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History of Physics Group

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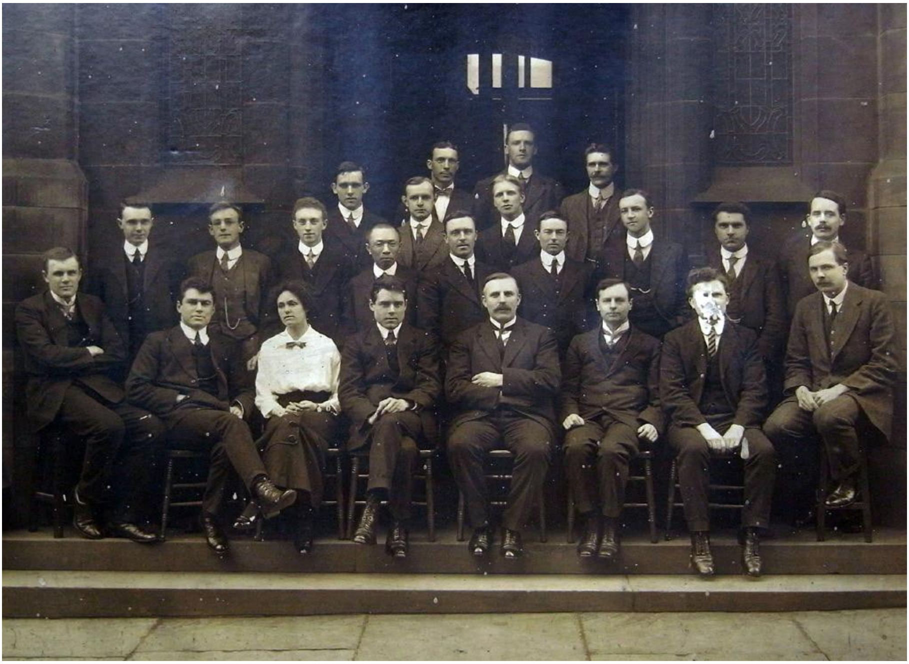
Newsletter

Nucleus to Neutrons

Manchester 1911-



- Cambridge 1932

Special Issue December 2012

Cover picture: The Physics group, 1913 at entrance to 1900 building, Manchester

TS Taylor AS Russell

H Richardson JM Nuttall B Williams W Kay

AB Wood E Green RH Wilson S Oba E Marsden H Gerrard J Chadwick FW Whaley HGJ Moseley

H Robinson DCH Florance Miss M White JN Pring Prof. E Rutherford W Makower EJ Evans CG Darwin

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Nucleus to Neutrons

Manchester 1911 to Cambridge 1932

Members of the History of Physics Group tour outside the same entrance, 2012

Contents

Disclaimer

Foreword

‘Nucleus to Neutrons – Manchester 1911 to Cambridge 1932’

I am very pleased indeed to introduce this, the third special issue of the newsletter published by the HoP Group, following the first on William Stroud and the second, celebrating the work of Lord Rayleigh.

Three of these articles ‘*The 1912 extension to the Physical Laboratories of the University of Manchester and the birth of the Electron Volt*’, ‘*Rutherford’s Resonance’*, and *‘The Apparatus used for Discovering the Neutron’* are based on lectures given to the group in the old Physical Laboratories, Manchester on March 31st this year, as reported in issue 30 of the newsletter. As I commented in that report the organisers – Dr. Peter Rowlands and Dr. Neil Todd brought a new look to the event. This approach was adopted because it was felt appropriate that the meeting should concentrate on new angles, based on entirely original research, since so much is already known about Rutherford.

A *‘Physics Heritage Tour of Manchester University’* summarises the background and details of a tour which the participants enjoyed during the Manchester meeting, completing a most successful event. As Neil Todd commented ‘delegates assembled in the morning to soak up some atmosphere by listening to recordings, watching some DVD transfers of film clips and by participating in a short tour of the buildings associated with physics at Manchester’.

We should like to thank the University of Manchester for their kind permission to hold the 31st March meeting in the Coupland Building, the site of the 1912 Extension to the old Physical Laboratories, and in particular for tour access to the Rutherford Building (formerly part of the Coupland Building), which was the site of the original 1900 Physical Laboratories.

First of all, though, based on an earlier meeting of the group, Professor Edward Davis opens this special issue with an introductory article *'Lord Rutherford and the Nuclear Model of the Atom'*, which includes a timeline of Rutherford's career, an account of the scattering experiments of Geiger and Marsden, and a summary of developments in the decades following his classic papers of 1913 and 1914.

Malcolm Cooper
Newsletter Editor

Introduction

Dr. Peter Rowlands

Physics Department, University of Liverpool

Ernest, Lord Rutherford is well known as the physicist who did more than any other to create our modern understanding of the atom. In fact, Rutherford was probably the most significant experimental physicist of the first half of the twentieth century and he was equally important as a research director. Chadwick, Bohr, Moseley, Geiger, Marsden, Cockcroft, Walton, Blackett, Occhialini, Oliphant, Harteck and Goldhaber were only a few who worked under his direction who made significant contributions of their own to physics. Rutherford was significant because he, more than anyone else, saw the immense importance of the newly-discovered phenomenon of radioactivity as creating a whole new frontier for physics because of the high energies and completely new forces involved. The eventual outcome was the development of the new disciplines of nuclear and particle physics, which are still regarded as the cutting edge of the experimental side of the subject today. Interestingly, Rutherford abandoned a fruitful line of work in the applied area of radio communication to take up a field which was then research of the purest kind, although it has since led to momentous applications.

Manchester is fortunate that, of all Rutherford's scientific achievements, probably the greatest, the discovery of the atomic nucleus, was made while he was Langworthy Professor of Physics there between 1907 and 1919. The original laboratories in which he worked (housed in what is now called the Rutherford building) survive, although they are no longer dedicated to physics. Dr. Neil Todd, who knows more about the layout of the Rutherford building than anyone else and has identified the rooms where, for example, Rutherford himself, Rutherford and Royds, Geiger and Marsden, and Moseley, did their main work, has organized a tour of the parts of the building which it is possible to visit, and he has unearthed sound recordings of some of the participants describing the incidents in which they were involved, as well as film clips of Rutherford and his most important student and collaborator, James Chadwick, describing their discoveries. The Pear Theatre, dating from 1912 still exists, as does the Coupland Building, which was an extension to the laboratory complex built in Rutherford's own time.

Radioactivity may have provided an opportunity for frontier research without complex machinery, but radioactive sources took a great deal of management, as is clear from Neil Todd's article *'1912 extension to the Physical Laboratories of the University of Manchester and the Birth of the Electron Volt'*. He has created a new field of historical research in 'radioarchaeology', examining early laboratories, finding out how the pioneers obtained their sources, how they handled them and organized their laboratories, and investigating the short- and long-term consequences of using such hazardous materials.

Apart from being a scientific investigator of extreme originality, Rutherford was also a great leader and research director, and he early on realized the significance of public relations and public understanding of science for obtaining funding and other public support. In his article on this, Brian Cathcart, a professor of journalism, made a fascinating contrast between the complete lack of organized publicity over the momentous discovery of the nucleus in 1911 and the organized news management that surrounded the Cockcroft and Walton discovery of accelerator-induced nuclear disintegration in Rutherford's laboratory in 1932. In his article *'Rutherford's Resonance: responses to discoveries in 1911 and 1932'* he draws attention to how difficult it was then (as it still is now) for scientists to put out their stories without a sensationalist slant being applied by the journalists. It raises questions about why the world that made so much of the big story in 1932 was apparently not ready for the, at least equally important, one of 1911.

By 1932, of course, more sophisticated technologies were making the 'string and sealing wax' tradition of the earlier part of the century increasingly redundant. Cockcroft and Walton's particle accelerator was one example. Another was the development of electronic recording techniques to replace the difficult, labour-intensive and much less reliable method of scintillation counting which had been used from early in the century for the detection of individual particles. In Rutherford's laboratory, one such development, led by C. E. Wynn-Williams, is well known, but there was another, equally significant one by Jack Constable, which has not so far been researched in detail. Jack Constable was a research student in the Cavendish Laboratory under Rutherford, and our third author, Jack's son, Geoffrey Constable, in his article *'The Apparatus used for Discovering the Neutron'* reveals the results of an expert investigation into the details of his father's electronics and to what precisely it had led. In fact, the clue is available in the film clip of Chadwick, where he refers to the new methods of electronic counting without which his long search for the neutron would not have been successful. Geoffrey indicates exactly what this meant and how Chadwick's insight led him to realize the significance of a number of recent experimental results and to devise new experiments, in which Jack Constable's electronics was an important component, to prove conclusively that the neutron must exist. Geoffrey also notes that, sadly, Jack died young, very probably from radiation poisoning, showing how some of the great achievements of early twentieth century physics came only at the cost of personal sacrifice.

Lord Rutherford and the Nuclear Model of the Atom

Edward A. Davis

Department of Materials Science and Metallurgy, University of Cambridge

The paper by Rutherford published in the *Philosophical Magazine* in 1911 entitled '*The scattering of α and β particles by matter and the structure of the atom*' (reference 1 and Figure 1) marked no less than the discovery of the atomic nucleus. Its importance, historically, can hardly be overstated and yet it took a full two years before the scientific world accepted the full significance of his proposal.

[669]

LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom. By* Professor E. RUTHERFORD, *F.R.S., University of Manchester* *.

§ 1. IT is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle. There seems to be no doubt that such swiftly moving particles pass through the atoms in their path, and that the deflexions observed are due to the strong electric field traversed within the atomic system. It has generally been supposed that the scattering of a pencil of α or β rays in passing through a thin plate of matter is the result of a multitude of small scatterings by the atoms of matter traversed. The observations, however, of Geiger and Marsden † on the scattering of α rays indicate that some of the α particles must suffer a deflexion of more than a right angle at a single encounter. They found, for example, that a small fraction of the incident α particles, about 1 in 20,000, were turned through an average angle of 90° in passing through a layer of gold-foil about ·00004 cm. thick, which was equivalent in stopping-power of the α particle to 1·6 millimetres of air. Geiger ‡ showed later that the most probable angle of deflexion for a pencil of α particles traversing a gold-foil of this thickness was about 0°·87. A simple calculation based on the theory of probability shows that the chance of an α particle being deflected through 90° is vanishingly small. In addition, it will be seen later that the distribution of the α particles for various angles of large deflexion does not follow the probability law to be expected if such large deflexions are made up of a large number of small deviations. It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter, for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter.

Recently Sir J. J. Thomson § has put forward a theory to

* Communicated by the Author. A brief account of this paper was communicated to the Manchester Literary and Philosophical Society in February, 1911.

† Proc. Roy. Soc. lxxxii. p. 495 (1909).

‡ Proc. Roy. Soc. lxxxiii. p. 492 (1910).

§ Camb. Lit. & Phil. Soc. xv. pt. 5 (1910).

Figure 1. Opening page of Rutherford's classic paper in *Philosophical Magazine* 125 (1911) 669-688

1. Introduction

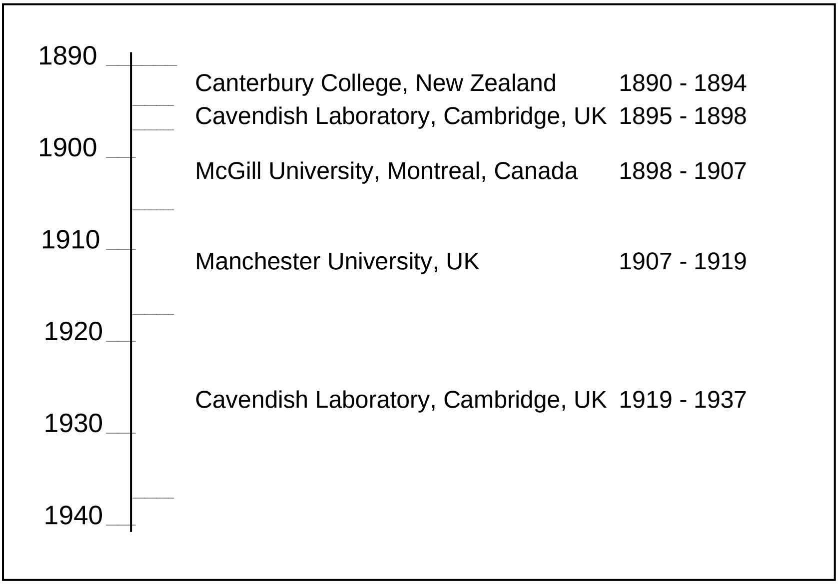
Ernest Rutherford was born in 1871 in Nelson, New Zealand, as one of ten children. Following inspired teaching and encouragement from his school mathematics and science teachers, he entered Canterbury College in 1890 where he studied for, and was awarded, three degrees – a BA, a Masters and a BSc. At the age of 23 he joined J J Thomson in the Cavendish Laboratory, Cambridge, UK, with whom he undertook research on the ionisation of gases using the recently discovered X-rays and radioactive emissions. Interestingly, while in Cambridge he built a detector of electromagnetic waves (still on display in the Cavendish Museum) with which he achieved the record of half a mile for the transmission of wireless signals. It was also during his time in Cambridge that he identified two types of radioactive emanations, denoting them α and β emissions.

In 1898, Rutherford was appointed a professor at McGill University in Montreal where, together with the chemist Frederick Soddy, he unraveled the mysteries of radioactive transformations and the decay series of the unstable elements, uranium, thorium and radium, recognizing lead as the final decay product and showing how this could be used to detect the age of rocks and the earth itself. He is reported to have said after being awarded the Nobel Prize for Chemistry for this work that "*the fastest transformation of all is my own – from a physicist to a chemist*"!

Meanwhile at the University of Manchester, Arthur Schuster had inherited a large fortune and gave up the headship of the Physics Department on condition that Rutherford was appointed as his successor, which he truly was. A most prolific period of activity followed, achievements during which included the demonstration that α particles were in fact helium nuclei, the development (with Hans Geiger) of the Geiger counter, the discovery of the atomic nucleus, and – working alone apart from the assistance of a technician during the First World War – the transformation of nitrogen into oxygen and hydrogen by α-particle bombardment.

During his final position as Cavendish Professor from 1919 to 1937 Rutherford oversaw, amongst other significant discoveries, experiments by Cockroft and Walton, which led to the first artificial disintegration of an atomic nucleus in 1932.

However, as mentioned above, it was during his tenure at Manchester University that he conceived the idea of the nuclear model of the atom and it is the details of this discovery that will form the remainder of this article.



2. Scattering Experiments

The experimental result which convinced Rutherford that atoms were largely devoid of material – with essentially all their mass concentrated in a tiny positively charged central core – was the observation that when α particles from a radioactive source were allowed to pass through a thin metal foil, a few of them underwent deflections through large angles. Indeed some were found to rebound backwards, an observation that led Rutherford later to recall that the effect ‘was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you’.

The seeds for the nuclear model of the atom had been sown back in 1905 when Rutherford himself drew attention to the dispersion of a beam of α particles as it passed through air or a thin sheet of mica.

After his move from McGill University in Toronto to the University of Manchester in 1907, Rutherford undertook work with Geiger on methods of detecting single α particles. Prior to the development of the Geiger counter, this involved direct observation by eye of individual scintillations on a zinc sulphide screen.

Rutherford suggested to one of his research students, Marsden, that he use this technique to study the scattering of α particles as they passed through thin metallic sheets. Within days, Geiger and Marsden reported that about 1 in 20,000 of the particles were turned through more than 90° on encountering a 0.00004 cm thick foil of gold.

Such large-angle scattering events could not be explained on the basis of a model for the atom that had been proposed by J.J. Thomson following his discovery of the electron in 1897. Thomson considered the main constituents of atoms to be electrons, which swirled around in a massless sea of positive charge – the so-called ‘plum pudding’ model. On such a model, the scattering of particles α through large angles would not occur - a succession of many individual scattering events results in only a small deflection, as shown theoretically by Rutherford in his paper. Instead a single encounter at close range between an α particle and a more massive point charge is needed to account for the experimental results.

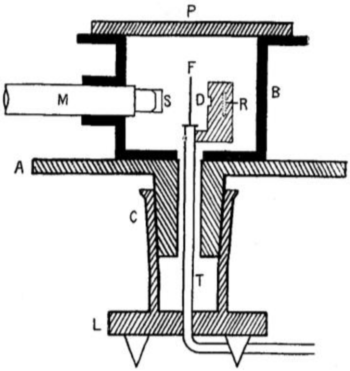
Rutherford’s theory of scattering, assuming an inverse square law of electrostatic repulsion from a central fixed charge, is now textbook physics. Analysis of the resulting hyperbolic trajectories leads to the following expression (equation 5 in Rutherford’s paper: reference 1) for the number of particles scattered into a unit area at a distance *r* after deflection though an angle ϕ from a foil of thickness *t* containing *n* atoms per unit volume:

$$y = \frac{ntb^2\,Q\,\mathrm{cosec}4(\phi/2)}{16r^2}$$

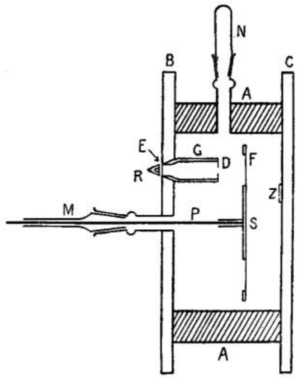
where $b = \frac{2NeE}{mu^2}$ and *Q* is the number of incident α particles.

Here *Ne* is the magnitude of the central charge, *E* the charge on the particle being scattered and *m* and *u* are its mass and velocity respectively.

Later detailed experiments by Geiger and Marsden [reference 2], using the two items of apparatus shown in Figure 3a and Figure 3b, were to confirm all the essential predictions of the Rutherford’s model for α-particle scattering from foils of various metals, in particular the dependence on angle, the foil thickness, and the central charge – the latter being verified by using different elements for the foil.



(a) (Left) Apparatus used by Geiger and Marsden to study the angular dependence of scattering of α-particles by a metal foil.
The conical joint C allowed the radium source R and the detector S to be rotated about the foil F in an evacuated chamber B.



(b) (Right) Apparatus used by Geiger and Marsden to study the number of α-particles scattered at a fixed angle as a function of foil thickness and atomic weight. Various foils F were mounted on a disc S which could be rotated in front of the radium source R. Z is a ZnS detector, scintillations on which were viewed with an external telescope.

Figure 3. Geiger and Marsden's apparatus.

In the final section of his paper, Rutherford writes: "*Considering the evidence as a whole, it seems simplest to suppose that the atom contains a central charge distributed through a very small volume, and that the large single deflexions are due to the central charge as a whole and not to its constituents.*"

3. Subsequent developments

Neils Bohr was just 26 when, working with Rutherford in Manchester away from his own university in Copenhagen for four months in 1912, he recognized the far-reaching implications of the new model and proceeded to develop it in relation to the system of electrons necessary to ensure a neutral atom. In 1913, he wrote a paper entitled '*On the Constitution of Atoms and Molecules*' [reference 3]. Bohr realized that if the electrons circulated in orbits around the central charge, they should radiate energy and quickly spiral into the nucleus. His answer to this seemingly insurmountable difficulty was to assert that, on the very small scale of the atom, classical electrodynamics does not apply. Furthermore he proposed that, unlike orbits in a gravitational attractive field, the electron orbits were finite in number. Then in a somewhat unjustifiable mixture of classical and quantum theories, Bohr postulated that electrons could jump between orbits, losing or gaining energy in units of $h\nu$ where h is Planck's constant. This condition is, as he shows in his paper, equivalent to the electron in each orbit having an angular momentum quantized in units of $h/2\pi$. An immediate result from his analysis was a formula for the frequencies of the spectral lines of hydrogen that proved to be in excellent agreement with experimental data.

