

If we are correct in contending that in 1919 Rutherford wanted the public to have some understanding of what he was doing and really hoped that the press – then the only mass news medium – would be a means of achieving this, then he was clearly mistaken. But things changed, and Rutherford had

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[6] "The Mighty Atom", *Sunday Times*, 12 March 1922, p15.

[7] "The Mighty Atom", *Sheffield Independent*, 18 September 1919, p1.

his hand in that change. In the late 1920s J.G. Crowther, who had studied physics at the Cavendish as an undergraduate but dropped out of the course, persuaded the editor of the *Manchester Guardian*, C.P. Scott, to try him out as an occasional specialist science journalist. Crowther had also worked as a scientific book publisher so he was informed and had contacts. He became a frequent contributor to the paper.

So it was that, on 28 February 1932, Crowther was able to publish in his newspaper an exclusive report of James Chadwick's discovery of the neutron. In the style of the time there were three decks of headline:

'A NEW FORM OF RADIATION
DR. CHADWICK'S IMPORTANT DISCOVERY.
THE NUCLEUS OF THE ATOM.'[8]

Datelined 'Cambridge, Saturday', it began:

> *'The Cavendish Laboratory has now contributed a new and important chapter to the development of the theory of physics.*
> *'For two years a variety of experiments have been carried out on the radiation excited in beryllium under bombardment by the alpha particle. The particles of the new ray are the fastest and most penetrating known: they are indifferent to the strongest electrical and magnetic forces, and they can be detected only when they register a direct hit on the inner core of an atom.'*

There followed five paragraphs of uninterrupted quotation from Chadwick himself, in effect summarising his famous *Nature* paper, 'Possible existence of a neutron'. He concluded:

> *'I am afraid that no practical application of the vast energy of the particles is likely, as, for instance, electricity and water pressure are harnessed, but they have a definite interest from the point of view of the structure of the nucleus of the atom.'*

To the modern eye this is hardly a model of science communication – it makes little attempt to engage readers who have no relevant knowledge – but at least it had the merit that it did not 'miss the whole idea' and was accurate in its detail. Nor did it simply announce that it was all too difficult

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[8] "A New Form Of Radiation", *Manchester Guardian*, 28 February 1932, p19.

to understand. Crowther's report set the tone for other newspapers, and it seems that he was entrusted by Rutherford and Chadwick with the task of explaining and briefing other journalists. That people at the Cavendish were satisfied with the outcome on this occasion can be seen from the reaction of John Cockcroft when, just two months later, another important announcement went haywire.

'Dear Crowther,' wrote Cockcroft, 'you have let us down badly – we really relied on you to get all this business straight in the press first so that we could simply refer all other people to you.'[9]

Cockcroft was annoyed with Crowther, somewhat unreasonably, because the journalist had been abroad (at the Bohr Institute in Copenhagen) when news broke of the first disintegration of the nucleus using a machine (as opposed to the natural radiation previously employed, including by Rutherford in 1919). Cockcroft and his Cavendish partner Ernest Walton had succeeded in doing this after nearly four years of effort. In Crowther's absence a number of confused or downright incorrect accounts of the experiments had gained currency in the press and indeed had travelled around the world and Cockcroft was appealing to Crowther to help redeem the situation.

There is irony here. When, finally, the news media – including radio – paid due attention to a development in nuclear science, they made a mess of it. The Cockcroft-Walton experiment – usually billed as 'splitting the atom' – made almost instant worldwide headlines in a manner rarely if ever seen in science before, but much of the reporting fell far below Rutherford's expectations in terms of context and accuracy. We know this because weeks later he would still have the offending clips in his pocket, and he drew them out and waved them in the air as he harangued the young reporter Ritchie Calder about the 'rot' and 'drivel' usually to be found in newspapers.[10]

To return, in conclusion, to 1919: it was certainly not Rutherford's fault that his little attempt to promote understanding of the breakthrough through the pages of the press was unsuccessful. The able article in the *Yorkshire Post* shows what was possible at the time – the experiments could be made comprehensible, interesting and apparently relevant – and it is revealing that other papers did not copy it or follow it up by commissioning articles of

[9] Cathcart, B.J., *The Fly in the Cathedral*, Viking, 2004, pp252-3. Chapter 14 provides a full account of the reporting of the Cockcroft-Walton experiment.
[10] Ibid, p270.

their own. The problem, almost certainly, was the very ignorance that Rutherford sought to remedy: editors did not understand science and they assumed their readers were in the same boat. As the events of 1932 demonstrated, correcting this fault was no quick or simple matter. And as the story of climate change has shown, even today the relationships between science, news media and public perception present many complexities and problems.