In 1914 Rutherford published a second paper, '*The Structure of the Atom'* [reference 4] in which he surveyed the nuclear model of the atom in the light of relevant experimental results and theories published since his 1911 paper. These enabled him to expound more confidently his ideas on atomic structure and to considerations of the nature of the nucleus itself. Naturally he cited the experimental results obtained by Geiger and Marsden but in addition he was able to refer to the beautiful cloud-chamber tracks of α particles obtained by C.T.R. Wilson, many of which displayed abrupt bends at the ends as their velocity fell and they suffered single large deflections. He also referred to Moseley's studies of X-ray spectra [reference 5], which provided information of the charge of the nuclei of about 30 elements. It is of interest to note that the name *proton* was not introduced until 1919, thus accounting for Rutherford's usage in this paper of the term *positive electron* for the component of the nucleus carrying the charge.

In the same paper, Rutherford refers to (as then) unpublished results of Marsden on the scattering of α particles from hydrogen, which provided evidence for a 'knock-on' effect whereby a hydrogen atom acquires a velocity several times that of the α particle itself. Subsequent experiments of this type were later to lead Rutherford to identify, for the first time, the artificial disintegration of a nucleus (actually nitrogen) [reference 6], but here he uses the data to estimate the size of a hydrogen nucleus which, he argues, must be less than 1.7×10^{-13} cm (1.7 fm). With the knowledge that the helium atom had a mass nearly four times that of hydrogen, Rutherford proposed that the nucleus of helium contained four positive electrons (protons) and two negative electrons. What other conclusion could he have reached at the time? The concept of a neutral particle with a mass equal to that of the proton was unknown. The neutron was anticipated ten years later (in fact by Rutherford and Chadwick) but not discovered until 1932. Furthermore Rutherford's insistence that the nucleus must contain negative electrons found its strongest argument in the phenomenon of radioactive β decay. Rutherford guessed (correctly) that the high energy of β rays could not arise if the electrons were ejected from the external distribution of electrons, but could do so if they were liberated from the nucleus. Of course the actual mechanism of β emission was subsequently shown to be the decay of a nuclear neutron into a proton, an electron and an antineutrino.

Rutherford's 1911 theory of scattering, which led to the nuclear model of the atom, was classical. By 1928, it had been shown that exactly the same formula is obtained from a quantum mechanical treatment (see reference 7]. In this same reference, corrections to the formula are given for situations when the incident particles have relativistic velocities and, in the case of electron rather than α-particle scattering, for electron spin. There are also quantum mechanical modifications to the formula for α-particle scattering by He^4, owing to identical-particle symmetry.

4. Final Comments

It is impossible to say how our understanding of atoms might have been delayed had not Rutherford's insight been brought to bear on explaining the unexpected scattering results of Geiger and Marsden. His proposal that atoms are largely devoid of material was naturally greeted with incredulity by scientists who believed, along with Democritus 2000 years earlier, that the smallest unit of matter was billiard-ball like – uniform and indivisible. About 13 years before Rutherford published convincing evidence for the nuclear model, J. J. Thomson had shown that much smaller units - namely electrons - formed part of the atom, but its internal structure was still a mystery. Rutherford's revolutionary proposal took time to be accepted but the work of Bohr, Moseley and others added considerable supporting evidence and, once the neutron was discovered in 1932, the nuclear model was clearly established.

Rutherford's 1911 paper marked not only the discovery of the nucleus but also the beginning of an era of discoveries concerning the structure of matter.

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1. E. Rutherford, Phil. Mag. 21 (1911) p.669.
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4. E. Rutherford, Phil. Mag. 27 (1914) p.488.
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The 1912 Extensions of the Physical Laboratories of the University of Manchester and the birth of the electron-Volt.

Dr. Neil Todd
University of Manchester

Introduction

It is widely accepted that the key dates marking the discovery of the atomic nucleus are March 7 1911[1], when Rutherford's scattering law was first publicly announced before the *Manchester Literary and Philosophical Society*, and May 1911[2], when it was published in more detail in the *Philosophical Magazine*. However, according to Norman Feather[3], the term "nucleus" was actually first used in a published work by Rutherford a while later in the chapter on α-particles, in his book *Radioactive Substances and their Radiations*[4]. This was published in 1913, the forward dated October 1912. Prior to this, the preferred term was "central charge", rather than "nucleus". Of course, the α-scattering experiments carried out by Geiger and Marsden, which had initiated the train of thought leading to the scattering law, were started in the spring of 1909, and subsequently published in the *Proceedings of the Royal Society*[5], received May 19th, 1909. So there was a period of some 18 months between initial experiment and final formulation of the theory, and a further period of about 18 months before the word "nucleus" first appeared in print and the law was experimentally confirmed[6].

Figure 1. Rutherford's house in Withington, Manchester, birthplace of the nucleus. Photograph taken in 2010.

If one wishes to assign an actual date to the moment of discovery, i.e. the moment when Rutherford first correctly formulated his scattering law, the notes and calculations which record these are extant[7]. Although no date is recorded, these were probably composed in the winter of 1910. We know, however, from Marsden's recollections and a letter from Darwin that these calculations were carried out in Rutherford's study on the 1st floor of his Manchester home on Wimslow Road (Figure 1).

"I count it one of the greatest occurrences of my life that I was actually present half an hour after the nucleus was born. It was a Sunday supper at his Manchester house and I remember him saying to us that he had been looking into the big scattering of α-particles and that there must be enormous forces in the atom to do it." [C Darwin, quoted in Marsden 1950].

This was later coined the "Sunday night that changed physics"[8]. Probably the day after (a Monday morning), Geiger recalled Rutherford coming into his room and telling him that he "*now knew what the atom looked like*". Darwin and Geiger place these events as taking place before Xmas 1910. Wilson [9] suggests that it was early in December 1910, as Rutherford had written to Boltwood on the 14th telling him that he had devised an atom superior to Thomson's. This would give a date of either Sunday 13th or Sunday 20th December 1910.

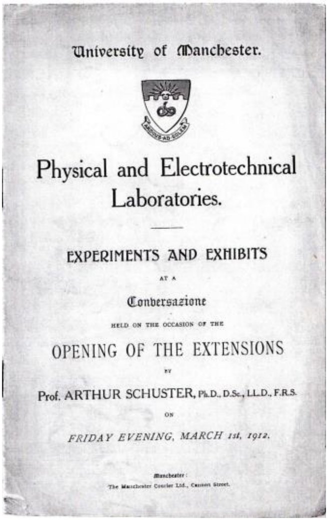
With all the subsequent discoveries that flowed from this momentous event, the Bohr-Rutherford quantum atom[10], Moseley's X-ray work[11] which proved the existence of the atomic number, isotopes and the modern periodic table[12], etc., it is all too easy for the other important work that came out of Manchester to be overshadowed. One thinks immediately of the work on transmutation, published in a quartet of papers in 1919[13], following several years of experiments during the war with only the help of the laboratory steward William Kay. However, there is another aspect of Rutherford's work which I wish to focus on in this article, namely his attempt to understand the origin of the beta and gamma ray spectra. As will be clear in the subsequent sections this work was only possible after 1912 at Manchester when an extension was built onto the original 1900 Laboratory. In particular it was only possible because the new physics rooms in the extension were initially free from the radioactive contamination which had by 1912 become widespread in the 1900 building, rendering it useless for the fine and delicate measurements made in spectroscopy.

This work is of considerable importance to the development of physics because by the end of the Manchester period in 1919 it signified the first phase of the integration of the quantum theory and relativity for the understanding of the interaction of matter and radiation, and in understanding the complexity of beta radiation. In particular I suggest, it laid the foundation for the modern unit of energy, the electron-Volt, which is commonly believed to only obtain wide currency much later after the invention of electrostatic particle accelerators in the 1930s. This should not be so surprising as in fact the first particle accelerators were cathode ray and associated X-ray tubes. Rutherford in his attempt to understand the relation between the beta and gamma rays made use of the most modern of X-ray device available at that time, the Coolidge Tube.

The 1912 Extension and problems of radioactive contamination

Our story begins on 1st March, 1912. On this date the Physical Laboratories of the University of Manchester were thrown open to the public for a conversazione and a spectacular exhibition of physical experiments (Figure 2)[14]. The whole of the laboratory was occupied with exhibits covering the range of activities within the Physical and Electrotechnical Laboratories and the Manchester Municipal School of Technology (the forerunner of UMIST). Among the exhibits were several rooms devoted to radioactivity, including alpha-ray tubes filled with radium emanation, high-voltage discharge apparatus, an exhibit of glass apparatus by the blower Otto Baumbach, and exhibits devoted to colour photography, optics, sound and meteorology. Of particular note was an exhibit in the basement run by Hans Geiger entitled “Counting atoms of matter”. Within the small lecture theatre was a special exhibit devoted to the Osborne Reynolds “Striking experiments on vortex motion, etc., due to the late Prof. Osborne Reynolds, illustrating his theory of the sub-mechanics of the universe”.

The can be no doubt that this exhibition would have been extremely impressive and inspiring, especially to the mind of a student or aspiring physicist. It was during March 1912, that a young Niels Bohr arrived in Manchester for the first time. Rutherford himself was very pleased with it, as is clear from his letter to his friend the chemist Bertram Boltwood on 18th March 1912[15].



University of Manchester.

Physical and Electrotechnical Laboratories.

EXPERIMENTS AND EXHIBITS

AT A

Conversazione

HELD ON THE OCCASION OF THE

OPENING OF THE EXTENSIONS

BY

Prof. ARTHUR SCHUSTER, Ph.D., D.Sc., LL.D., F.R.S.

ON

FRIDAY EVENING, MARCH 1st, 1912.

Manchester:
The Manchester Courier Ltd., Cannon Street.

Figure 2. Front cover from booklet produced for the opening of the 1912 extension[14].

"*In regard to my own little show, you will have received a pamphlet before this indicating what was on view. We had a very successful time of it, and had between 20 and 30 visiting professors. Experiments were going on not only on Friday evening, but on Saturday morning, and I think it was the best physical show we have had in this part of the world. It was a heavy business arranging everything for it took about six weeks of my time; but fortunately everything passed off like clock-work and everyone was pleased. I gave a dinner to about 50 people before the reception and that went off very well.*"

In the same letter Rutherford also gives a vivid description of the new extension (Figure 3), and also other gossip, not least the death of Osborne Reynolds.

"The new Laboratory looks very well, very bright and comfortable, and the new Physical rooms are already proving very useful. I have a little Chemical Laboratory attached, which is now being used by Russell. The new Museum building is pretty well up, and the new archway over Coupland Street improves the whole appearance of the Laboratory very much. All the old houses are pulled down and things generally look much more academic. You can imagine what a rush I have had of it this year, what with my regular work, the opening, and the new edition on my hands ...
... You may have heard that within a week three of the University people pegged out, including Osborne Reynolds, ..."

Figure 3. Photograph of the West Wing of the 1912 Extension, (reproduced from Schuster (1912)[16] with permission from Manchester University Press).

Of particular interest to our story is Rutherford's mention of the "new Physical rooms", shown in Figure 4 below, and the reasons for their construction. There can be no doubt that one of the most important reasons for the construction of the extension was that after Rutherford's arrival there was a great increase in the number of research students working with radioactive substances with the associated problem of space. This is clear from the following quote from a description of the extension in a University document to accompany the new extension[16].

"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...."

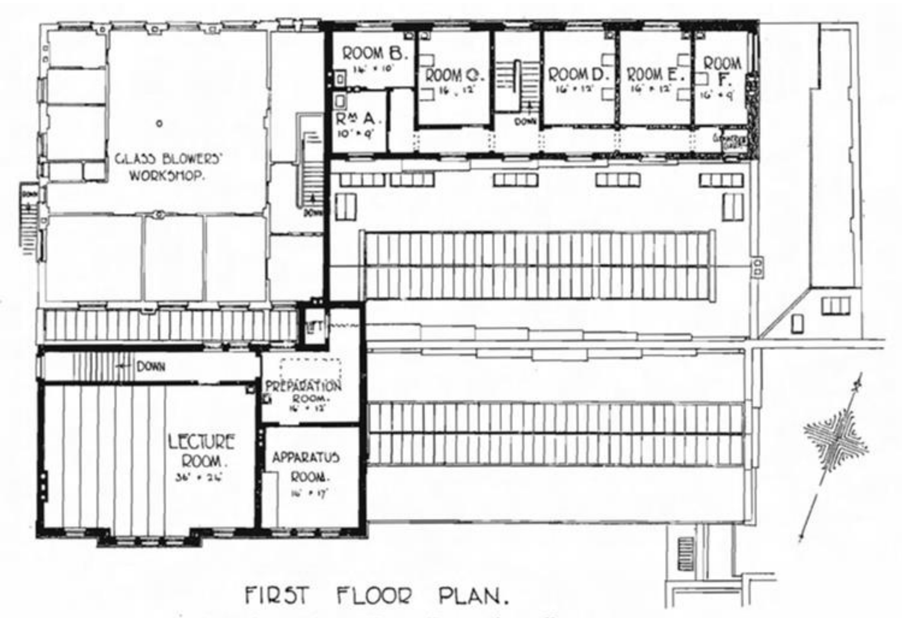


Figure 4. Plan of the 1st floor of the 1912 Extension, (reproduced from Schuster (1912)[16] with permission from Manchester University Press).

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 became 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 ..."

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 are given by Schuster in the same document as above (see Figure 4).

"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." [Schuster 1912]

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[17]:

"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."

In the 1911-1912 report[18]:

"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."

A question which naturally arises from these descriptions by Schuster and Rutherford is what exactly were the "refined experiments" and "delicate measurements" that Rutherford wished to carry out in the contamination-free new Physics Rooms? It was clearly a matter of considerable importance to him. The answer, I suggest, is that these experiments were primarily concerned with β and γ-ray spectroscopy. In order to appreciate why this was likely the case, it is useful to review briefly the situation regarding beta rays prior to 1912.

Beta rays before 1912

There no better authority on this subject than Rutherford himself. An excellent review can be found in his text book "Radioactive Substances and their Radiations" of 1913 mentioned above[4]. After the discovery of beta radiation in 1898 it was soon found that this was deviable by a magnetic field and shown to have essentially identical properties to those of cathode rays. However, it was also clear that the beta radiation was complex in nature because a narrow pencil of rays would be broadly deflected, indicating a distribution of velocities. An important step was made in unravelling the complexity by using a photographic method to record the deflected rays. It was clear as early as 1900 in experiments by Becquerel from the diffuse impressions recorded on a photographic plate that the distribution appeared to be essentially continuous. The photographic results were confirmed by an electric method using an ionisation chamber in conjunction with absorbers of various thicknesses.

Over the following years various experiments were carried out to determine the charge carried by the beta rays, and the *e/m* along with its variation with velocity. Assuming a charge *e* of 4.65 x 10^{-10} electrostatic units (E.S.U.) the number of β particles emitted from 1 gram of radium per second was estimated to be in the range 3.7 - 7 x 10^{10}. (The value for *e* used by Rutherford is very close to the current accepted value of 4.8 x 10^{-10} E.S.U. In SI units, 1 coulomb = 10^{-1} *c* E.S.U., where *c* is the speed of light.) Early experiments determined that β particles had a velocity of about 1.6 x 10^{10} cms per second and an *e/m* of about 10^{7} electromagnetic units (E.M.U). (In SI units, 1 coulomb = 10^{-1} E.M.U.). It was possible to conclude that β particles had about the same mass as cathode ray particles, but their velocity was very much higher, and close to the speed of light. After early attempts to account for the variation in *e/m* with velocity, it became clear, after the work of Einstein and Lorentz, that a relativistic correction was required to provide a proper account of this. By the time of Rutherford's 1913 text the relativistic view had been fully taken on board. The e/m_0 was found be close to that for cathode rays, where m_0 is the rest mass, confirming that β ray and cathode ray particles were one and the same.

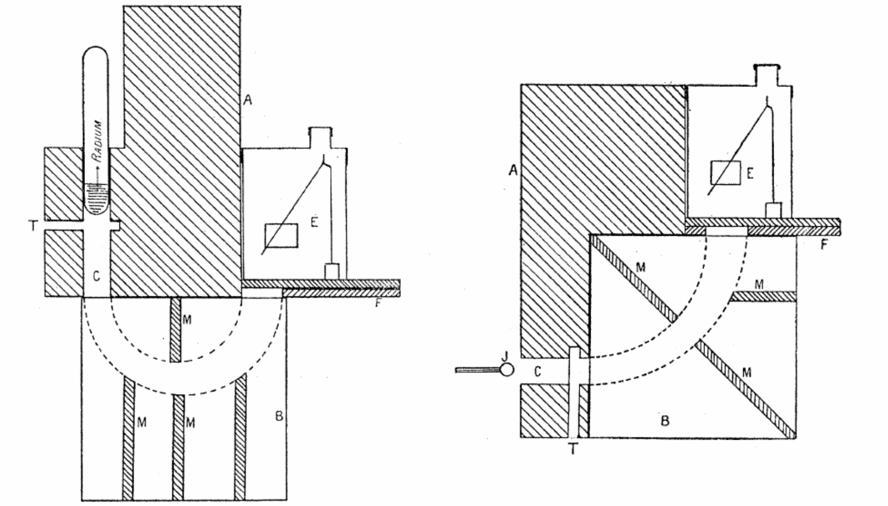


Figure 5. Apparatus used by Wilson (1909)[19] to measure the ionization effect of the beta ray distribution using radium (left) or radium emanation (right) sources after passing through a magnetic field, (reproduced with permission from the *Royal Society*).

Having established the relativistic basis for calculation and it was then possible to make accurate estimates of both velocity and energy of β particles. As noted above it had became clear early on that there was considerable complexity to the beta rays in that they consisted of heterogeneous β particles with a considerable range of velocities. If the magnetic distribution of velocities was measured, either by photography or by ionisation, then depending on the source at times a continuous distribution (from radium E (Bi210) and Uranium X) and at others a discrete "spectrum" could be observed (from radium B and C). Within the Manchester Physical Laboratory most notable in their contribution to the establishment of the continuous distribution using the ionization method were W. Wilson and J.A. Gray, an 1851 Exhibition Scholar from Melbourne. This was particularly important because prior to this work, the explanation that the spread in velocities observed by

Becquerel was due to transmission, absorption or scattering factors was widely accepted. Through their experiments Wilson and Gray showed that heterogeneity of velocity was almost certainly a property of the primary radiation, and hence a property of β decay.

To get an impression of the methods by them, a diagram of the typical apparatus is shown in Figure 5[19] above. In this a source was held within a lead block in order to obtain a pencil of beta rays and bent in a magnetic field. By appropriate shielding, effects of primary gamma and secondary beta and gamma radiation could be excluded, or reduced, and the properties of the velocity/energy distribution could be measured from the ionization effect of the rays as a function varying the strength of the magnetic field and the thickness of various absorbers. Balancing centrifugal and Lorentz forces the relation between magnetic field strength *H* and velocity *v* was given by

$$\frac{v}{e/m} = H\rho$$

where ρ is the radius of curvature of the path of the beta particle. Thus the product *Hρ* (in Gauss cm) was the principal experimental measure from which the velocity could be derived, taking into account *e/m* from the Lorentz formula

$$e/m = \frac{e}{m_0}\left(1 - \frac{v^2}{c^2}\right)^{1/2}$$

The value for e/m_0 was taken to be 1.74 x 10^7 E.M.U.

Using similar experimental measures but with a thin film of radium E (Bi210) Gray and Wilson (1910)[22] confirmed earlier experiments by them, using a photographic method, that suggested β-ray heterogeneity data. These results are reproduced in Figure 6. Although some variability in velocity would be expected from the finiteness of the transmission apertures within the apparatus, the fact that the peak velocity (or *Hρ*) increased with absorber thickness confirmed that the original source was heterogeneous.

Although the continuous nature of the radiation from radium E was confirmed, v. Baeyer, Hahn and Meitner[20] in Berlin showed using a photographic method that other sources, such radium B+C, could produce definite sets or bands. Further work by them and the Paris group refined these methods to the extent that it was possible to measure the velocities of β-rays from each of the bands with remarkable precision. Danysz[21] in particular published in 1911 a detailed description of the β-spectra from radium emanation which was reproduced in Rutherford's book, and reproduced below.

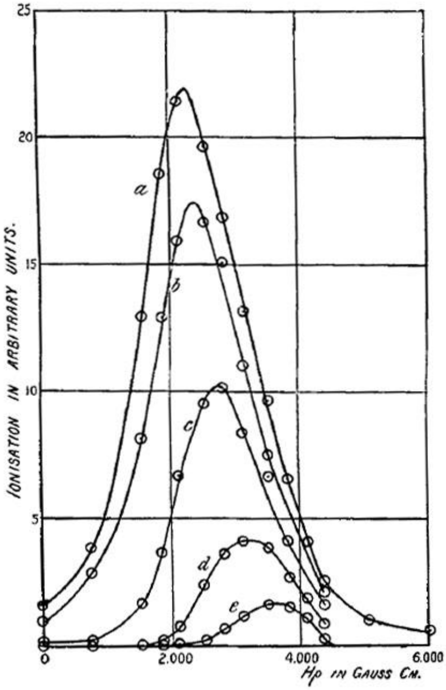


Figure 6. Ionisation curves as a function of *Hρ* after passing through different thicknesses of absorber, from Wilson and Gray (1910)[22], (reproduced with permission from Taylor and Francis).

It is clear in reading through the chapter on β-rays that Rutherford had become intrigued by the exquisite complexity of these results and he would have become extremely frustrated that he was not able immediately to put his own men onto this work. The requirement for photographic methods almost certainly accounts for why prior to 1912 he was not able to do so. By 1911 the laboratory had become widely contaminated which would have severely limited photographic methods, due to the well-known fogging effect on photographic plates from a high background level. Although Gray did use the photographic method it would have been difficult to carry out successfully for low intensities and it was probably for this reason that prior to the 1912 extension he had Gray working in the attic above the Large Lecture Theatre (which we know from his letters to Boltwood).

Beta and gamma-ray spectrometry at Manchester 1912 – 1914

The opening of the 1912 extension and the use of the six new physics rooms gave a new lease of life to the Manchester Physical Laboratory, or at least it enabled a line of work that would not have been possible otherwise. It was in 1912, shortly after the opening of the new extension, that Rutherford published a paper entitled, "The Origin of β and γ Rays from Radioactive Substances"[23] submitted on August 16th 1912 to the *Philosophical Magazine.* Thereafter, between 1912 and the outbreak of the war in 1914, this was the major thrust of Rutherford's experimental work at the Schuster Laboratory.

β and γ Rays from Radioactive Substances. 457

Intensity.	No.	Hρ.	β.	Energy.	Intensity.	No.	Hρ.	β.	Energy.
	A	Hahn	·36	$0{\cdot}353\times10^{13}$ *e.*	f	11	2190	·790	$2{\cdot}595\times10^{13}$ *e.*
	B	Hahn	·41	0·468 ,,	s	12	2870	·862	3·711 ,,
s	1	1320	·615	1·218 ,,	f	13	3140	·882	4·155 ,,
f	2	1390	·634	1·322 ,,	f	14	3420	·897	4·60 ,,
vf	3	1490	·660	1·475 ,,	f	15	4000	·920	5·52 ,,
s	4	1580	·682	1·616 ,,	s	16	4670	·940	6·585 ,,
f	5	1680	·703	1·771 ,,	f	17	4800	·943	6·79 ,,
vf	6	1750	·718	1·885 ,,	f	18	4980	·946	7·07 ,,
s	7	1830	·735	2·017 ,,	m	19	5100	·949	7·26 ,,
m	8	1900	·748	2·132 ,,	s	20	5700	·957	8·18 ,,
f	9	1970	·760	2·246 ,,	f	21	5990	·962	8·63 ,,
s	10	2150	·786	2·535 ,,	complex	22	11200	·988	16·6 ,,
					complex	23	18100	·996	27·0 ,,

Figure 7. Table of velocities and energies of the discrete beta particle groups from radium B+C, from Rutherford (1912)[23], (reproduced with permission from Taylor and Francis).

The essential idea contained within his first 1912 article, and a similar description in his 1913 book, was that he was convinced that there must be a connection between the beta and gamma ray spectra because the beta complexity was highest for those radioactive substances which had the most intense gamma activity, such as radium B+C. Conversely those substances which produced a continuous beta spectrum had little or no gamma activity. He conceived of a kind of proto-quantum electrodynamic scheme in which energy could be exchanged between beta particles and gamma-rays in a manner analogous to the production of characteristic X-radiation by cathode ray bombardment. For this reason he converted all the measured velocities from the Berlin and Paris data into energies, as shown in Figure 7. Thus in a beta-ray decay the escaping electron might give up some of its energy in integer multiples of a basic unit to gamma radiation, the basic unit being a characteristic of each element.

The energy was calculated from

$$\frac{1}{2}mv^2 = \frac{1}{2}H\rho\beta ce$$

where β is the ratio of electron velocity to speed of light, c is the speed of light and *e* is the electronic charge. (Note that energies (in ergs) are expressed as an equivalent voltage multiplied by the electronic charge, i.e. $E = eV$. Care is needed in converting to SI units. 1 Rutherford energy unit (henceforth a "reu") = 10^{13} *e* ergs, where *e* the electronic charge is 1.6 x 10^{-20} in E.M.U.! Thus 1 reu = 10^{-14} J or 10^5 eV or 100 keV or 0.1 MeV.)

At the end of this paper he expresses a view on the origin of the beta decay as being essentially electronic in origin, where the gamma-rays are essentially a form of X-ray, as opposed to alpha decay which is due to nuclear instability.

"In a previous paper I have given reasons for believing that the atom consists of a positively charged nucleus of very small dimensions, surrounded by a distribution of electrons in rapid motion, possibly of rings of electrons rotating in one plane. The instability of the atom which leads to its disintegration may be conveniently considered to be due to two causes, ..., viz. the instability of the central nucleus and the instability of the electronic distribution. The former type leads to the expulsion of an α particle and the latter to β and γ rays. The instability which leads to the expulsion of a β ray may be mainly confined to one of the rings of concentric electrons, and leads to the escape of a β particle from this ring with great velocity. The β particle in escaping the atom passes through the electronic distribution external to it, and in traversing each ring may lose part of its energy in exciting one or more gamma rays which have a definite energy, which is characteristic for each ring".

It is remarkable that these initial speculations were made prior to the publications of the work of Bohr and Moseley in 1913 which established a proper quantum explanation of the atom and their optical and X-ray spectra, and prior to Soddy's announcement of the displacement laws of nuclear transformation. We know from the Bohr literature that he advised him in discussions otherwise on the matter of the origin of beta decay on the argument that it involved a change in atomic number so it must be nuclear. This he acknowledged in a letter to Nature[24]. His position is, however, understandable - beta particles are electrons after all - but nevertheless, these speculations drove an intense experimental programme at Manchester in the years before the war from which his ideas evolved. The principal workers in the experimental work were H Richardson, E N da C Andrade, H Robinson and WF Rawlinson. Work was also done in this field by Florance, Makower, Chadwick, Moseley and Russell.

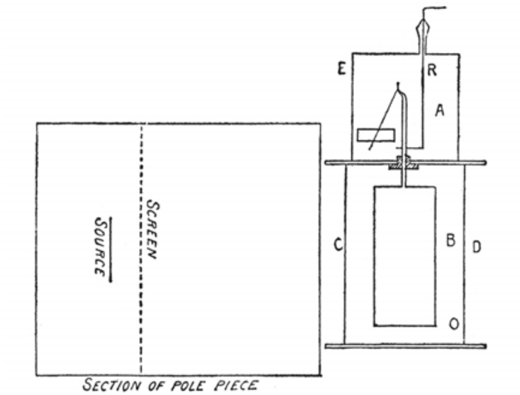


Fig. 1

Figure 8. The apparatus used by Rutherford and Richardson (1913)[25] to analyse gamma rays where the effect of ionization is measured by an electroscope, (reproduced with permission from Taylor and Francis).

Rutherford and Richardson published three successive articles examining the gamma-rays produced by radium (B+C), radium (D+E) and thorium and actinium products[25]. The apparatus used for these experiments is shown in Figure 8. Preliminary work was done using a 'radon tube'; thereafter, the sources were obtained from the active deposits of radium, thorium and actinium. The radium (D+E) source was prepared by Russell and Chadwick as were the thorium products (mesothorium 2, thorium B, C + D) and the actinium products (B+C+D).

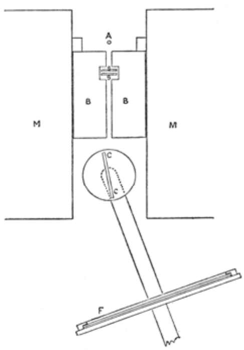


Fig. 1

Figure 9. The apparatus used by Rutherford and Andrade (1914a)[26] to measure the wavelength of gamma rays (reproduced with permission from Taylor and Francis).

Rutherford and Andrade published three papers using the method of crystal diffraction to obtain the wavelengths and spectra of the gamma rays from radium products[26]. The apparatus is shown above in Figure 9. The sources for these experiments were radon tubes of about 100 millicuries in strength. 24 hours exposure was needed to obtain a good photograph of the spectral lines. For obvious reasons, such fine photographs would need to be done in a part of the building with a low background. For comparison with X-ray spectra, they were assisted by Henry Moseley.

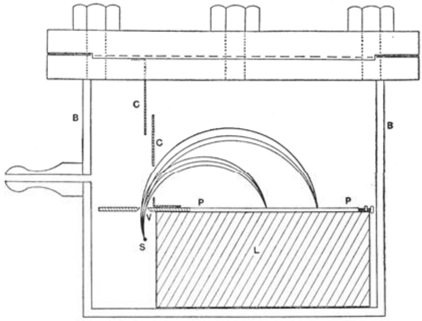


Fig. 1

Figure 10. The apparatus used by Rutherford and Robinson (1913)[27] to measure the velocity of beta-particles, (reproduced with permission from Taylor and Francis).

Two papers were published in 1913 and 1914 with H Robinson and WF Rawlinson concerning the measurement of the velocity of and energy groups of beta-particles from radium products and also secondary beta rays excited by gamma rays[27, 28]. This last paper provided some evidence that the excited beta rays depended on the material under bombardment. The apparatus used for these experiments is shown in Figure 10 and example results shown in Figure 11. The sources used were radon tubes and radium B+C active deposits.

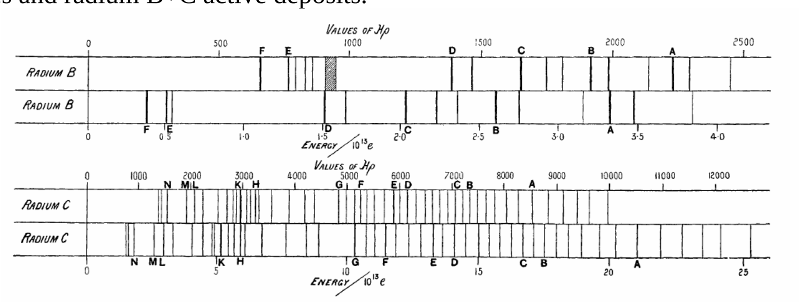


Figure 11 shows the velocity and energy spectra measured from radium B+C by Robinson and Rutherford (1913)[27], (reproduced with permission from Taylor and Francis).

Further to this Robinson and Rawlinson[29] separately published a paper showing that β rays could be excited directly by soft X-rays of iron and lead radiators (Figure 12). In the reported experiment they were able to produce β particles with energy closely in the range corresponding to the Fe K series (6 – 7 keV) X-rays, thus apparently confirming Rutherford's quantum speculation.

Fig. 1.

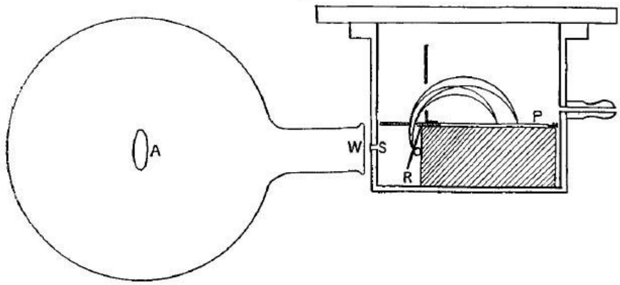


Figure 12. The apparatus used by Robinson and Rawlinson (1914)[29] to measure the velocity of beta-particles excited by X-rays, (reproduced with permission from Taylor and Francis).

By the end of this period in 1914 just before the war, as well as the wealth of new experimental information, Bohr, Moseley and Soddy's ideas has been published, as well as work by Chadwick on the concept of internal conversion. Rutherford's own proto-quantum theory had also evolved, including a role for Planck's constant in defining the energy of gamma ray quanta. It is clear that he now made a distinction between primary beta rays, which give rise to the continuous velocity distribution, and which are nuclear in origin, and secondary betas which constitute the discrete spectra and which are electronic in origin[30].

"It will be seen that the present theory of the origin of the β rays differs somewhat from that advanced in the earlier papers. I there supposed that homogeneous groups of β rays were due to the decrease of energy in definite units of the primary β particle in exciting vibrations in the atom. The present theory supposes that the homogeneous groups of β rays arise from the conversion of the energy of γ rays into the β ray form. In other words, the primary effect in the atom is the excitation of γ rays by the escape of the β particle from the nucleus. The appearance of groups of homogeneous β rays is a secondary effect due to the partial conversion of the γ rays into β rays in their passage through the radioactive atom. On the other hand, the continuous β radiation is ascribed mainly to the effect of the primary escaping from the nucleus which have lost energy, though not in definite quanta, in setting the electronic system into vibration."

Although this new position is correct in distinguishing between primary (nuclear) and secondary (electronic) β rays and in the origin of the discrete β energies arising from conversion of γ to β in definite quanta, his explanation of the origin of the continuous spectra of the primary β rays in their non-quantum interaction is, of course, arbitrary and incorrect. His view remained at this time that the γ rays are essentially a form of X-rays, but this is understandable given that the limitations of the crystal method in diffracting and measuring the wavelength (energies) of γ rays. Within this range the bulk of the electromagnetic radiation observed are X-rays associated with internal conversion.

Angles of reflexion and energies of lines in γ-ray spectra of radium B and radium C.

Angle of reflexion from rocksalt.	43′	1° 0′	1° 10′	1° 24′	1° 37′	1° 43′	2° 0′	2° 20′	2° 28′	2° 40′	3° 0′	3° 18′	4° 0′	4° 22′
$(E=h\nu)\div 10^{13}e$	1·74	1·25	1·07	·893	·773	·728	·625	·537	·507	·469	·417	·379	·312	·286

Figure 13. Angle of reflection and calculated energies of γ-rays measured from radium B+C, from Rutherford (1914)[30], (reproduced with permission from Taylor and Francis).

To appreciate this limitation the results from Rutherford and Andrade (1914) as shown by Rutherford (1914) are reproduced in Figure 13. Here Rutherford has converted the angle to a wavelength, and thence to an energy expressed in the same units as for the β particles in Rutherford and Robinson's results shown in Figure 11. Converting his values to electron volts the highest energy measured was 174 keV. If the sample of radium B+C was pure then the X-radiation observed would have been from the Pb, Bi and Po characteristic "K-level" series, in the range 75 – 90 keV, and these were the strongest lines observed, confirming his general view that the γ-rays were essentially X-rays. It was obvious from the total number of lines, however, that this account could not be complete. The fact that most penetrating γ rays measured had shorter wavelengths (higher energies) than the expected K series X-rays led him to speculate that there may be higher energy X-ray series beyond.

"We may consequently conclude that the penetrating γ rays from radium B, correspond to the characteristic radiation of the K series of this element. It had been previously supposed that the very penetrating rays from radium C belong to the K series … for that substance, but if the relation found by Moseley holds even approximately, …this cannot be the case. …We are thus driven to conclude that … an even more penetrating γ radiation than radium C, another type of characteristic radiation is emitted which is of higher mean frequency than for the "K" series. … This may for convenience be named the "H" series, for no doubt evidence of a similar radiation will be found in other elements when bombarded by high speed cathode rays" [Rutherford and Andrade 1914][26].

In this paper the idea of searching for the higher series “H” radiation by means of high-voltage X-ray tube is suggested for the first time. Indeed explicit reference is made to recent work by Coolidge in an earlier paragraph.

“The appearance of these high-frequency vibrations from radium B+C is accompanied by the expulsion of very high speed β particles from the atom. It does not however follow that it will be necessary to bombard the material with such very high speed β rays to excite the corresponding radiation. If we may assume, as seems probable, that Planck’s relation E = hv holds for the energy of the β particle required to excite radiation of frequency v, it can be deduced that the electron to excite this radiation in radium C must fall freely through a difference of potential of 180,000 volts, which is equivalent to a velocity of about 0.7 that of light. This is much smaller than the velocity of the swift β particles from radium B or C, and is not beyond the range of possible experiment. With the tube recently designed by Coolidge there should be no inherent difficulty in exciting the corresponding radiation in a heavy element like platinum or uranium”. [Rutherford and Andrade 1914][26].

Thus, the scene was set in 1914 for Rutherford to embark on a series of experiments with the newly invented Coolidge X-ray tube in order to explain the higher energy γ radiation he had observed and which could not be accounted for by the K series X-rays. Having been encouraged by the results of Robinson and Rawlinson, published 1st July 1914, in showing a direct relationship between X-rays and β spectra, they would have been the most natural co-workers for this purpose, but for the outbreak of the First World War at the beginning of August.