Finally, a word about that troublesome phrase ‘splitting the atom’. Every informed person knows that it does not accurately describe either the Rutherford experiments of 1919 or the Cockcroft-Walton experiments of 1932. However, not only headline writers but also the writers of blue plaques and other memorials will attest that it is a useful and indeed irresistible label for both experiments. In 1919 it was not used in the press – chiefly, no doubt, because Rutherford himself did not use it, but also, perhaps, because at that time the phrase was still under different ownership. So far as the newspaper world was concerned, and by extension therefore the public, the atom had been ‘split’ in 1897 by J.J. Thomson. That this view persisted long afterwards is demonstrated in a line from a weekly called *The Sphere*, which in 1921 described Thomson as ‘known to the world, in the crude phraseology of the *Daily Mail*, as “The Man Who Split The Atom”’.[11] It seems, however, that by 1932 that association with Thomson had faded from memory, because the very first newspaper report of the Cockcroft-Walton breakthrough, on the front page of *Reynolds’s News*, announced:

‘SCIENCE’S GREATEST DISCOVERY
THE ATOM SPLIT
AT 100,000 VOLTS’[12]

After that the phrase went around the world. The paper claimed that its report carried ‘the authority of Lord Rutherford’, and its editor would later write that a reporter showed a draft to Rutherford on the eve of publication and secured the written endorsement ‘Your conclusion is fairly correct.’[13] It is difficult none the less to believe that he approved of the words ‘the atom split’ in that context.

[11] “Cambridge In 1921”, *The Sphere*, 4 June 1921, p236.

[12] “Science’s Greatest Discovery” *Reynolds’s News,* 1 May 1932, p1.

[13] Cathcart, p246.

Transmutation, the concept of nuclear “disintegration” and the origin of the nuclear chemical notation.

Neil Todd and Peter Rowlands

One of the themes running through the presentations at the June 2019 meeting, and articles above in this issue, was the language used by Rutherford, his contemporaries and students to describe the meaning of the discovery documented in his 1919 tetralogy. In particular the term “disintegration”, originally coined by Rutherford and Soddy to refer to a spontaneous explosive atomic (nuclear) reaction which results in a chemical transmutation, is key here. The first use of the term in fact appears somewhat casually at the end of their 1903 paper “The radioactivity of uranium” and subsequently again once in “A comparative study of the radioactivity of radium and thorium” but the concept takes centre stage in their theoretical paper “Radioactive change” where the term is used 14 times[14]. As they put it

“Since radioactivity is a specific property of the element, the changing system must be the chemical atom, and since only one system is involved in the production of the new system and, in addition, heavy charged particles, in radioactive change the chemical atom must suffer disintegration.”

Unfortunately the term “disintegration” appears to have become much misunderstood, or even lost altogether, by the recent generation of physicists and an aim of this article is to trace its origin, use and fate.

There can be no doubt that at the time of the 1919 discovery of the “artificial disintegration” of nitrogen and in its immediate aftermath that it was recognised as an artificial transmutation, even if the details of the disintegration process were not resolved until 1925 by Blackett[15] when it became clear that it was a disintegration by capture of the alpha particle, as

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[14] Rutherford E, Soddy F. (1903). “The radioactivity of uranium”, *Phil. Mag. VI*, 5, 441–445.; Rutherford E, Soddy F. (1903). “A comparative study of the radioactivity of radium and thorium”, *Phil. Mag. VI*, 5, 445–447.; Rutherford E, Soddy F. (1903). “A comparative study of the radioactivity of radium and thorium”, *Phil. Mag. VI*, 5, 576–591.

[15]Blackett PMS. (1925). “The ejection of protons from nitrogen nuclei, photographed by the Wilson method’, *Proc. Roy. Soc. A*, 107, 349-360.

described in this issue by Campbell and Marshall. As is now common practice, the 1919 disintegration/transmutation reaction is written using a chemical notation, although neither Rutherford nor Blackett used the notation at that time. A second aim of this article is to determine exactly when the chemical notation was introduced as new field of nuclear chemistry developed at a rapid pace from 1925, an issue to which we now turn.

The origin of the nuclear chemical notation: William Draper Harkins (1873 - 1951).

The first use of the nuclear chemical notation appears to be by the American chemist William Draper Harkins (1873 - 1951)[16]. Harkins had in 1915[17] put forward a "hydrogen-helium" theory of nuclear structure independently of Rutherford and in 1920[18] very shortly after Rutherford's 1919 tetralogy published a more developed theory, which was cited by Rutherford in his 1920 Bakerian Lecture[19] including Harkins' concept of a (pe) "neutron" grouping. He was the first to employ a chemical nuclear model-based notation for writing nuclear processes, although he erroneously interpreted Rutherford's 1919 disintegration reaction. In a subsequent 1921 paper[20], communicated by Rutherford, he made the first use of the term "neutron" and shortly thereafter independently of the Cavendish constructed a Shimizu-Wilson type apparatus, publishing photographs in 1923[21] with images of alpha-collisions, although without successfully capturing a nitrogen disintegration. Shortly after Blackett's 1925 result in 1926[22] Harkins published disintegration tracks confirming the capture process, and also made the first suggestion that disintegration by capture reaction was

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[16] Mulliken RS. (1975). "William Draper Harkins 1873 – 1951. A Biographical Memoir" *Biographical Memoirs of the National Academy of Sciences* 47, 49-81.

[17] Harkins WD, Wilson ED. (1915). "The structure of complex atoms and the changes in mass and weight in their formation", *Proc. Nat. Acad. Sci.* 1, 276-286.

[18] Harkins WD. (1920) "The nuclei of atoms and the new periodic system", *Phys. Rev.* 15, 73.

[19] Rutherford E. (1920). "Bakerian Lecture: Nuclear constitution of atoms", *Proc. Roy. Soc. A*, 97, 374-400.

[20] Harkins WD. (1921). "The constitution and stability of atom nuclei" *Phil. Mag. VI*, 42, 305.

[21] Harkins WD, Ryan RW. (1923) "A method for photographing the disintegration of an atom, and a new type of rays" *J Am. Chem. Soc*. 45, 2095.

[22] Harkins WD, Shadduck HA. (1926) "The synthesis and disintegration of atoms as revealed by the photography of Wilson cloud tracks" *Proc. Nat. Acad. Sci.* 12, 707.

mediated by a short-lived isotope of fluorine. Although he did not write the chemical equation here, he did do so in a subsequent paper in 1930[23], which Blackett cites, along with the 1926 paper, in his later 1932 paper[24]. By this time O^{17} had been discovered in the atmosphere[25], four years after Blackett's hypothesis (as noted by Marshall in this issue), and it was thus possible to write the equation with confidence. The second appearance of the chemical equation appears to be in a paper by another chemist, Harold Urey, in 1931 entitled "The masses of O^{17}" followed shortly by Harkins in a letter to the editor under the same title in the same volume[26]. Evidently the notation established by these chemists caught on very rapidly and was employed by Chadwick in his 1932 paper[27] describing the production of neutrons by the disintegration of beryllium, by Cockcroft and Walton in their 1932 paper[28] on the artificial disintegration of lithium by protons and by Curie and Joliot in their work on artificial radioactivity[29]. Thus by the early 1930s the concept of artificial disintegration and the chemical notation to describe the resultant transmutations was firmly entrenched in the new field of *nuclear chemistry*[30].

From the above, it is clear that Blackett was very nearly pipped at the post by Harkins and it is a good question to ask why Blackett did observe the capture first. We think that the answer to this question is very clear. Harkins was labouring under the false belief that the disintegration reaction should involve four instead of three tracks, where the incident alpha-particle having disrupted the target was scattered away according to the false hypothesis.