Rutherford’s X-ray experiments at Manchester 1915 - 1918

As has been documented in the Rutherford biographies, WWI, which broke out during a visit by Rutherford to the British Association Meeting in Sydney Australia, had a major impact on the Manchester Physical Laboratory. The laboratory was drastically depleted of workers many of whom who went off to enlist in the forces on both sides of the conflict. Tragically, Moseley was killed at Gallipoli in August 1915. Chadwick was interned for the duration of the war, having been caught out on a visit to Geiger in Berlin. Baumbach the laboratory glassblower was interned in Manchester. Much of Rutherford's time was taken up by war work, which included the development of acoustic methods for submarine detection, for which purposes a large tank was constructed in the basement. In spite of this, during the war itself, apart from his war work, and his work on transmutation, his preoccupation with the X-ray problem continued and was practically the only subject on which he published in the years 1915-1918.

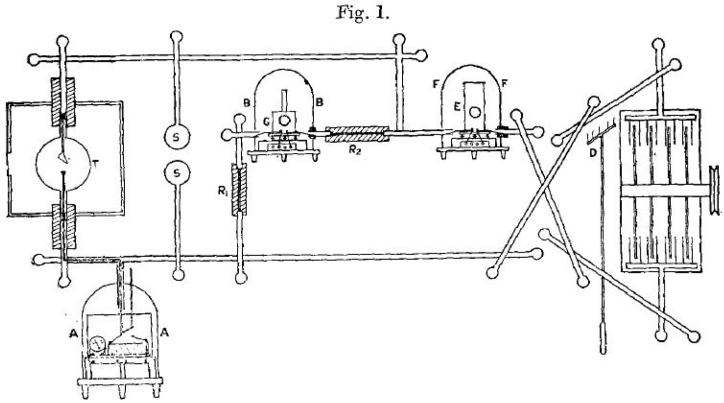


Figure 14. The apparatus used by Rutherford, Barnes and Richardson (1915)[31] to measure the maximum frequency of X-rays from a Coolidge Tube in conjunction with a Wimshurst generator, (reproduced with permission from Taylor and Francis).

In 1915 Rutherford was able to make use of co-workers J Barnes and H Richardson to publish two papers using the Coolidge Tube with the voltage generated by a large Wimshurst and an induction coil[31]. They found that the X-rays from a Coolidge Tube reached a maximum penetrating power at 142,000 volts and thereafter no further significant increase could be obtained up to 175,000 volts. Comparing the most penetrating X-rays obtained they concluded that these were comparable with the γ-rays from radium B but were much less penetrating than those from radium C. They were forced to conclude that the hard γ rays could not be explained as a form of X-ray of the supposed "H" series.

"It thus appears probable that the radiation from tungsten is analogous to the radiation from radium B. Since the speed of the beta rays issuing from radium B corresponds to a fall in potential of at least 400,000 volts, and from radium C of 2,000,000 volts, it seems clear that we cannot expect to obtain more penetrating radiation from tungsten unless possibly a voltage of 1,000,000 is applied. Even with electrons corresponding in energy to over 2,000,000 volts the wave-length of the strongest line due to penetrating gamma rays from radium C, …, is only 6/10 of the shortest wave from the Coolidge tube. The comparison of the results with the Coolidge tube with the gamma rays thus leads to the conclusion that there is a definite limit to the maximum frequency to be obtained from an element bombarded by swift electrons.

This limit is probably determined by the characteristic radiation of highest frequency which exists in the atom. Since radium C had an atomic number 83 and uranium – the heaviest known element – 92, we should anticipate from Moseley's relation that the shortest wave-length to be obtained with a uranium anticathode ... is $1.4*10^{-9}$ *[cm]. ... Under possible laboratory conditions, it thus appears very improbable that we can obtain X-rays as penetrating as the gamma rays from radium C".* [Rutherford, Barnes and Richardson, 1915][31].

The final piece of work in this line was carried out by Rutherford himself, and due to other considerations of war work it wasn't until 1917 he was able to publish[32]. In this he used essentially the same apparatus as shown in Figure 14, but used instead a large induction coil of 20 inch spark gap, from which he could obtain voltages up to 196,000 volts. From this work he discovered what is now known as an X-ray "absorption edge" which was able to account for the results observed by Rutherford, Barnes and Richardson with lead absorbers. He was then able to conclude that "*the absorption measurements are not themselves inconsistent with the view that the maximum frequency of radiation from a Coolidge tube is given by the quantum relation E=hv, over the range of voltage measured*." Having removed this road block to progress he was able to compare absorption properties of X-rays produced at the highest voltages with those of γ rays from radium B+C in order to make inferences about the properties of the most penetrating gamma rays. It became clear that they must have much shorter wavelengths than previously supposed or measured by the crystal method.

"In our present ignorance ..., it is only possible to estimate the actual wavelength of the most penetrating gamma rays. It is clear, however, that the waves are at least three times shorter than those which correspond to 200,000 volts, i.e. they correspond to waves generated by voltages between 600,000 and 2,000,000 volts, ... It is thus clear that the gamma rays from radium C consist mainly of waves of about 1/100 the wavelength of the soft gamma rays from radium B, and are of considerably shorter wavelength than any so far observed in an X-ray tube, with the highest voltages at our disposal."

He was then able to make a connection between the energies of the hard gamma rays from radium B+C with those of the β-rays measured by the magnetic spectrum, which he did in a table reproduced below in Figure 15.

β rays from Radium B.				β rays from Radium C.			
Group.	Intensity.	Energy $\div 10^{13}e$.	Voltage (volts).	Group.	Intensity.	Energy $\div 10^{13}e$.	Voltage (volts).
A	s.	3·332	333,200	A	m.f.	21·02	2,102,000
B	v.s.	2·610	261,000	B	m.f.	17·51	1,751,000
C	v.s.	2·039	203,900	C	m.	16·71	1,671,000
D	v.s.	1·519	151,900	D	m.	14·09	1,409,000
E	s.	·503	50,300	E	m.s.	13·28	1,328,000
F	v.s.	·376	37,600	F	m.	11·49	1,149,000
				G	m.s.	10·31	1,031,000
				H	m.s.	5·94	594,000
				K	s.	5·16	516,000
				L	m.	2·96	296,000
				M	m.	2·59	259,000
				N	m.	1·81	181,000

Figure 15. Table showing energies and equivalent voltage for the β rays of radium B+C, from Rutherford (1917)[32], (reproduced with permission from Taylor and Francis).

"Apart from the low-velocity groups L, M and N, the b rays from radium C consist mainly of groups lying between 500,000 and 2,000,000 volts. This is about the same range of voltage as we estimated to excite the penetrating gamma rays from a consideration of the absorption of X-rays and gamma rays by aluminium and lead. It would thus appear probable that the observed groups of β rays are due to the conversion of the energy, E = hv, of a wave of frequency v into electronic form, ...".

Having made the above connection Rutherford expressed a hope that this might furnish a new method of gamma ray spectroscopy, via to γ to β conversion, which would overcome the limitations of the diffraction method. At this time though the possibility that the high energy gamma rays may have a nuclear origin did not appear to have occurred to him, firm in his conviction that they were produced by the interaction of the primary β rays with the electronic distribution. Thus was concluded this particular episode in Rutherford's science at Manchester. In his own publications he did not return to the problem the origin of the gamma rays until 1931, although the work was continued by CD Ellis at Cambridge.

Discussion and Conclusions

The story told here is a relatively unknown chapter in Rutherford's career but the period from 1911 to 1919 has been recognised as the "Rutherford Era" in the history of beta decay[33]. It is remarkable to consider the progress made in such a short space of time. Barely two decades had passed since the discovery of X-rays, radioactivity, the electron, less for the discovery of Planck's relation, only a decade since the Einstein-Lorentz relativistic correction was formulated and a mere handful of years since the nuclear discovery, with all that followed in the work of Bohr, Moseley and Soddy. Although from the current perspective we can see much that was wrong in the position which Rutherford had arrived at in 1917 on the origin of beta and gamma radiation, there is also much that is essentially correct. He had correctly arrived at the view that beta decay was nuclear in origin (although the first suggestion of this can be attributed to Bohr) and distinguished between the primary and secondary beta radiation with respectively continuous and line magnetic spectra. The origin of the line spectra was correctly attributed to the conversion of γ to β radiation and he had provided a hint that this was element specific, although he had not at this time distinguished in the gamma spectra between lines of nuclear origin and X-rays resulting from the secondary beta excitation. The origin of the continuous nature of the primary beta radiation was also wrongly attributed to electron-electron scattering effects.

The first weakness in this account was actually soon corrected in the work of Ellis at Cambridge, which followed on from Rutherford, Robinson and Rawlinson. Ellis (1921)[34] refined their work to show that it was indeed possible to infer the high-energy gamma lines (beyond the limits of the crystal method) by their conversion of beta rays produced by expulsion from the K and L electron shells of different elements by the photoelectric effect, taking into account the ionisation energy. The definitive statement of the nuclear origin of the gamma rays appears in Ellis (1922)[35] which is worth quoting.

"The wave-lengths of these γ-rays depend on the structure of that part of the atom which emits them, and considerable information about this structure can be deduced from the experimental results.

The first point to settle is the origin of the γ-rays. Sir Ernest Rutherford has pointed out on several occasions that the general results indicate that γ -rays are emitted from the nuclei of radio-active atoms, and the numerical values now obtained lend very strong support to the view.

Except as regards the constitution of the nucleus, the radium B atom is identical with the lead atom in every respect. In particular, the K and the L rings, and the fields of force in which they are situated, must be precisely the same in the two atoms, since Rutherford and Andrade found that radium B emits the complete K and L spectrum of a body of atomic number 82. But this last fact indicates something more than this, it suggests that the γ -rays are emitted previous to the emission from the nucleus of the disintegration electron resulting in the atomic number changing to 83. In fact it would appear that the γ -ray is emitted, travels out to the L ring, from where it may eject an electron, this electron then goes clear of the atom and another electron falls into the vacant place in the L ring and the nucleus had still not disintegrated. "

Not only is the γ -ray now clearly established as nuclear in origin, it has also been made independent from β-decay, which follows it. The previous position had been that the γ ray was somehow associated with the primary beta decay. Although Rutherford in not a co-author on this paper Ellis attributes these insights to him. Since Ellis does not provide a reference here we can only assume that the new and correct position emerged in laboratory discussions sometime in 1921 or 1922, within a decade of Rutherford's first 1912 paper on the origin of the beta and gamma rays.

The origin of the continuous beta spectrum was, of course, not understood until much later in the early 1930s with Pauli's proposal of the neutrino[33]. Until this time beta decay remained a conundrum and was the source of Bohr's greatest blunder, his proposal to abandon the conservation of energy for beta decay. Given the disarray among the physicists at this time Rutherford's position on this issue is perfectly understandable. An important point to be made from this review, however, is that it could be argued that the first definite proof of the continuous beta spectrum came from the Manchester Laboratory in 1910 from the work of Wilson and Gray, although the proof that it could not be explained by secondary effects was not provided until 1927 by Ellis and Wooster.

In concluding this paper, there are several other important observations which should be made. Contrary to the position expressed in the introduction, the first printed use of the term "nucleus" would appear in fact to be made in Rutherford's 1912 paper on the origin of the beta and gamma rays, as it appeared in October 1912. This may though be a moot point as the foreword for his 1913 book is also dated October 1912. The fact is, though, that the speculation in the 1913 book and the 1912 paper record the same period in the development of his thought.

Perhaps the most significant new observation that can be made concerning the contribution of the Rutherford era of beta decay research to the development of physics is that it includes the first expression of energy as an equivalent voltage, i.e. it witnessed the birth of the electron volt as a fundamental unit. It was in his search for an equivalent footing for the high-energy beta rays characterised by magnetic spectra and the relativistic mass correction formula and gamma rays characterised by diffraction and the Plank quantum relation that Rutherford found the energy unit of 10^{13} *e* ergs most natural. Indeed, it could be said that this represented the first integration of relativity and quantum theory. As noted above the "reu" is in SI units equivalent to 0.1 MeV. In his final paper of the Manchester episode, following his experiments with the Coolidge X-ray tube, he made the explicit link to the equivalent voltage, as shown in Figure 15. By the time of Ellis' 1921 and 1922 papers the electron-volt unit had become firmly established. It took a little longer to permeate into the alpha-scattering and transmutation literature, which clung on for a while to the equivalent stopping distance as a measure of alpha-particle energy. In Rutherford's papers the electron-volt first appears in his writing on alpha-particles in 1927[36], predating the invention of electrostatic particle accelerators in the 1930s with which it is commonly associated.

We might also speculate on the influence which his proto QED theory had on the young Bohr's own thoughts in 1912. Certainly Bohr refers to Rutherford's 1912 paper in his own 1913 paper "On the constitutions of atoms and molecules". Further historical investigation will be required to establish the importance of any such role in the development of quantum theory. Bohr himself was clear about the importance of the nuclear discovery[37].

"Indeed, the discovery of the atomic nucleus offered a decisive influence at all stages of the ensuing development, by which it became gradually possible to achieve the incorporation of the quantum in a consistent generalisation of the classical approach".

Finally, we may ask, could all of the above have taken place without the initially contamination-free six little physics rooms of the 1912 Extension to the Physical Laboratories of Manchester? Undoubtedly this work would have been done somewhere at around this time, if not in Manchester. We may be clear that Manchester's contribution to the history of physics would not have been the same. In the words of Rutherford himself, on returning in 1931 to open a new Physics Building (formerly the Bragg Building)[38],

"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".

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Rutherford's resonance: responses to discoveries in 1911 and 1932

Professor Brian Cathcart
Kingston University London

The unveiling of the nuclear atom and the first artificial disintegration of the nucleus, events divided by 21 years, represent two high points in the career of Ernest Rutherford and yet the responses, both scholarly and among the press and public, could hardly have been more different. The former met a sullen silence while the latter prompted what today might be called a global media frenzy, complete with sensational speculation. How can we explain the contrast?

We need first to see what happened, so let us start with 1932, and the so-called splitting of the atom by John Cockcroft and Ernest Walton.

The story begins on the morning of April 14 of that year, when Walton fired up his Heath Robinson apparatus in a stripped-down lecture theatre next to the Cavendish laboratory in Cambridge, crawled across the floor (to avoid electrocution) into a box not unlike a tea chest, drew down a curtain and put his eye to a microscope. There, on a zinc sulphide screen, he beheld scintillations which left him in no doubt that he was witnessing the effects of the first controlled artificial disintegration of the atomic nucleus. With his colleague Cockcroft he had been working for this for more than three years. For Lord Rutherford, who had overseen and driven their efforts, this capped twenty years of effort – now at last he had a tool to dismantle the nucleus more or less at will, and make it reveal its secrets.

What happened next was a news blackout. For what is thought to have been the first time in his career Rutherford decreed that no one outside a circle of half a dozen Cavendish people should be told. A letter written by Walton at the time explains:

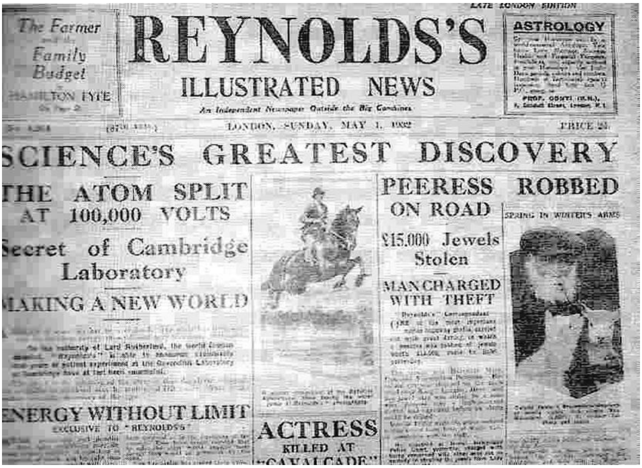
'He suggested this course because he was afraid that the news would spread like wild fire through the physics labs of the world and it was important that no lurid accounts should appear in the daily papers etc before we had published our own account of it.'

Rutherford was determined that the official account, in the form of a letter to *Nature* by the two men, should be in print and available to, or at least on its way to, the physics laboratories of the world before the press got its hands on the story. He was worried that the press would report the news in the form of 'lurid accounts'.

And there was more to the media strategy. A few days later Cockcroft wrote to J. G. Crowther, saying: *'. . . 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.'* Crowther was the science correspondent of the *Guardian*, well known and trusted at the Cavendish, where he had been an undergraduate before embarking on a pioneering career in publishing and journalism. When James Chadwick had announced the discovery of the neutron in Cambridge in February Crowther had been the only journalist in the audience and his subsequent report for the *Guardian* was a model of its kind. The plan, clearly, was to repeat that success.

A modern PR consultant might recommend just such an approach. First keep the story under your hat until you are ready to tell it in precisely the way you choose, and then feed it to a friendly, informed reporter who can be relied upon to get it right, and whose article will set the tone for subsequent journalism. Alas, this was one of those cases where the best-laid plans gang aglay. They held the story back for two whole weeks, and on the evening of Thursday 28 April, with the letter due to appear in *Nature* on the Saturday morning, they made the announcement at a gathering at the Royal Society, where it was greeted with applause and appreciation. Then things started to go wrong. First, Crowther was in Copenhagen, by a nice irony following up the discovery of the neutron at a symposium at Bohr's institute, so the friendly, competent journalist was out of reach.

How *Reynolds's Illustrated News* got wind of the story is not known, though Cockcroft suspected someone from Bristol University who had presumably attended the Royal Society event. A mid-market Sunday, *Reynolds's* had no track record with science stories but whoever tipped it off about this story managed to get the paper excited. A draft of its report was apparently thrust in front of Rutherford at a dinner on the Saturday and he is said to have written on it: 'This information is generally correct'. If the draft bore any relation to the text published the next day, that is hard to credit.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REYNOLDS'S
ILLUSTRATED NEWS
An Independent Newspaper Outside the Big Combines

ASTROLOGY

LONDON, SUNDAY, MAY 1, 1932

SCIENCE'S GREATEST DISCOVERY

THE ATOM SPLIT
AT 100,000 VOLTS
Secret of Cambridge Laboratory
MAKING A NEW WORLD

ENERGY WITHOUT LIMIT
EXCLUSIVE TO "REYNOLDS'S"

PEERESS ROBBED
ON ROAD
£15,000 Jewels Stolen
MAN CHARGED WITH THEFT

ACTRESS
KILLED AT
"CAVALCADE"

The headline, across the top pf the front page, read: 'Science's Greatest Discovery'. The text began: 'A dream of scientists has been realised. The atom has been split, and the limitless energy thus released may transform civilisation. On the authority of Lord Rutherford, the world-famous scientist, *Reynolds's* is able to announce exclusively that years of patient experiment at the Cavendish Laboratory at Cambridge have at last been successful. The effect of splitting the atom is that the electrical power now available to mankind may be multiplied 160 times. This is the greatest scientific discovery of the age.'

Helped by this lively presentation, the story 'took off'. Even rival Sunday papers rushed to follow it up in the middle of the night, so that Walton's landlady in Cambridge, a reader of the *Sunday Express*, was able to alert her tenant to his newfound fame. Sunday in Cambridge was spent fielding phone calls from reporters and on Monday the scientists turned up at the laboratory to be greeted by the 1930s version of a media scrum.