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[23] Harkins W, Schuh AE. (1930). "The frequency of occurrence of the disintegrative-synthesis of oxygen 17 from nitrogen 14 and helium", *Phys. Rev.* 35, 809-813.
[24] Blackett PMS, Lees DS. (1932). "Investigations with a Wilson chamber. I.—On the photography of artificial disintegration collisions", *Proc. Roy. Soc. A*, 136, 325-338.
[25] *Giauque WF, Johnston HL. (1929). "An isotope of oxygen, mass 17, in the Earth's atmosphere", J. Am. Chem. Soc. 51, 3528–3534.*
[26] Urey HC. (1931). "The masses of O^{17}", *Phys. Rev.* 37 (8), 923-929.; Harkins WD. (1931). "The masses of O^{17}", *Phys. Rev.* 37 (12), 1671-1672.
[27] Chadwick J. (1932). "Possible existence of a neutron", *Nature* 129, 312.
[28] Cockcroft JD, Walton ETS. (1932). "Disintegration of lithium by swift protons", *Nature* 129, 649.

[29] CurieI, Juliot F. (1934). "Artificial production of a new kind of radio-element", *Nature* 133, 201-2.

[30] Harkins WD. (1936). "Nuclear chemistry, the neutron and artificial radioactivity", *Science* 83 (2162), 533-542.; Rutherford E. (1937). *The Newer Alchemy*, CUP, Cambridge.

Blackett, in contrast, benefitted by working in a laboratory environment in which Rutherford and Chadwick had in their three papers on artificial disintegration of light elements (1921, 1922, 1924)[31], and especially the 1924 paper, clearly hypothesized the strong nuclear force and the possibility that the alpha particle was captured.

"*In our first Paper on the disintegration of elements by a-particles we gave a picture of the nucleus of a disintegrable atom which consisted of a main central nucleus with one or more hydrogen nuclei as satellites. We assumed that the law of force in this region of the nucleus was one of attraction between like charges.*

The force at large distances must become the usual repulsive force varying inversely as the square of the distance. On this view there must, then, be a critical surface around the nucleus at which the force is zero or the potential a maximum. The H-satellite is, of course, inside this surface and cannot escape from the nucleus with less final energy than corresponds to the potential at this critical surface.Thus the disintegration particles must have a certain minimum range corresponding to this potential. .....

The fate of the a-particle is a matter about which we have no information. It is unlikely that the field of force remains central at very close distances. ***It is possible that the a-particle is in some way attached to the residual nucleus. Certainly it cannot be re-emitted with any considerable energy, or we should be able to observe it***."

The recollections of those who worked with Rutherford: The Rutherford Memorial Lectures

As we noted above, during this remarkable period the concept of a nuclear disintegration reaction was clear to all who were concerned with the development of the new field of nuclear chemistry. Even some three to four decades later in the 1950s in the run up to the 1961 Jubilee meeting the language of disintegration was still current when the occupants of the Physical Laboratories of Manchester were able to erect the commemorative

[31] Rutherford E, Chadwick J. (1921). "The artificial disintegration of light elements", *Phil. Mag. VI*, 42, 809-825.; (1922). "The disintegration of elements by alpha particles", *Phil. Mag. VI*, 44, 471-432.; (1924). "Further experiments on the artificial disintegration of elements", *Proc. Phys. Soc.* 36, 417-422.

plaque above Rutherford’s bench noting that “*the artificial disintegration of nitrogen was first achieved by Rutherford*”. This is testified by those former Rutherford students who had worked closely with him on the disintegration experiments and who gave an account of this period in their recollections during a series of Rutherford Memorial Lectures (RMLs).

Among those attending the 1961 meeting was Ernest Marsden who worked on the very first H-particle experiments. In his 1954 RML[32] he was clear that Rutherford had

“the intuition to try out the experiment in oxygen and nitrogen separately and the crowning achievement was the observation that in the case of collisions of an a-particle with a nitrogen nucleus the latter was transformed and a hydrogen nucleus ejected at great speed. .... Blackett a few years later confirmed the assumption by a remarkable observation and photograph of the tracks in a cloud chamber. This result of Rutherford's was the first observation made of artificial transformation of one element into another 'the deliberate transformation of matter'.

Another of the 1961 Jubilee old boys, James Chadwick[33], who in the early 1920s prior to Blackett’s 1925 paper had worked with Rutherford in Cambridge on disintegration of light elements (as described above), in 1953 presented the 2nd RML at McGill University, the birthplace of the term disintegration. As Chadwick put it of Rutherford’s McGill period:

“*Rutherford laid bare the salient features of radioactivity, and he explained, in a beautiful and complete way, all the diverse and mysterious phenomena which had been observed at that time. More than that, he saw already that his work was leading to new conceptions about the nature of matter; the first steps towards his later discoveries of the nuclear structure of the atom and of the artificial transmutation of matter can be plainly seen in his writings of that time*”.

He went on to describe the significance of Rutherford and Soddy’s articulation of the disintegration theory:
“Thus step by step, by experiment and by reasoning, they came with inescapable logic, though with much heart-searching, to the conclusion that

[32] Marsden E. (1954). “The Rutherford Memorial lecture, 1954: Rutherford, his Life and Work 1871 - 1937”, *Proc. Roy. Soc. A*, 226, 283–305
[33] Chadwick J. (1953). “The Rutherford Memorial Lecture, 1953”, *Proc. Roy. Soc. A*, 224, 435–447

radioactivity is a spontaneous disintegration of the atom, in which one kind of matter changes into another kind of quite different chemical and radioactive properties, with the simultaneous emission of energy in the form of ionizing radiations."

After describing his subsequent career up to the discovery of the nucleus, Chadwick highlighted a remarkable passage of Rutherford's own words from a William Hale lecture of 1914[34] where he described his thoughts at the time that he initiated the disintegration experiments. Rutherford was quite clearly anticipating artificial transmutation either by a nuclear *"disruption"* or *"combination*", corroborating Campbell's reference to Rutherford's letter to Bohr of *"breaking up atoms".*

"'There is no doubt that it will prove a very difficult task to bring about the transmutation of matter under ordinary terrestrial conditions. ... the building up of a new atom will require the addition to the atomic nucleus of hydrogen or of helium, or a combination of these nuclei ... it is possible that the nucleus of an atom may be altered by direct collision of the nucleus with very swift electrons or atoms of helium such as are ejected from radioactive matter ... under favourable conditions, these particles must pass very close to the nucleus and may either lead to a disruption or to <u>a combination with it</u>."

Bohr himself describes this period in his own RML of 1959[35] and a visit he made to Manchester in 1919 shortly after the publication.

"In Rutherford's famous papers in the Philosophical Magazine, 1919, *containing the account of his fundamental discovery of controlled nuclear disintegrations, he refers to the visit to Manchester, in November 1918, of his old collaborator Ernest Marsden who at the Armistice had got leave from military service in France…… In July 1919, when after the Armistice travelling was again possible, I went to Manchester to see Rutherford and learned in more detail about his great new discovery of controlled, or so-called artificial, nuclear transmutations, by which he gave birth to what he liked to call ' modern Alchemy '"*

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[34] Rutherford, *op. cit.* (note 8).
[35] Bohr N. (1961). "The Rutherford Memorial Lecture, 1958: Reminiscences of the founder of nuclear science and of some developments based on his work", *Proc. Phys. Soc.* 78, 1083-1115.

In the same year as Bohr's Lecture to the Physical Society in London Patrick Blackett also gave a RML at McGill University[36]. We feel that it is worth quoting in full Blackett's own account with the key phrases underlined.

"My own personal contact with Sir Ernest Rutherford, as he was then, began in 1921 when I graduated in physics at Cambridge. Rutherford had then held the Cavendish Chair for two years and was still in the process of building up the laboratory and collecting some of his old colleagues of the Manchester days after the dispersal resulting from the first World War. In the first year after the War a young Japanese physicist, Shimizu, had come to work in Cambridge, and Rutherford had started him on the problem of using C. T. R. Wilson's beautiful cloud-chamber method to study <u>the process of disintegration of nitrogen nuclei, which he had discovered in Manchester</u> during the last years of the War, by means of the scintillation technique. Rutherford himself, together with Chadwick, was actively pursuing these experiments and succeeded in showing that <u>most of the light elements could be disintegrated by fast a-particles</u>. Rutherford realized that the scintillation method, which was well suited to the detection of the fast protons emitted from the struck nuclei, was not capable of revealing the details of the collision process.