The world was reading exactly the kind of 'lurid accounts' Rutherford had feared. The reports suggested (a) that the efforts of Cockcroft and Walton were set to make coal and oil redundant and to usher in an age of ease for humanity, (b) that the ultimate destruction of civilisation, and perhaps the planet itself, might be a step closer, and (c), in the US press, that the effect of the experiment had been to convert helium into hydrogen rather than lithium into helium. It is unthinkable today, but Rutherford simply banned all reporters and photographers not only from the lab, where they could have seen the apparatus, but also from the entire building. Grudgingly, he agreed to just one photo opportunity on the doorstep, from which a couple of stills survive. When a film crew from Movietone News turned up from London a few days later, they were sent packing.

And the story was a global one. Collections of cuttings assembled by or on behalf of both Cockcroft and Walton survive in their archives, and they contain reports sent from papers in Argentina and India, Italy and South Africa. From Ireland Walton's girlfriend and future wife, Freda, wrote that the papers were full of the local boy's great exploit. From Todmorden a relative of Cockcroft's wrote asking him to send half a proton to his aunt so that she could show it to her neighbours, who wanted to know the meaning of it all. Perhaps most striking of all was the response of the New York Times, which devoted substantial news stories to the subject on three days in the same week, culminating in a Saturday analysis article filling most of a page.


The New York Times.

THE ATOM IS GIVING UP ITS MIGHTY SECRETS

The Latest Success in Smashing the Ultimate Particle of Matter Leads Onward Toward the Solution of The Mystery of the Cosmos and the Day When Vast Stores of Energy May Be Unlocked for Man

By now a more reasoned version of the story had prevailed, so it was accepted that neither nirvana nor armageddon was at hand. That the atom had been split, however, had become extraordinarily widely known in a remarkably short space of time. And this was the month in which Amelia Earhart flew the Atlantic, in which the body of Charles Lyndbergh's child was found, and in which a president of France was assassinated. Splitting the atom held its own against some stiff competition.

Let us turn now to another of Rutherford's great achievements, and probably his greatest: the description of the atomic nucleus in Manchester in 1911. That story begins in early 1909 When Rutherford asked Ernest Marsden, a final-year undergraduate, to investigate large-angle scattering of alpha particles. Marsden found significant large-angle effects from target materials including gold, aluminium and platinum, and duly reported this to Rutherford, whose response is famous. It was, he said, 'as if you fired a fifteen-inch shell at a piece of tissue paper and it came back to hit you'. Marsden, with Hans Geiger, turned this into a paper for the Royal Society proceedings, while Rutherford set himself to working out what it meant. Again famously, he thought long and hard until in December 1910 he was able to tell his colleagues that he 'now knew what the atom looked like'. The following March he revealed his thinking to the Manchester Literary and Philosophical Society and two months later published his famous paper in the Philosophical Magazine: 'The scattering of alpha and beta particles by matter and the structure of the atom'.

Now let us look at a couple of curiosities here – dogs that did not bark. The first is that, so far as I have been able to establish, this entire episode went unrecorded by the press. Neither the Marsden-Geiger paper, nor the Manchester lecture, nor the Philosophical Magazine paper was reported as news. There were no lurid accounts and there was no huddle of reporters at the laboratory door. The second curiosity is more subtle. Besides the key scientific papers, none of the accounts of these events relied upon in the histories and biographies is contemporaneous. Rutherford's descriptions date from the 1920s and 1930s; Geiger's from 1938; Marsden's from 1948 and 1961. Besides causing some fuzziness about the details of events in 1909-11, this lacuna tells us something else about those years. Marsden, for all the pride in his results that he recalled in 1948, does not appear to have taken up his pen in 1909 and written about it in a diary or letter. Or if he did, no one thought fit to preserve it. Nor did any laboratory colleague make or preserve a personal record of historical value that has come to light. Strikingly, so far as we know nobody thought of taking a photograph of Rutherford when he delivered that landmark lecture to the Manchester society.

Compare those two great moments in Rutherford's career. In 1932 he and his subordinates make a breakthrough. Carefully, they plan a media strategy that will give them some control over the message. It falls apart, not least because the demand for information is far greater and more urgent than they expected. Word travels around the world and their exploit (described sometimes accurately and sometimes inaccurately) is established in the public mind as a heroic event, with the catchphrase 'split the atom' entering the language. In 1911, by contrast, when

Rutherford announces a fundamental new insight into the nature of matter he is ignored by the press, and if his colleagues feel excitement it is apparently not sufficient to prompt any of them to record it for posterity. In one case there was silence, in the other cacophony.

How do we explain this? First, it is worth saying that why some things are more newsworthy than others is very often a mysterious and not entirely rational matter. Even journalists routinely argue amongst themselves about such things, and the social theorist Stuart Hall has described journalistic news values as ‘one of the most opaque structures of meaning in modern society’. But this does not necessarily mean it is a barren field of inquiry, and the pursuit of an explanation here may be able to tell us something about Rutherford and his discoveries.

There are a few simple possibilities that can be addressed first. With science stories, for example, it helps gain coverage if there are dramatic images, and this factor would have been more influential in 1932 than it was in 1911, when photographic reproduction in the daily press was in its infancy. Could that be an explanation? No. The Cockcroft-Walton apparatus was certainly impressive, but thanks to Rutherford’s ban no photographs of it were available to the press until some weeks after the frenzy died down, so we can rule out visual appeal as a factor.

Could radio coverage help account for the difference? BBC radio existed in 1932 but did not in 1911, and it appears to have brought the first word of the experiment to Todmorden, where Cockcroft’s relatives learned of his triumph from the evening news bulletin. But it would be hard to make the case that the BBC drove the story. Like the rest of the news media it took its lead on the day from *Reynolds’s Illustrated*, and the rest of the print press was already on the case by then. This was not a radio story.

Is it possible that the press simply missed the 1911 story, that they didn’t know it was happening and didn’t have the chance to address it? It is possible, though the Manchester event was a relatively public one – more public for sure than the 1932 Royal Society event. The *Philosophical Magazine* article was also there for all to see, just as the *Nature* letter would be in 1932. It is true that Manchester is not the metropolis, and an event there is always less likely to have coverage than an event of equal standing in London. But it is also the case that the *Manchester Guardian* did not report the 1911 events, though they took place on its doorstep.

There may be a temptation to assume that newspapers had simply not attained the sophistication in 1911 they enjoyed in 1932. This would not be fair on the quality papers of 1911, which were more than capable of tackling and debating intellectual matters. It is probably the case however, that science was a little more likely to be reported in 1932 than in 1911, but it would be wrong to exaggerate the contrast. By 1932 J.G. Crowther was writing for the *Manchester Guardian*, but he was an occasional contributor rather than a staff reporter. Elsewhere, Ritchie Calder was at the *Daily Herald* and was interested in science, but he was junior and it was not explicitly his beat. In short, the 1932 the press can not be called science-aware, and it is telling that it was a popular Sunday paper with no science correspondent at all that broke the story.

Then there is fame. As we all know, journalists like to hang a story around the neck of somebody famous, and Rutherford was more of a celebrity in 1932 than he was in 1911. By the later date he had been elevated to the peerage, he had been president of the Royal Society, he had delivered several series of Royal Institution lectures and he was well established among the great and the good. The second paragraph of Reynolds's article acknowledged this, referring to him as 'the world famous scientist'. At the same time it is worth noting that in 1911 he was not unknown – he had won the Nobel prize for chemistry in 1908. And for a journalist he had, at the earlier date, the glamour of brilliance combined with relative youth – he was not yet 40 – in a scientific world generally peopled by greyer figures. That might have enhanced the appeal of a story in 1911.

One more possible factor is an intrinsic difference between what Rutherford revealed in 1932 and what he revealed in 1911: the former was a hypothesis and the latter an experimental result. It might be thought that a fact is more newsworthy than a speculation. But this is not how the news media work, for speculation is meat and drink to them. That Rutherford could not prove his nuclear theory beyond all doubt in 1911 is very unlikely to have played a part in the fact that he was ignored. Journalists do not apply such tests.

This issue of hypothesis versus experimental result none the less brings us closer to an explanation for our contrast and that explanation may be put simply: what Rutherford announced in 1911 – that redefinition of all matter – was too new to be news. An astute, informed journalist might well have presented this as a dramatic story, telling readers that this brilliant New Zealander, a professor at a leading university and a winner of the Nobel prize, was suggesting that the houses they lived in, the chairs they were sitting on, the teacups from which they were drinking their morning cuppas as they read, were almost entirely made of . . . nothing. A good editor would surely have jumped at such a story.

But it was never written, not because it was too outlandish (editors like it when professors say outlandish things) but because it came from nowhere.

It was too new even for scientists. Rutherford's biographers have pointed out that the *Philosophical Magazine* article met a reception around the world that can only be described as muted. Even in the Manchester lab there seems to have been a failure to grasp or acknowledge the momentousness of the event. A couple of years passed before the idea found any real echo in the scientific community, and then it was two of Rutherford's own protégés – Moseley and Bohr – who began the process of confirming and elaborating his ideas.

What made the difference in 1932 – which is interesting for the understanding of how journalism works – was that by then the journalists and the public were prepared for the story Rutherford had to tell. And so was the international scientific community, which very swiftly repeated Cockcroft and Walton's results. Partly this was Rutherford's own work, both through his further discoveries over the years since 1911 and his public communication of the science in lectures and articles. Partly too there was probably a general stretching of the public imagination about science associated with the acceptance of Einstein's theories.

Two works in particular seem to have contributed to this change. The first is Frederick Soddy's 1912 book, *The Interpretation of Radium*. Look at some short passages from that book:

'Transmutation of the elements carries with it the power to unlock the internal energy of matter'.
'it can scarcely be doubted that one day we shall come to break down and build up elements in the laboratory as we now break down and build up compounds, and the pulses of the world will then throb with a new source of strength'.
'A race which could transmute matter would have little need to earn its bread by the sweat of its brow.'
'A £1 bottle of uranium oxide contains the energy of at least 160 tons of coal... the energy in a ton of uranium contains enough energy to light London for a year.'

Compare these with the language used in that *Reynolds's* scoop:

'A dream of scientists has been realised. The atom has been split, and the limitless energy thus released may transform civilisation.'
'The effect of splitting the atom is that the electrical power now available to mankind may be multiplied 160 times.'
'Science, remorseless in pursuit of truth, has brought into being a new factor which will dominate human affairs.'

It is surely likely that the writer of that news report had read or was aware of Soddy’s book. Soddy’s ideas had been echoed many times in literature since 1912, not least in H.G. Wells’s *The World Set Free*, which combined talk of a world of limitless power supply with concern over the destructive potential of atomic energy. And this destructive risk is also reflected in the 1932 coverage: one headline that first Sunday morning read: ‘The atom split, but world still safe.’ Even more vivid is the well-known role of a play, *Wings over Europe*, by Robert Nichols and Maurice Browne, which opened in the West End four days before the news of Cockcroft and Walton’s achievement broke. It is the story of a physicist who gains control of the energy in the atom and ends up holding the world to ransom. This power over matter, he says, is the power of a god. He can turn metal to rubber and, with a bomb the size of a sugar lump, create a crater as big as Vesuvius. ‘At one o’clock tomorrow,’ he warns, ‘England ends.’

*

On one level this examination of the contrast between 1911 and 1932 merely confirms something that every student of Rutherford knew: his nuclear atom was, to adopt the popular phrase, far ahead of its time. Relying on the very first tell-tale experimental results (Marsden’s), which happened to be from his own laboratory, he painted an entirely new picture of the atom. It was speculative, and that he was right about the nucleus could not be confirmed or accepted until a great deal more thinking and experimenting had been done. No one anywhere was ready for it.

The 1932 experience shows us something entirely different: a seed falling into ground that is well prepared. The international scientific community, by then much larger, was certainly ready. But journalists and their readers were also ready in 1932, thanks to years of increasing familiarity with the idea of atoms and thanks to the work of Soddy, Wells and many others. This does not make 1911 any less of a journalistic failure: there was undoubtedly a very good news story that could have been told and it was not told. But it helps explain the failure. No one in 1911, not even Rutherford and his colleagues, was alert to the possibility that the nuclear atom might be news, and more interestingly it seems likely that even if they had been alert, the soil was not prepared: the public probably lacked the familiarity and the knowledge to read and process such a story. For all that is said and written about journalistic news having to be new, journalism can sometimes be incapable of coping with something that comes out of the blue as Rutherford’s nuclear atom did.

The Apparatus used for Discovering the Neutron

Geoffrey Constable

Introduction

The discovery of the neutron in 1932 by Dr James Chadwick is one of the most famous experiments in physics. The science involved is uncontroversial, and is assumed to be well known to the reader.

Contemporary scientific papers give a description of Chadwick's apparatus that is sufficient for scientific purposes but there are gaps in what is known about the hardware . Beyond the published papers, there are few formal records or drawings in the public domain. None of the apparatus has survived and the exhibition in the Cavendish Laboratory relies upon a replica of Chadwick's source chamber, omitting the rest of what was a fairly extensive system.

The object of this paper is to fill in some of these gaps, describe the difficulties in making this apparatus work as intended, and explain how and by whom such difficulties were overcome.

Those Involved

The story is complicated and involves several personalities. A review of fig 1 – a photograph of the Cavendish team in 1931 – may help to put names to faces.

To the right of Professor Sir J J Thomson in the front row – not directly involved in this story but a scientist too famous to be ignored – is Professor Lord Rutherford, who certainly is involved. Moving one to the right is F W Aston whose mass spectrograph work in measuring the atomic weights of various isotopes was essential for Chadwick's discovery and, next, is Dr Chadwick himself.

At the extreme left of the front row is Dr Wynn-Williams, a brilliant young scientist with a particular talent for instrumentation, whose oscillograph was part of Chadwick's apparatus.

In the second row, just behind Chadwick, is Dr Feather whose assistance in obtaining a strong polonium source and undertaking cloud chamber experiments were important.

Fig 1

In the third row, four from the extreme right, is Jack Constable, a research student supervised by Chadwick and almost at the end of his third and final year. (Jack later became my Father). Two from the extreme right in the fourth row is Mr H C Webster whose experiments yielded part of the evidence for the neutron. At the extreme right of the second row is Miss Marie Sparshott, another research student but in her second year, i.e. one year behind Jack. Later, married to Jack, she became my Mother. Jack died in February 1939 but Marie had a long life and died, aged 102, in April 2010.

Source Material

The main sources, sufficient to outline this story, are as follows.

1) November 1930:

Royal Society paper entitled 'Artificial Disintegration by α Particle', authors Chadwick, Constable and Pollard. (Ernest Pollard was another research student, one year ahead of Jack and a great friend). This paper, submitted November 1930 and published in Feb 1931, describes a means of exposing various light element targets to α particles and explains how, through the use of an innovative electrical 'valve counter', the protons thereby emitted were counted, their range measured, and their energies calculated. The paper is significant because it includes a broad description of the apparatus used and gives important details. It is referred to subsequently as 'The 1930 paper'.

2) Jan1932:

Proceedings Academie Des Sciences – Séance du 18 Janvier 1932 'Emission de protons de grand vitesse par les substances hydrogénées sous l'influence des rayons γ tres penetrants,' Irene Curie & F Joliot. An experiment was reported in which beryllium was exposed to α particles and the resulting (beryllium) radiation fell upon paraffin wax. Energetic protons resulted, assumed to arise from very high energy γ rays (ca 50 Mev) being part of the beryllium radiation.

3) Feb 1932:

On receiving this news, Chadwick consulted Rutherford and both thought the γ radiation explanation was improbable. Chadwick very rapidly conducted a series of experiments that indicated the effect might be caused by the existence of neutrons. He immediately wrote a letter to the journal 'Nature' entitled 'The possible existence of a neutron' – referred to subsequently as 'The Letter to Nature'.

4) May 1932:

Chadwick's paper, submitted to the Royal Society, entitled 'The Existence of a Neutron', wherein he described a series of experiments that refuted the γ radiation proposal and showed that the existence of an uncharged particle of mass very similar to that of a proton fitted the facts much better. The paper included a brief description of the source and ionisation chambers of the apparatus, and the recording device, but for information concerning the 'valve counter' the reader was referred to the 1930 paper, with the statement that the apparatus in this regard was unchanged. This later paper is subsequently referred to as the '1932 paper'.

5) December 1935:

Chadwick's Nobel Address 'The Neutron and its Properties'.

6) Autumn 1928 – Autumn 1931:
Jack's PhD Thesis which describes the defects associated with counting particles by observing scintillations, the need for a better means and apparatus, the design brief that resulted, the difficulties encountered during design and development and how they were overcome, the fully developed apparatus as Jack left it, and the results yielded by the apparatus while Jack was working at the Cavendish. This document is subsequently referred to as 'The Thesis'.

7) Autumn 1928 – Autumn 1931: photographs taken from Jack's album.

8) June 1931: testimonial written by Chadwick for Jack.

9) Summer 2009: statements made by Marie Constable.

This list is not comprehensive and there are other sources that are significant. However, listing them now might yield more confusion than enlightenment so they will be quoted later, as the story unfolds.

The Elements of Chadwick's Apparatus

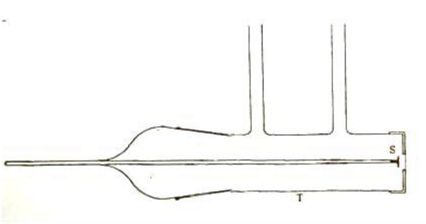
The apparatus used by Chadwick to discover the neutron can be broken down into the following four elements.

a) **Source chamber**. This chamber included a source of α particles (typically a polonium source) and provision for mounting a target to be exposed to such particles. The object was to achieve artificial disintegration in the target and to study or use the particles (normally protons) that might result.
b) **Ionisation chamber**. This chamber was close to the source chamber and received disintegration particles from the target. It had a collection plate to gather the ions produced by such particles. This plate was charged to 1,000 volts relative to the case, to make such collection swift and efficient. In some experiments, particularly those associated with Chadwick's neutron work, radiation from the first target was passed to a second target, the particles thereby produced being received by the ionisation chamber.
c) **Amplifier**. Tiny voltage spikes from (b) above (that resulted from the production of ions) were passed to the grid of the first valve in a linear, thermionic valve, amplifier.
d) **Recording device**. The amplifier output was passed to a recording device that produced a hard copy record of the train of spikes, so that the results of the experiment could be analysed remotely and at leisure.

Comparison between the apparatus described in the 1930 paper and that described in the 1932 paper.

The Source Chambers

(a)



(b)

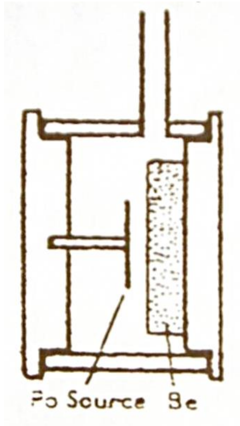
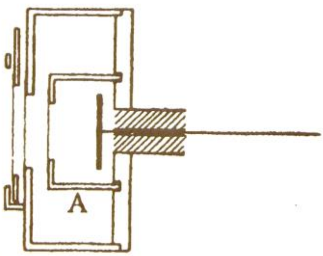


Fig. 2: (a) from 1930 paper; (b) from 1932 paper

As can be seen from Fig 2, the two source chamber diagrams taken from the respective papers are not the same. The 1930 version, in which the location of the source is marked by ‘S’, seems to be made from glass, while the 1932 version, in which the locations of the polonium source and beryllium target are clearly shown, seems to be of a metal construction. However, both accommodate source and target, and both can be evacuated, if needed.