By 1911 Wilson, after fifteen years of careful and laborious experimentation, had perfected his cloud-chamber method of revealing the tracks of individual atomic particles. Some of his earliest photographs remain today the most beautiful, technically, ever taken. <u>Rutherford saw that the cloud-chamber technique was excellently suited to the elucidation of the finer details of atomic disintegration processes</u>. The only difficulty was the number of photographs needed.

Now, the scintillation experiments had shown clearly that <u>the fraction of a-particles which would disintegrate a nitrogen nucleus in a cloud chamber was exceedingly small</u>. One could not reckon on more than ten nitrogen disintegrations for every million a-particle tracks photographed. Rutherford boldly set Shimizu the task of making a cloud chamber with which to take a very large number of photographs. Shimizu tackled this problem by replacing the individual sharp expansion of the now conventional cloud

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[36] *Blackett* PMS. *(1959). "The Rutherford Memorial Lecture, 1958", Proc. Roy. Soc. A, 251, 293–305.*

chamber with a piston worked off a crank and moving continuously in a simple harmonic manner, so giving an expansion several times a second. .... He also designed an elegant little camera by means of which two images of the chamber were projected on to a single cinematograph film. With this apparatus he photographed some 3000 a-ray tracks and observed a number of forked tracks due to the collisions of a-particles with nitrogen nuclei. Unfortunately, Shimizu had to return rather suddenly to Japan so that the work came to an end. It was then that Rutherford asked me if I would continue the work, which I, of course, was most excited to do.

Thus it came about that my first research problem was to carry on the work begun by Shimizu. I made use of many parts of his original apparatus and the camera design, ... I first studied in detail the frequent forked tracks formed when an a-particle collides with the nucleus of an atom of the gas, and showed by accurate measurements of the angles of the fork that the collisions were elastic within the experimental error of the measurements. However, among some 400000 tracks photographed during 1924 six forks were found which clearly were not elastic collisions. After careful measurement these were shown to represent the disintegration of a nitrogen nucleus by the impact of a fast a-particle, with the ejection of a proton and the capture of the a-particle. The resulting nucleus formed in the process clearly was that of a then unknown isotope of oxygen of mass 17. Thus the problem set four years before by Rutherford of what happens to the a-particle on disruption of a nitrogen nucleus was solved. Much of my subsequent research work was profoundly influenced by this first problem set me by Rutherford. I realized that I could not by myself, as a newly graduated physics student, have possibly selected my own problem with a fraction of the success that attended Rutherford's selection of it for me. So I learnt early the vital importance of the role of the director of research in selecting promising problems for his research students".

Blackett couldn't be clearer. Rutherford having articulated the disintegration theory of radioactivity with Soddy in 1902 as a form of spontaneous transmutation, and after his discovery of the nucleus in 1911 foresaw the possibility of artificial disintegration by close collision which he did indeed achieve at Manchester for the first time in 1919. Rutherford had also clearly foreseen that the cloud chamber method was ideally suited to "*elucidate the finer details of atomic disintegration*" and Blackett's 1925 result that "*the disintegration of a nitrogen nucleus by the impact of a fast a-particle, with the ejection of a proton and the capture of the a-particle"* was a detail of the disintegration process that had been hypothesized well in advance by Rutherford, Chadwick and others. Tellingly in Blackett's account the term *disintegration* appears seven times but the term *transmutation* not once. It is not unreasonable to suppose then that Blackett was instrumental before he left Manchester in the early 1950s of seeing the erection of the commemorative plaque above Rutherford's bench noting "*the artificial disintegration of nitrogen was first achieved by Rutherford*".

Bernard Lovell in his memoir of Blackett published in 1975[37] makes the interesting observation that: "*In his book on Rutherford, A. S. Eve (1939) quotes a letter dated September 1924 from Chadwick to Rutherford (who had left for Canada late July 1924): 'Blackett has got two more photographs which are somewhat clearer than the others. They show the track of the H particles and the track of the recoil atom, but no track for the alpha. If this is true it is a very fine addition to the evidence for the attractive field, and fits in very well with our expectation'* ". This confirms our case above that disintegration by alpha capture was a working hypothesis that Blackett had been bequeathed by Rutherford and Chadwick.

John Cockcroft[38] who, with Walton had worked with Rutherford on the 1932 result of disintegration/transmutation by particle accelerators, was clear in his 1952 Rutherford Memorial Lecture that Rutherford had "*concluded that nitrogen atoms are disintegrated under the intense forces developed in a close collision and that the hydrogen atom which is liberated forms a constituent part of the nitrogen nucleus. This was the first artificially produced transmutation of an atomic nucleus*.". In the later parts of his lecture Cockcroft continues to employ the terms disintegration/transmutation to describe the many later reactions that became available after the invention of particle accelerators.

The language of "disintegration" continued well after the 1961 Jubilee, as evidenced by the subsequent RMLs. Philip Dee in his 1965 RML[39] used the term "disintegration" nine times to describe outcomes of collisions

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[37] Lovell B. (1975). "Patrick Maynard Blackett. Baron Blackett of Chelsea. 18 November 1897 – 13 July 1974", *Biographical Memoirs of Fellows of the Royal Society* 21, 1-115.
[38] Cockcroft JD. (1953). "The Rutherford Memorial Lecture", *Proc. Roy. Soc. A*, 217, 1–8.
[39] Dee PI. (1967). "The Rutherford Memorial Lecture", *Proc. Roy. Soc. A*, 298, 103–122.

produced by particle accelerators. Peter Fowler's 1971 RML[40] on the origins of the elements uses "disintegration" both for spontaneous transmutation and transmutation due to collisions. Norman Feather's 1977 RML[41] used the term 12 times distinguishing "α-disintegration" and "β-disintegration" to describe spontaneous transmutation versus "disintegration collision" associated with artificial transmutation. WE Burcham's 1983 RML[42] makes eight uses of the term to describe both spontaneous and artificial transmutations. Like all predecessors he is clear that Rutherford achieved artificial disintegration in 1919 "*But by the end of the war, Rutherford's attention was engaged, in conclusion of his Manchester period, with the notable series of experiments that culminated in the disintegration of the nitrogen nucleus. The Cambridge period 1919-1937 was dominated by artificial transmutation*." The first RML in which the term does not appear is in the 1979 lecture by particle physicist EHS Burhop[43] in his account of the development of high energy particle physics. For Burhop, like most particle physicists, the significance of 1919 was the naming of the proton as an elementary particle rather than artificial transmutation. The growth out of, and subsequent overshadowing of, nuclear physics by particle physics may account for the relative decline in the language of disintegration, perhaps alongside the passing of the last of the generation of physicists who had contact with Rutherford's Cavendish: Marcus Oliphant (1901 – 2000), Sam Devons (1914 – 2006), Bill Burcham (1913 – 2008).

Conclusions

Given the amount of time that has passed since Rutherford's discovery of artificial transmutation and the ever increasing volume of material that the science generates, it is understandable, if lamentable, that the history of it has become confused. We, as co-organizers of the 2019 meeting and co-editors of this volume, are very pleased that the articles presented here within collectively enshrine Rutherford's 1919 discovery of artificial disintegration/transmutation in its rightful place in the history of physics.

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[40] Fowler PH. (1972). "The Rutherford Memorial Lecture: Evolution of the elements", *Proc. Roy. Soc. A*, 329, 1–16.

[41] Feather N. (1977). "The Rutherford Memorial Lecture: Some episodes of the alpha-particle story", *Proc. Roy. Soc. A*, 357, 117–129.

[42] Burcham WE. (1983). "The Rutherford Memorial Lecture. Rutherford and beta decay", *Proc. Roy. Soc. A*, 389, 215-239

[43] Burhop EHS. (1982). "The Rutherford Memorial Lecture, 1979: The new physics", *Proc. Roy. Soc. A*, 380, 1–28