The Ionisation Chambers.

Fig 3



From 1930

From 1932

At first sight, the two illustrations shown in Fig 3 seem to be different. However, this impression might not be so. The 1932 diagram replicates the inner case of the 1930 diagram, the outer shell of which is a screen intended (amongst other things) to isolate the chamber from external electronic noise. Thus the 1932 diagram may be merely a simplified version of the 1930 diagram and the two chambers may, in fact, be similar.

The amplifiers

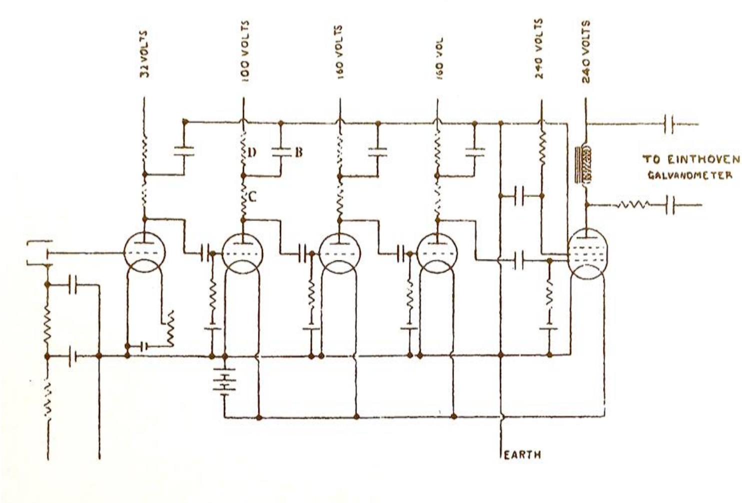


Fig 4

The 1932 paper does not include a circuit diagram of the amplifier and Fig 4 has been taken from the 1930 paper. This diagram reveals a simple, five stage, linear amplifier of (as judged by later standards) primitive design. However, such amplifying methods were commonplace at that time and could be found in most radios (wirelesses). An input from the ionisation chamber (on the left) is amplified and then passed to a recording device (Einthoven Galvanometer) - on the right.

There are some features to be noted.

- The diagram omits any component values. Thus, as indicated by the 1932 paper, the circuits for the 1930 and 1932 amplifiers may have been identical but, through refinement and development, the component values may have changed (evidence quoted later indicates that this was so).

- The components B, C, &D form a filter, repeated in the anodes of all five valves, the purpose of which was to eliminate unwanted signal feedback from one stage to another through the high tension (HT) rail.
- The steady-state voltages of the grids of the final four valves are controlled through the use of grid bias batteries. Separate batteries are used in order to eliminate unwanted stage-to-stage feedback that might otherwise take place through a single battery.
- The HT voltages for the five valves are not identical and are unusually low. From left to right they are: 32, 100, 160, 160, and 240 volts.
- The grid of the first valve is not connected to the rest of the circuit, merely to the output of the ionisation chamber and, therefore, 'floats'.
- The heater coil of the first valve emitter is powered by a separate battery - the other four valves have a common heater battery- the voltage of which as fed to the coil can be adjusted by a potentiometer.

The recording devices.

Early experiments with the 1930 apparatus did not use a recording device. Instead, the output from the amplifier was fed to headphones so that the experimenter(s) could count clicks. Fig 5 below shows Jack and Ernest thus occupied.

Fig 5

Later experiments made use of an Einthoven String Galvanometer – see Fig 6 below. This device had a slender filament (probably glass), rendered conducting by a silver coating, and located between the poles of a powerful electromagnet. A single electrical pulse caused the filament to 'twitch' and an image of the twitch was projected optically on to a motorised strip of bromide paper which, when suitably developed, yielded a recording of the sequence of twitches (referred to in the literature as 'deflections').

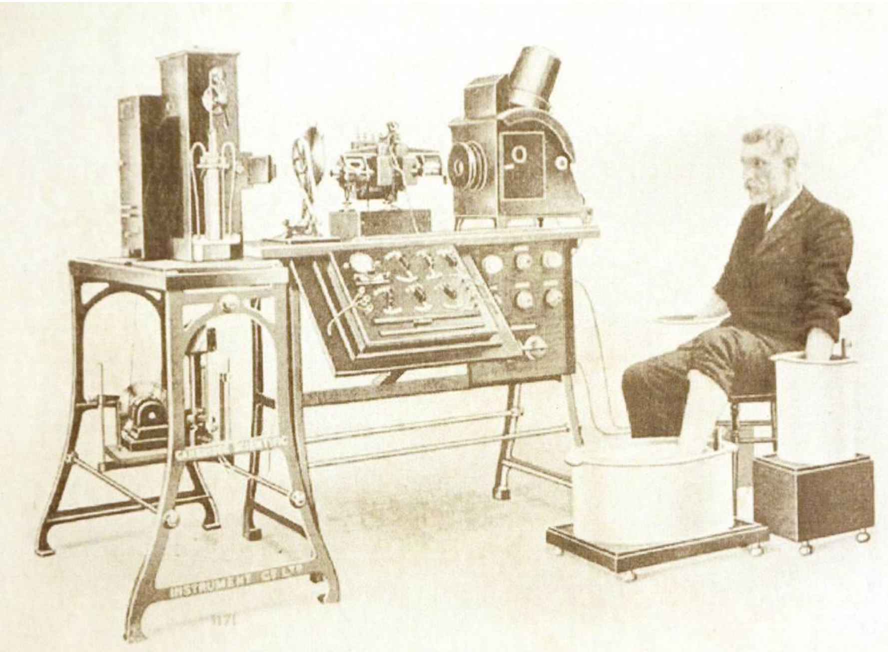


Fig 6

This galvanometer was much used medically for producing early forms of electro-cardiograms, which it did quite well. The gentleman with the apprehensive expression and the rolled-up trouser leg is the patient. His arm and leg are immersed in buckets of brine in order to achieve good electrical contact.

The 1932 paper states that the recording device was an oscillograph. Indeed, such is indicated in Fig 3 showing the '32 ionisation chamber. An oscillograph was a moving iron/mirror device, a forerunner of the (now) well-known oscilloscope. As invented by Duddell, it had a resonance at ca1KHz and a linear bandwidth of some 500Hz – inadequate for the task in hand.

However, a variant oscillograph was invented by Wynn-Williams (which operated in a manner similar to that of a conventional loud speaker) and, with a resonance at ca 3KHz, had a useful bandwidth of at least 1KHz. This performance was just about OK for Chadwick's purposes and the 1932 paper is clear that it is the Wynn-Williams recording device that was used.

Sample Recordings

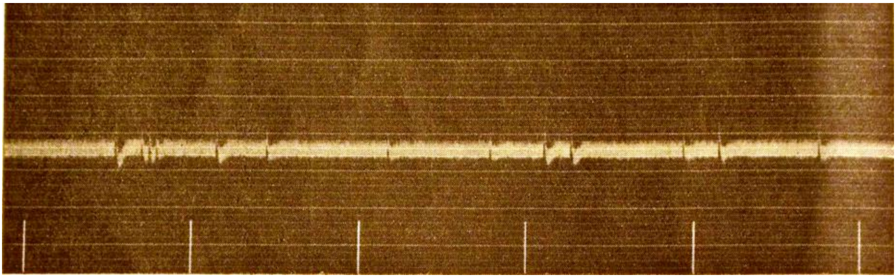


Fig 7

Fig 7 illustrates the type of recording produced by the Einthoven String Galvanometer for the experiments described in the 1930 paper. The twitches are clearly visible and can be counted. Although some are noticeably larger than others, it is doubted whether comparisons of height (i.e. indications related to the numbers of ions created by each particle) could have been other than crude. With respect to the experiments conducted, therefore, this record was restricted to providing a means of counting deflections.

According to Jack's thesis, the height of the spikes caused by protons entering the ionisation chamber varied from 10 – 100 μV. At a guess, one of the stronger twitches illustrated might correspond to, say, a spike of 80 μV. On comparing the height of this twitch to the scale of the noise shown by the trace, it seems unlikely that spikes of less than, say, 20 – 30 μV would have been detectable. Consequently some lower-level spikes might not have been counted.

Fig 8 shows the type of recording produced by the Oscillograph when coupled to the fully developed apparatus as described in the Thesis. Immediately it is obvious that the recorded spikes vary considerably in amplitude and can be used both for counting events and for assessing particle energies and, thus, the numbers of ions created.

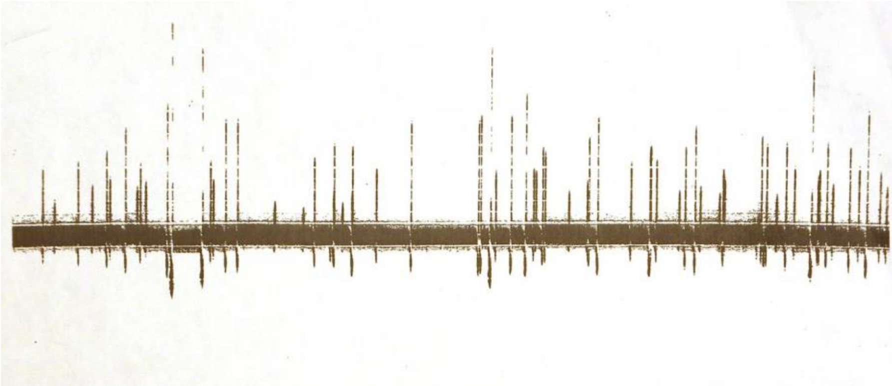


Fig 8

Moreover, the signal-to-noise ratio has been much improved. If, again, it is guessed that one of the higher spikes indicates a pulse of 80μV then, assuming that the datum for any spike is at the mid-point of the noise, simple scaling indicates that any pulse of more than, say, 4 – 5 μV should have been discernible. This considerable improvement in signal-to-noise ratio suggests that very few, if any, spikes would have been missed.

First Set of Conclusions

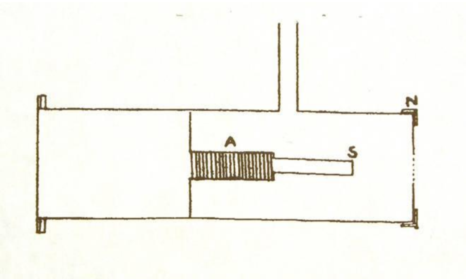
A comparison between the 1930 and 1932 apparatus descriptions indicates

- The source chambers are different.
- The ionisation chambers are similar.
- Amplifier circuit diagrams are similar (but the 1932 amplifier was probably more developed).
- Recording devices are different.
- Performance of 1932 apparatus superior to that of 1930 apparatus.

It is concluded that the 1930 apparatus may have been a forerunner, but is not exactly that used by Chadwick for discovering the Neutron.

Comparison between the apparatus described in the Thesis and that in the 1932 paper.

The Source Chambers



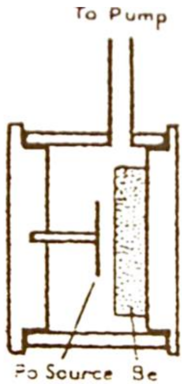


Fig 9 comparing the Thesis Source Chamber (above) with the 1932 chamber (right).

The Thesis chamber has some interesting features.
The threaded shaft A enables the distance between the source and target to be adjusted. The flanged nut N can be unscrewed to gain access to the source and target. A gas-tight seal is achieved through the use of a rubber washer. Although the two diagrams appear different, the functions seem similar. Hence it is assumed that the 1932 diagram is schematic only and that the chambers were, in fact, similar – an assumption supported by evidence quoted later.

The Ionisation Chambers

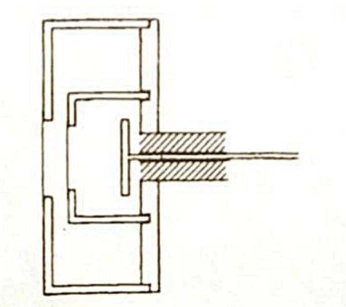


Fig 10 Thesis chamber (left), 1932 chamber (above)

It seems very likely that the two chambers were similar or identical, the external screen again being omitted from the 1932 diagram. This conclusion is confirmed by evidence quoted later. A significant detail is that sealing wax was used to insulate the collecting plate from the case.

The Amplifier

The circuit diagram included in the Thesis is the same as that included in the 1930 paper and, hence, according to Chadwick's 1932 statement, is also the same as the 1932 version. However, at the time of writing the Thesis (late 1931), Jack's development of the amplifier had been completed so, in all probability, the Thesis amplifier and the 1932 amplifier were one and the same.

The Recording Devices.

Both the Thesis and 1932 paper confirm that the recording device used was the oscillograph developed by Wynn-Williams.

Differential Counting

The Thesis describes this technique in detail, particularly its use in experiments where the object was to measure the different ranges (i.e. energy levels) of various groups of protons as emitted when a single element target was exposed to α particles.

An emitted proton does not create ions at a constant rate throughout its entire range. As the proton slows, so the rate of ion creation increases and a spike with the highest peak (as passed by the ionisation chamber to the amplifier) will arise from a proton in the chamber at the extreme end of its range. (A spike with a lower peak indicates a proton just passing through, not at the end of its range.)

If a histogram is plotted showing the number of high-peak protons versus range (ignoring protons that produce lower peaks), a series of maxima may emerge, each maximum identifying the maximum range of any one group of protons. The resolution between different ranges that could be achieved in this manner exceeded that produced by plotting a conventional histogram showing the numbers of all spikes, large and small, as a function of range. Consequently, differential counting yielded a significant improvement in measurement technique.

However, this technique required an apparatus that enabled higher spikes to be differentiated from all other spikes – which could be achieved easily with the Thesis/1932 recordings but not with the 1930 recordings.

Fluorine

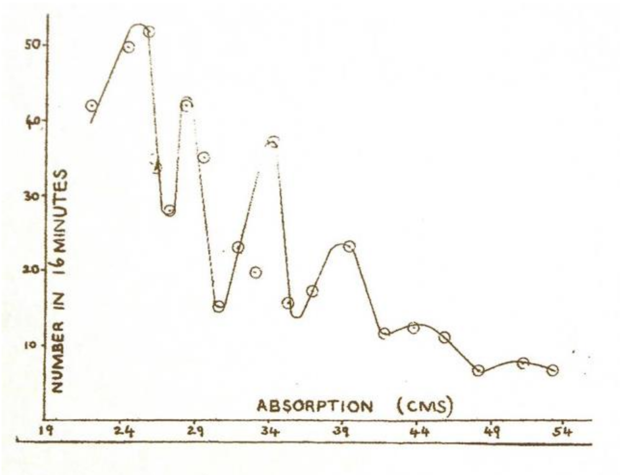


Fig 11 Absorption curve for protons from fluorine

Fig 11 shows the results achieved by Chadwick and Constable when their apparatus was used to examine the different energy levels of the protons emitted by fluorine when exposed to α particles. Six peaks are clearly visible. (A previous attempt to find such peaks using the 1930 apparatus was a failure, no separate peaks being revealed – an indication of the degree to which the apparatus had been developed in the intervening period and its performance improved).

There are two particular points of interest. First, it is obvious that differential counting has been used because, as the successive maxima reveal, the numbers of protons counted alternately rise and fall. If all protons had been counted, both fast and slow, it would have been impossible (apart from experimental error) for numbers to rise as range increased.

Second, the ‘y’ axis of the graph records the ‘number (of protons) in 16 minutes’. At higher ranges, this number is roughly one per minute. If a low rate such as this could not have been measured – for example, due to radioactive contamination in the ionisation chamber producing unwanted spikes – these higher range maxima would have been missed.

1931 Royal Society paper (Chadwick and Constable)

This jointly authored paper, received December 1931, was entitled 'Artificial disintegration by α particle – Part 2'. Recent experiments (also recorded in the Thesis) on identifying the different energy levels of protons emitted from fluorine and then aluminium are recorded in full.

This paper also includes brief descriptions of the source and ionisation chambers. The diagrams are interesting in that the source chamber diagram strongly resembles that in the Thesis and the ionisation chamber diagrams appear identical. As the submission date of this paper is about one month before Chadwick's neutron work commenced - and the letter to Nature was written – it is likely that, during this brief interval (including Christmas), the apparatus remained unchanged. In other words, the chambers used by Chadwick for his neutron work were probably exactly those described in the 1931 paper and in Jack's Thesis.

Furthermore, the text reads as follows, 'We have been able, <u>by using new materials for the ionisation chamber, and by assembling it outside the laboratory</u>, to reduce the natural effect (i.e. the number of unwanted spikes generated by contamination and other causes such as γ rays) of the ionisation chamber by about five. The chamber gave…..about 20 deflections per hour.' The full significance of these quotes, and the conclusion above, will be apparent later.

Second set of Conclusions

- The apparatus described in the thesis and in the 1932 paper are, essentially, one and the same.
- The technique (e.g. differential counting) of using this apparatus could vary from that used with the 1930 apparatus.

So, who did what?

- The concept?
- The design?
- The construction?
- The development?

These questions are addressed by examining evidence from the sources itemised thus far and from other sources as well.

Quotes from the Thesis

'Greinacher (1927) broke away from earlier methods….. He used a small ionisation chamber in which ions from an entering particle were collected upon a low capacity electrode connected to the grid of a low capacity valve'.

'…….Meanwhile, the author, working with Dr Chadwick and E C Pollard, had constructed and developed a valve counter.'

Greinacher was an Austrian physicist in the University of Vienna. There is general agreement that the concept of valve amplification in this context came from him.

Jack's statement, without reservation or qualification, concerning his 'construction' and 'development' of a valve counter is corroborated in several ways as will be described.

The Thesis also contains a set of 'Design Desiderata' for the valve counter apparatus which, somewhat simplified, can be quoted as follows.

- Count over as large an area as possible, minimum 1 sq cm.
- Count protons in the presence of strong γ radiation.
- Self-recording.
- Deflections to indicate particle energy.
- 100% efficient in counting particles.
- Robust, reliable, work for long periods with little attention.

The first requirement is needed because too small an aperture would restrict the number of protons entering the chamber which, if the source were weak, would give numbers too small to measure.

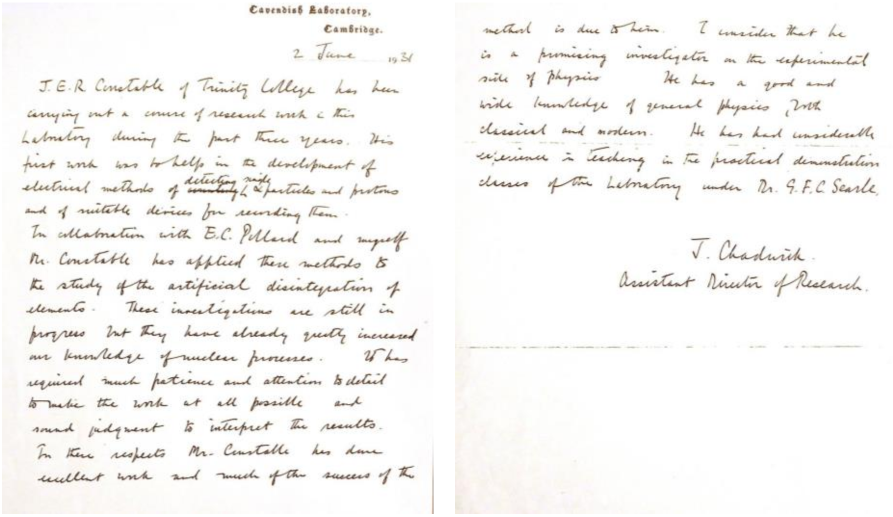
The second was important because Jack could foresee that future workers might wish to use α particles of higher energy than those from polonium. Such particles are emitted by Radium C and Thorium C but are accompanied by hard γ rays.

The third arose from the need for differential counting, where it is necessary to count the higher spikes and ignore others.

The needs for the other requirements are probably self-evident.

The inclusion of these desiderata in the Thesis is an indication that Jack had some involvement with the design of the apparatus, as did other members of the team.

Testimonial written by Chadwick for Jack.



Cavendish Laboratory,
Cambridge.
2 June 1934

J. E. R. Constable of Trinity College has been carrying out a course of research work in this Laboratory during the past three years. His first work was to help in the development of electrical methods of ~~counting~~ detecting single α particles and protons and of suitable devices for recording them. In collaboration with E. C. Pollard and myself Mr. Constable has applied these methods to the study of the artificial disintegration of elements. These investigations are still in progress but they have already greatly increased our knowledge of nuclear processes. It has required much patience and attention to detail to make the work at all possible and sound judgment to interpret the results. In these respects Mr. Constable has done excellent work and much of the success of the method is due to him. I consider that he is a promising investigator on the experimental side of Physics. He has a good and wide knowledge of general physics, both classical and modern. He has had considerable experience in teaching in the practical demonstration classes of the Laboratory under Dr. G. F. C. Searle.

J. Chadwick.
Assistant Director of Research.

Fig 12

In Chadwick's own hand, this testimonial is illustrated by Fig 12. Two extracts are particularly relevant:

'His first work was to help in the development of electrical methods of detecting single particles and protons and of suitable devices for recording them.' and

'It has required much patience and attention to detail to make the work at all possible and sound judgement to interpret the results. In these respects, Mr Constable has done excellent work and much of the success of the method is due to him.'

Difficulties encountered in making the apparatus work as planned

Stability Problems. As explained earlier, the input to the amplifier varied from 10 – 100 µV. Assuming the desired output was several volts, the gain needed was about one million. Any high gain, low input amplifier is likely to encounter stability problems and, to judge from Jack's later comments in the Thesis, this one certainly did. Unwanted feedback paths had to be eliminated and stable performance was achieved through the following measures.

- The previously described filters in the valve anode circuits
- The previously described multiplicity of valve grid bias batteries
- Very careful screening around each amplifier stage
- Comprehensive screening around the complete amplifier and its connection to the ionisation chamber.

Signal to noise ratio

Because the input spikes were so very small, the need to reduce electronic noise from every source was paramount. Otherwise, important information would be buried in the noise and erroneous experimental results would result. To this end, the following measures were taken.

- Valves of that era were microphonic – some highly so. Thus, any form of mechanical vibration or shock would cause movement of the elements within the valve and unwanted variations in the valve output. When magnified by later stages in the amplifier, error signals of significant scale could result. To counter this effect, all valves were mounted on anti-vibration, sponge rubber mounts.
- Furthermore, the whole amplifier was mounted on a massive stone pillar which, as the experiments were conducted in a basement, would have been reasonably stable.
- The screening around the whole amplifier served a second purpose in that it prevented extraneous electronic noise from entering the amplifier enclosure and creating false signals.
- Electronic components, typically resistors, produce what is known as Johnson Noise. The scale of the noise is related to the size of the resistor and its absolute temperature. As calculated by Wynn-Williams in one of his later papers, a resistor of one million Ohms at room temperature might typically generate 30μV of noise, well exceeding the smallest spikes to be counted. For this reason, the values of the electronic components were carefully optimised in order to keep the Johnson Noise to a minimum. As implied in the Thesis, such optimisation continued well into the development phase and often relied upon experimentation in addition to calculation. (The value of the anode resistor of the first valve was particularly important in this regard and Jack records that he spent some time conducting experiments to optimise its value).
- Shot Noise is another form of electronic noise, typically generated at that time by the varying flow of emitted electrons through a valve. (Jack comments that another cause of such noise arose from the imperfect evacuation of his valves and the consequent noise caused by the

generation of ions from residual gasses). It was found that Shot Noise from both effects could be reduced significantly by the previously noted reduction of HT rail voltages. In fact the first four valves were under-run in this regard by some 30% - such a reduction appearing to optimise the signal-to-noise ratio.

- Obviously, the noise generated by the first stage of the amplifier was more concerning than that caused by subsequent stages. For this reason (and others) this valve was selected with great care, the Mullard DEV valve being the final choice. DEV is the abbreviation for ‘dull emitter valve’ and indicates that the emitter is made from ‘thoriated tungsten’ which emits electrons far more readily than plain tungsten, and consequently can be recommended by the manufacturer to be run at a lower temperature – hence the DEV title. This feature significantly reduces both the Shot Noise generated within the valve and the Johnson Noise from the heater resistance. Also, it was decided to under-run the heater coil – recall the potentiometer circuit etc. noted previously – which further boosted the signal-to-noise ratio through extra reduction in the valve Shot Noise and heater Johnson Noise.

All-in-all, barrel-scraping the signal-to-noise ratio down to an acceptable level was probably the most testing difficulty to be overcome, and Chadwick’s reference to ‘attention to detail’ is probably most aptly applied to this aspect of the development of the apparatus.

System response time.

The Thesis states that the width of a typical spike was about 1 millisecond. In order to obtain discrimination between adjacent spikes – and to avoid other problems such as loss of definition and rounding, an overall system bandwidth of about 1 KHz was needed. The following measures sufficed for this purpose.

- The grid of the first valve needed to have the lowest capacitance possible. Very fortunately, the Mullard DEV valve, a good choice for reasons already given, proved to have the lowest input capacitance of any valve tested by Jack. The lag introduced by the product of this capacitance and the floating grid leakage resistance proved to be less than 1 millisecond and so was acceptable.

- It was then necessary to balance this lag with other lags in the system, principally with any lags in the recording device. As described earlier, the Wynn-Williams oscillograph had an appropriate bandwidth and was, therefore, selected. (Jack knew about electronic oscilloscopes and forecast that these would ultimately be a better choice, having a much superior bandwidth. However, he doubted whether existing versions produced a spot of sufficient brightness to produce a bromide paper recording and so stuck with the oscillograph as being good enough – which it was.)

The γ ray problem.

Gamma rays knock out electrons on striking parts of the ionisation chamber. Each electron gives rise to, say, 100 pairs of ions. In contrast, each proton might yield, say, 10,000 ion pairs. So, 100 electrons could mask one proton. The problem was addressed thus:

- The Gamma ray effects were reduced greatly by making the ionisation chamber from thin film aluminium sheet, plus introducing extensive lead shielding around the source chamber. (Presumably, it is more difficult to knock out electrons from aluminium than from most other metals – hence the benefit gained).
- Further, the time window in which gamma rays can interfere depends upon the system response time which, in this case, was reasonably brisk– the faster the response, the slimmer the spike, and the less the chance of interference.

Robust?

In the 1932 paper, Chadwick remarks: *'I wish to express my thanks to Mr H Nutt for his help in carrying out the experiments.'*

In Fig 13 we see Mr Nutt facing an enormous pile of unread bromide paper recordings. This is evidence of everyone's confidence in this lab. assistant's ability in interpreting such recordings – a role in which he had built up special skills - but also shows that the apparatus could produce such recordings in large quantities.

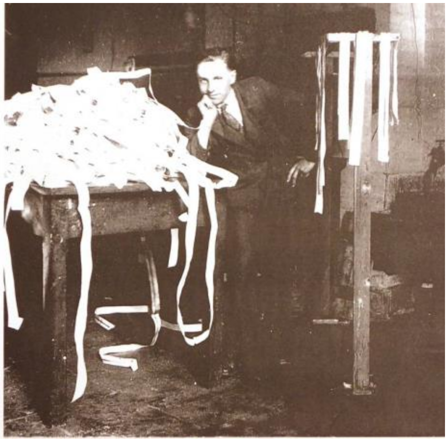


Fig 13

Construction of the apparatus.

Jack states in the Thesis, *'There was very heavy contamination in the laboratory and, hence, risk of spurious deflections caused by contaminated apparatus'*. Several similar comments can be found in the Thesis.

When asked about this in 2009, Marie Constable made the following statements.
'To eliminate contamination, Jack made the apparatus at his parental home. There were two versions of the amplifier, one a prototype.'

This home was a small semi. in Welling, Kent. Its garden shed had a workbench, a set of good quality hand tools, and a small lathe. That is where the apparatus for discovering the neutron was made. The only firm evidence on this matter comes from my mother, but her memories of the Cavendish days were vivid, she was there at that time, and can be assumed to know about Jack's activities.

There are some pointers to suggest that Marie's account is accurate.

- Such an account could explain why the lack of drawings or similar records in the public domain.
- Marie's statements provide an explanation as to how Chadwick gained access to an ionisation chamber with such a remarkably low 'natural effect'. The radioactive contamination at Welling, Kent was certainly much lower at that time than at Free School Lane, Cambridge.
- An explanation is also provided for the remark in Chadwick's 1931 paper that the ionisation chamber with the very low natural effect of 20 deflections per hour was 'assembled outside the laboratory'. (Incidentally, the reference there to the use of new materials suggests that this chamber was the one made from 'thin aluminium sheet', the better to avoid interference from gamma rays.)

- Finally, the photograph of the prototype amplifier shown in Fig 14 shows apparatus that very much looks as though it was 'made at home'.

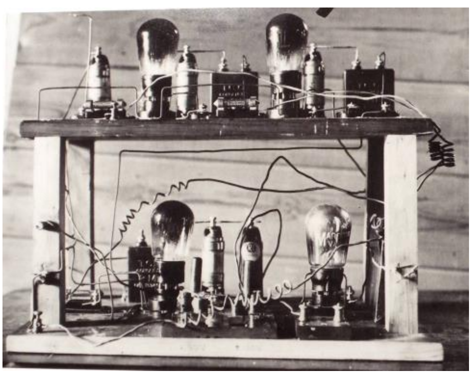


Fig 14

The electrical hardware.

This photograph (Fig 14) was discovered in Jack's album above the caption 'Our First'. It is obviously a prototype. There are only four valves, the first being at that time a pre-amplifier, located close to the ionisation chamber. No anti-vibration mountings can be seen nor is there any evidence of screening. It is believed that it worked sufficiently well for headphone clicks to be counted but later work would have needed a successor with all refinements.

Unfortunately there is no photograph of such a successor. However, a photograph might have told us little, due to the screening that enclosed everything.

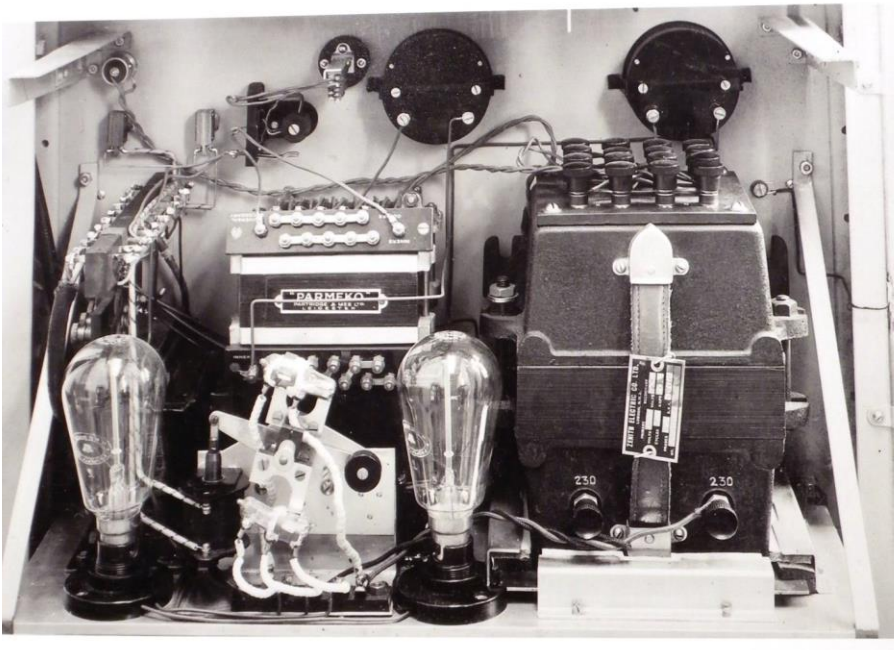


Fig 15

However, Fig 15, which was adjacent to Fig 14 in the album (but uncaptioned), shows the power supply for the prototype. Evidently, the full apparatus, even at this stage and ignoring a stone pillar, was a fairly large piece of kit.

The 1932 Ionisation Chamber

Chadwick's 1931 paper, submitted in December of that year and referred to earlier, describes the ionisation chamber as having a natural effect of 20 deflections per hour. In contrast, Chadwick states in the 1932 paper, 'This chamber had a very low natural effect giving on the average about seven deflections per hour'. Could these statements relate to the same chamber?

It all depends. If the former report were drafted by Jack as co-author, who also made the measurement, and the latter by Chadwick, who then made a different measurement, it is possible that the measurements were different although made with the same chamber. For example, deflections can come from different sources, some of which can vary in strength. If, for example, the contamination source was a small amount of polonium, the rate of deflections would decline significantly over a few weeks due to the short half-life of all polonium isotopes. Moreover, both rates are unusually low and deflections arrive randomly – two different experimenters could well arrive at somewhat different results.

The 1932 paper gives some dimensions: *'...an opening of 13 mm and a depth of 15 mm'.*
The 1931 paper also gives dimensions, *'The opening was 11 mm in diameter and the depth from the opening to the collector was 12mm'*.

The depth dimensions may not be in conflict; 12mm from the opening to the collector could well accord with 15 mm from the opening, past the collector, to the back of the chamber. However, a 13 mm opening is different from one 11mm in diameter. The answer may be that this ionisation chamber was made with several front plates, each one with an opening of different size, to suit the varying needs of different experiments.

Even though the argument may be less than cast iron, it is believed, nevertheless, that both descriptions do relate to the same chamber. To suggest otherwise requires that another very low natural effect chamber was made prior to Chadwick commencing his Neutron work very early in 1932. This seems unlikely. By December 1931 Jack had left Cambridge, then Christmas and New Year celebrations had taken place, and it is doubtful whether such a chamber could have been made at short notice by anyone else.

The Contribution from Wynn-Williams.

The 1930 paper states, ‘For the experiments described here we have adopted the method of amplification by valves. This method was first successfully employed by Greinacher, and has been further developed by Ortner and Setter, and by Ward, Wynn-Williams and Cave. Certain modifications to the designs used by these workers were made for the present application.’ A reference was included for the November 1929 Royal Society paper by Wynn-Williams et al.

This paper reveals that the Wynn-Williams team responded to a suggestion by Rutherford that the concept of amplification by valves be used to measure the number of α particles emitted by a gram of radium in unit time. Apparently this constant, known as ‘Z’, had already been measured by several workers but with inconsistent results. It would be a good test of the new technology if this matter could be resolved.

An apparatus was designed and constructed. It had an ionisation chamber, a linear amplifier and an Einthoven string galvanometer, each not unlike that used by the Chadwick team, and a useful result was achieved. It is hardly surprising, therefore, that in the view of some commentators, Chadwick’s neutron success depended very largely, even entirely, upon Wynn-Williams’ electronic skills and instrumentation.

A closer examination of the facts reveals that such a view may be somewhat overstated. The task defined by Rutherford required the counting of a large flow of α particles, all approaching the end of their range and all of the same energy. Wynn-Williams reports that with his (very shallow) ionisation chamber, each particle yielded a spike of some 150μV – very different in scale from the 10μV yielded for the Chadwick team by a fast proton.

So, counting end-of-range α particles is a different kettle of fish from detecting and counting single fast protons, especially if differential counting techniques are involved. Consequently, the demands placed on the Wynn-Williams apparatus were noticeably less severe than those for the Chadwick apparatus.

For example, for this experiment Wynn-Williams did not need a DEV valve, and a Marconi V24 was sufficient for the first stage. Although he was well aware of both Shot and Johnson Noise, he had no need to make extra special provision for these due to the relatively hefty spikes he had to count. By the same token, the performance provided by the Einthoven Galvanometer was sufficiently sensitive to count α particles, but would have missed fast protons.

Perhaps the best indicator of the differing performance requirements was that the Wynn-Williams ionisation chamber had a natural effect of three deflections per minute (considered at that time to be remarkably low), not seven per hour. The Chadwick fluorine findings could not have been revealed by the Wynn-Williams apparatus – at least some of the maxima would have been obscured by unwanted deflections.

Also one apparatus was different in construction from the other. Wynn-Williams used entirely Osram/Marconi Valves while the Chadwick team preferred those from Mullard/Philips. Wynn-Williams mounted his valves upside down in their anti-vibration mounts; the reverse was so with Chadwick. Wynn-Williams' amplifier was suspended from the ceiling by four large springs; to counter mechanical vibration, the Chadwick team used a massive stone pillar. And so on.

What is being described is a typical sequence of research. Greinacher showed what might be possible. Wynn-Williams showed the method worked for counting α particles. The Chadwick team showed that much development and refinement allowed fast and slow protons to be counted and their energies measured. Finally Wynn-Williams, who (as shown in his later Royal Society paper published May 1931) had kept pace with all these developments, capped the research story by showing how thyratron valves could work as switches and be used to provide very fast electronic counters, with a diode circuit to set detection levels in order to facilitate differential counting, if needed. No more recording devices and no more bromide paper – a great advance indeed!

So, who did do what?

Concept: that the concept came from Greinacher is not disputed.

Design: the 1929 Wynn-Williams achievement gave the Chadwick team confidence concerning the method and provided a most useful 'point of departure' from which to progress. Furthermore, Wynn-Williams' Oscillograph was a vital part of the Chadwick apparatus and worked well. Thus, Wynn-Williams' contribution to Chadwick's neutron work was significant and important.

The many 'modifications' referred to by Chadwick were designed by the Chadwick, Pollard and Constable team, and there is insufficient information to say who designed precisely what. There is some evidence that Wynn-Williams did not participate to any extent in this phase; Jack in his Thesis gives a long list of those at the Cavendish with whom he had discussions or by whom ideas were provided. Wynn-Williams is not on this list.

Construction: the evidence points to the apparatus being constructed by Jack and, noting his family's 'working class - factory employment' culture and the facilities at his home, to take on such a task would have been second nature to him. It is not absolutely certain that everything was constructed in this manner, and some items (such as power supplies perhaps) wherein contamination was not too serious a problem, might have gone through the Cavendish workshop – we don't know for certain and this comment is speculation. What we do know for certain is that he was alarmed by the high levels of contamination in the laboratory and was prepared to go to great lengths to avoid contamination spoiling any of his research.

Development: Chadwick's testimonial gives strong evidence of Jack's role in this regard, particularly the observation that, 'much of the success of the method was due to him'. Although a large slice of this development was concerned with improving the performance of the amplifier and replacing the Einthoven galvanometer with the oscillograph, perhaps an equivalent contribution lay in the dramatic reduction of the 'natural effects' of ionisation chambers.

With the benefit of hindsight, given the quality of the electronic components of the day (e.g. valves), the crudeness of contemporary electronic design techniques, and the scale of the challenges faced, it is indeed surprising that the apparatus worked as well as it did. That it served Chadwick in his neutron work is a most welcome bonus.

How was the apparatus used for Chadwick's neutron work?

Chadwick's initial experiments were aimed at replicating the input from France, i.e. exposing paraffin wax to the radiation from a beryllium target which itself was under bombardment by α particles. In subsequent experiments the wax was replaced by a variety of light elements, such as nitrogen and argon in particular. Beryllium was then replaced with boron and the tests repeated.

Considerations such as the conservation of energy and momentum led Chadwick to the view that, in these circumstances, neutrons were emitted by beryllium and boron, and what was observed from the second target consisted of recoil particles after collision with a neutron. Thus, using wax, the recoil particles were protons, resulting from neutron collisions with this hydrogenous material. In other experiments, recoil atoms of nitrogen and argon were observed, again resulting from neutron collisions.

To what degree was the performance of the apparatus tested by such experiments? Recoil atoms would have produced large deflections and would have been relatively easy to observe. However recoil protons travelling swiftly (Chadwick calculates a speed of 3.3 x 10^9 cm/sec for protons knocked out of paraffin wax) would have needed the full sensitivity of the apparatus to be detected and counted.

There is a striking example, in which Chadwick describes one of his very first experiments, of how the apparatus' performance was tested to the full, but in a different way. 'When the source chamber was placed in front of the ionisation chamber (no secondary target involved at this point), the number of deflections immediately increased (above the natural effect of 7 per hour). For a distance of 3 cm between the beryllium and the counter, the number of deflections was nearly 4 per minute. Since the number of deflections remained sensibly the same when thick metal sheets, even as much as 2 cm of lead, were interposed between the source vessel and the counter, it was clear that these deflections were due to a penetrating radiation emitted from the beryllium. It will be shown later that the deflections were due to atoms of (atmospheric) nitrogen set in motion by the impact of the beryllium radiation'.

Using an ionisation chamber with a normal natural effect of, say, 3 deflections per minute would have introduced significant distortions to Chadwick's 'four per minute' observations. The availability of the seven-deflections-per-hour chamber was, in this instance, important.

It might be thought that the low rate of observed deflections – 4 per minute – was due to the weakness of Chadwick's original α particle source, but this is probably not so. Chadwick already had a much more powerful source, facilitated by Dr Feather, and derived from used medical radon tubes kindly shipped across the Atlantic by Drs Burnham and West of the Kelly Hospital, Baltimore.

Chadwick's Nobel Lecture 1935

This paper states, 'The first suggestion of a neutral particle with the properties of the neutron we now know was made by Rutherford in 1920'. Anyone who reads Rutherford's 1920 Bakerian Lecture will be struck by his lucid and cogent arguments concerning the theoretical existence of a Neutron.

Chadwick continues, 'The possibility that neutral particles might exist was not lost sight of. I, myself, made several attempts to detect them – in discharge tubes, and in artificial disintegrations produced by α particles.'

Marie Constable added the interesting comment that, ‘They (Rutherford and Chadwick) knew about the existence of the neutron, long before it was discovered’.

Yet the puzzling fact is that the word ‘Neutron’ does not occur at all in Jack’s Thesis. Even though Chadwick was in close contact as his supervisor, Jack’s extensive speculations in the Thesis about the nucleus and its structure rely entirely on what must have been the teaching at that time that a nucleus consists entirely of protons and electrons.

In the 1935 paper Chadwick also refers to work undertaken by Mr H C Webster, which showed ‘the ‘the radiation emitted by beryllium had some rather peculiar features which were very difficult to explain’. In his own Royal Society paper, ‘The artificial production of Nuclear Gamma Radiation’ 1932, Webster notes that the radiation from beryllium (under α particle bombardment) is not isotropic, more flowing ‘forwards’ than ‘backwards’ – not what one might expect from gamma radiation which, subject to some other considerations, could be expected to radiate equally in all directions. This finding later became part of the evidence compiled by Chadwick for the existence of the neutron, as such anisotropy was far more compatible with the emission of particles (neutrons in particular) than gamma rays.

Interestingly, Webster concludes, ‘My thanks are due to Professor Stratton for permission to carry out these experiments, free from radioactive contamination, at the Solar Physics Observatory, Cambridge.’

Appendix to Thesis

Jack’s Thesis has a small appendix which states, ‘Sealing wax was used as an insulator for the collecting plate of the ionisation chamber. This wax, when freshly put into position, caused a large number of positive particles to be recorded, some similar in scale to that caused by the entry of an α particle’.

This observation anticipates that of Joliot/Curie concerning particles emitted by paraffin wax by at least several months. So the stimulus that led to the discovery of the neutron was available in the Cavendish well before the French proceedings arrived early in 1932.

Jack struggled to find an explanation for this effect. Was it associated with the energy of crystallization? Unlikely, if the substance in question was sealing wax. Was it something to do with the Piezo-electric effect? Perhaps. Jack left the question unanswered and the puzzle unsolved.

Final Remarks

There is little doubt that the apparatus 'constructed and developed' by Jack is essentially that used by Chadwick to discover the Neutron.

Could Chadwick have made this discovery without this this apparatus? Possibly. Chadwick was a determined and resourceful scientist, and should not be under-estimated. Perhaps using a different apparatus - possibly one involving a Geiger Counter or another relying on Wynn-Williams latest work - would have sufficed. But what can be asserted with some confidence is that, without the apparatus constructed and developed by Jack, the neutron discovery by Chadwick would probably have taken longer.

Although the French stimulus that led to this famous discovery was anticipated by Jack's observations re sealing wax, he failed completely to perceive the implications. It took a scientist of Chadwick's outstanding ability and insight to grasp the full significance of the Joliot/Curie input and, on any reckoning, his Nobel Prize must be judged as richly deserved.

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Illustrations for figures 2 to 5 and 7 to 15 were taken from:

The proceedings of the Royal Society vol 130 1931. '*Artificial disintegration by alpha particles'* by J. Chadwick, F.R.S., J.E.R. Constable, and E.C. Pollard.

The Proceedings of the Royal Society series A 1932 vol 126. '*The Existence of a Neutron'*, by J. Chadwick F.R.S.

Ph.D thesis 1931, *'Disintegration of the nuclei of light elements produced by their interaction with alpha particles',* by J.E.R. Constable M.A.
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A Physics Heritage Tour of Manchester University

Dr. Neil Todd
University of Manchester

Background

Manchester's Scientific Legacy

Among the greats of Manchester's scientific heritage perhaps the two most outstanding figures of 18th and 19th century science are John Dalton (1766 – 1844) and James Prescott Joule (1818 – 1889). Dalton arrived in Manchester in 1790 to teach mathematics, physics and chemistry at New College, joining the Manchester Literary and Philosophical Society in 1794. In 1809 he published his most influential work "A new system of chemical philosophy" which established the modern principle of the chemical atom. Joule, Salford born, studied for a short time with Dalton at the Literary and Philosophical Society in 1834 before producing his most influential work on the mechanical equivalence of heat in 1845. He was also associated with the development of the principle of conservation of energy, work he would later develop with William Thomson (Lord Kelvin).

Figure 1. Owens College at Quay Street, 1850s

A significant event in the development of Manchester science was the establishment of Owens College in 1851, made possible by a gift of £100,000 from the wealthy industrialist John Owens. The original building housing Owens College at Quay Street still stands today. Influential early figures within Owens College included the chemist Henry Roscoe (1833 – 1915), physicist Robert Clifton and engineer Osborne Reynolds (1842 – 1912). A later important successor to Clifton was Balfour Stewart (1828 – 1887), who became the first Langworthy Professor of Physics in 1879, endowed in 1874 following a gift of £10,000 from E.R. Langworthy.

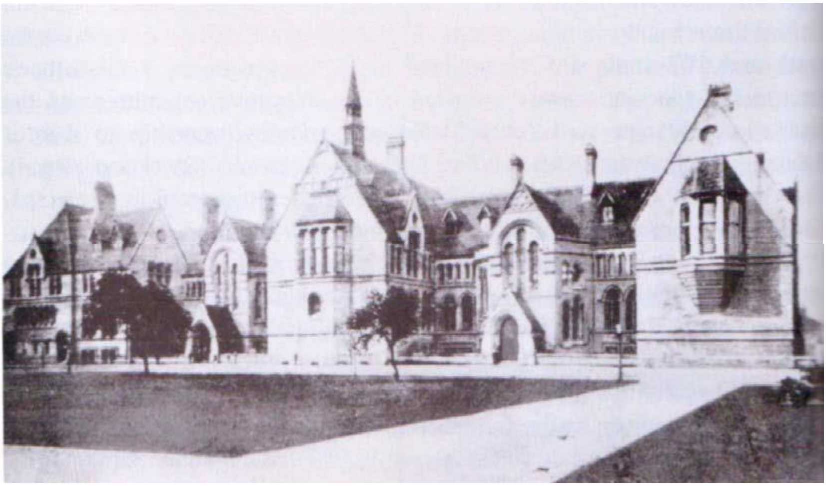


Figure 2. Architect's drawing of New Owens College 1873.

After the removal of Owens College to the present site in 1873 there was a steady development of the physical sciences and engineering under the leadership of the above scientists, as well as others including and Arthur Schuster (1851 - 1934) in physics, and Horace Lamb (1849 – 1934) in Mathematics. Schuster succeeded Stewart in 1887 to the Langworthy Chair following Stewart's untimely death. The most prominent alumni of this period are John Joseph Thomson (1856 – 1940) and Arthur Stanley Eddington (1882 – 1944), to name just two.

The New Physical Institute established by Arthur Schuster (1900)

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 1873 building. 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 equipping. 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.

Figure 3. Architect's drawing of the New Physical Laboratory, circa 1898 (from Schuster and Hutton (1906) with permission from Manchester University Press).

The official opening of the new Physical Laboratories of the University of Manchester was conducted by Lord Rayleigh in May 1900 during a conversazione to which the public were invited. 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 J.J. Thomson. There were a number of inaugural lectures that year including one by Sir Oliver Lodge. The new Physical Institute was without doubt one of the most modern and advanced in the world at that time.

Organised on four levels the new Institute was shared between Physics and Electro-technics (later to become Electrical Engineering). The basement was devoted to research, including in spectroscopy, photometry, photography and low-temperatures (now occupied by Manchester Museum). The ground floor included a large private laboratory (now called the Rutherford Room), a workshop and rooms devoted to experimentation in electricity and magnetism. The first floor 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 featured a magnificent large lecture theatre (sadly now demolished) and associated apparatus and preparation rooms. 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). 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) and an electro-chemical laboratory (now demolished).

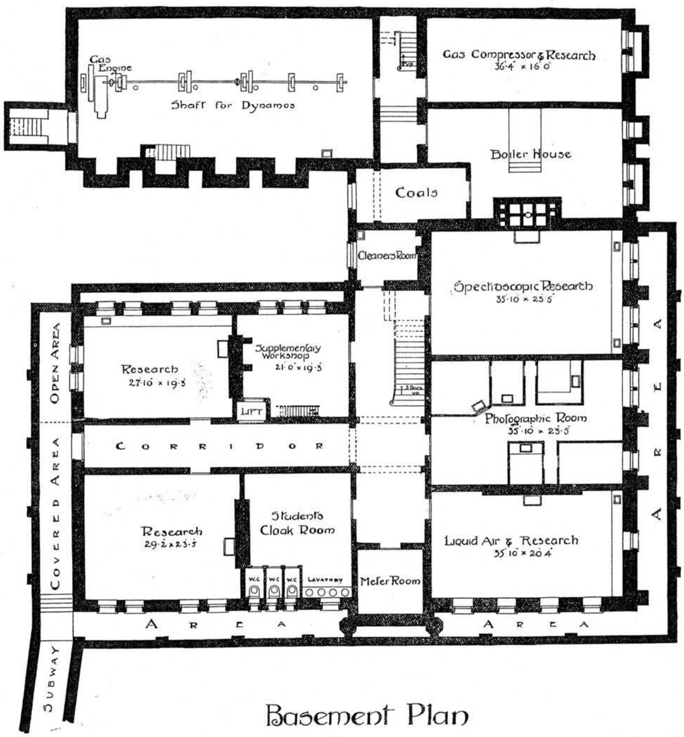


Figure 4. Plan of the basement floor of the New Physical Laboratories (from Schuster and Hutton (1906) with permission from Manchester University Press).

Ernest Rutherford at Manchester (1907 – 1919)

In 1906 Schuster was planning to retire but was successful in persuading Ernest Rutherford, then Professor of Physics at McGill University in Montreal, 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 theory of successive transformations to explain radioactivity which he put forward with the chemist Frederick Soddy, and for which he was awarded the Nobel Prize in chemistry in 1908 (see blue plaque on entrance to Coupland Street).

Rutherford soon set about moulding Schuster's laboratory for his own purpose. After obtaining in early 1908 a loan of a large quantity of radium from Austria, he was able to initiate a series of experiments which he had been planning. As was by then standard practice, 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. This was after hard lessons learned at Montreal where radium was kept in the basement resulting in the entire laboratory becoming contaminated from the emanation diffusing through the building.

Schuster's transit room with its large bay window was considered to be ideal and from then until 1919 this was designated as the room where the radium was kept and where radioactive sources were prepared for experiments in the rest of the building. Radium as a salt (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, purified in a separate glass apparatus and compressed into small glass tubes to make radioactive sources for experiments. The radium room, as it was known, 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.

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. 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. 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.

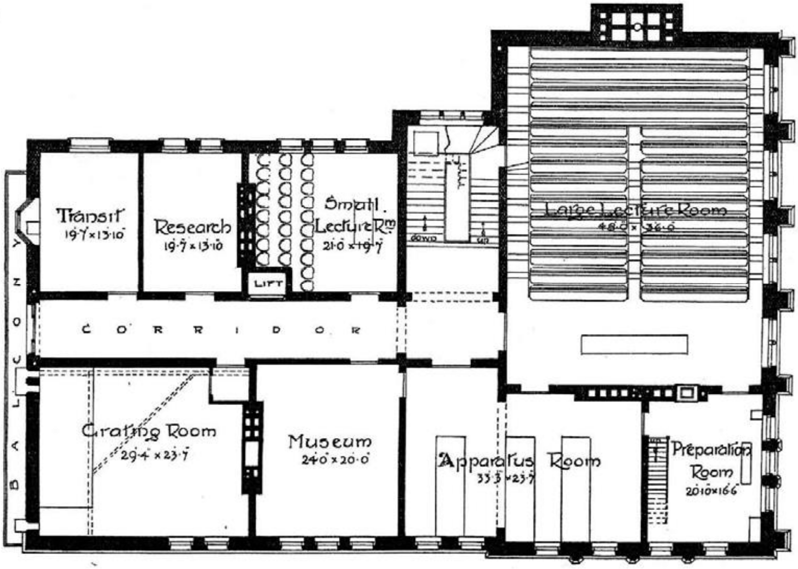


Figure 5. Plan of the 2nd floor of the New Physical Laboratories (from Schuster and Hutton (1906) with permission from Manchester University Press).

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 assistants and students, not least Hans Geiger, who has 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 foundation stone in laid). This was the room where the famous photograph of Rutherford and Geiger was taken in 1912. 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. This eventually led to the famous "Geiger Counter".

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.

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. 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 1910 as a Demonstrator. Initially working on beta-decay, of his own volition he became interested in X-ray diffraction and inspired by the revolutionary new theories of Niels Bohr conducted a series of experiments in 1913 which proved that every element can be classified by the number of positive charges in the nucleus, the atomic number. Thus was born the modern periodic table, which we now tend to take for granted. 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 snipers 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.

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). William Kay at that time occupied the preparation room behind the large lecture theatre. The outcome of this research, which had originated in another aspect of Marsden’s later work on scattering of alpha-particles from light gasses, resulted in a quartet of papers published in 1919 announcing the first artificial nuclear reactions.

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 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 traces of his occupancy remained in the form of radioactive contamination and contamination from mercury, which was employed in the early vacuum pumps.

The Schuster laboratory after Rutherford (1919 – 1967).

Rutherford was succeeded at Manchester by WL Bragg, whose primary interest was in X-ray crystallography. 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 (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.

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 William Hartree, 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 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, 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.

Bragg left Manchester in 1937 to take up a position at the National Laboratory, and then shortly after to the Cavendish to succeed Rutherford who died in October 1937. Bragg was in turn succeeded at Manchester by Patrick Blackett, whose primary interest was in cosmic rays, for which purpose he commandeered the old electrochemical lab. Dramatically, William Kay was evicted from his top floor room and moved to the old workshop on the ground floor. During his 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 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).

After Blackett's departure in 1952 and a short interim, he was succeeded in the Langworthy Chair by Samuel Devons, 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 Graff accelerator, one of which (the small) was housed next to the Theoretical Physics block on Coupland Street, and the other (the large) on Acker's 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). 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.

The re-occupancy and re-naming of the old Schuster (1967 – 2012)

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 evicted. 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.

The Tour

1. The 1912 Lecture Theatre.

The tour begins in the 1912 Lecture Theatre. Constructed as part of the 1912 Extension to the Physical Laboratories, during the official opening Conversazione of 1st March 1912 it was used to house an exhibition dedicated to the then late Osborne Reynolds. It is the sole remaining original theatre from the Rutherford era, the Large Lecture Theatre having been destroyed in 2004. The 1912 theatre is still used today as part of the Department of Psychology.

Figure 6. The 1912 Lecture Theatre.

2. The view from Coupland Street

The next station is in Coupland Street opposite the 1912 Extension. When the new Physical Institute was opened in 1900 Coupland Street was paved and had a tramline running along it. There are a number of buildings on the north side of significance to Physics, which included, in addition to the 1912 Extension, the old 1909 Engineering Building, the old Bragg Building, opened by Rutherford in 1932, and the old 1900 Physics Building. On the opposite side of Coupland Street one can view the old Medical School and the old Beyer Laboratories.

Figure 7. The view of the old Medical School from Coupland Street in 1900.

3. The quadrangle of the old Medical School

Proceeding across Coupland to the quadrangle opposite the old Medical School Buildings there is a clear view of the old Medical School, the old Chemistry Building and the rear part of the old Owens College main building (now the Owens Building) which housed the Department of Physics from 1873 until the opening of the new Physical Institute in 1900 (now the Rutherford Building).

4. In the old, old Physics Department.

The ground floor of the Owens Building is where Physics would have been located. It occupied most of the base of the west side of the quadrangle to the front of the building, with lecture room and apparatus room above on the first floor. From 1873 when the Owens College relocated to the present site Physics was directed by Balfour Stewart until his death in 1887 when Arthur Schuster was appointed as Professor.

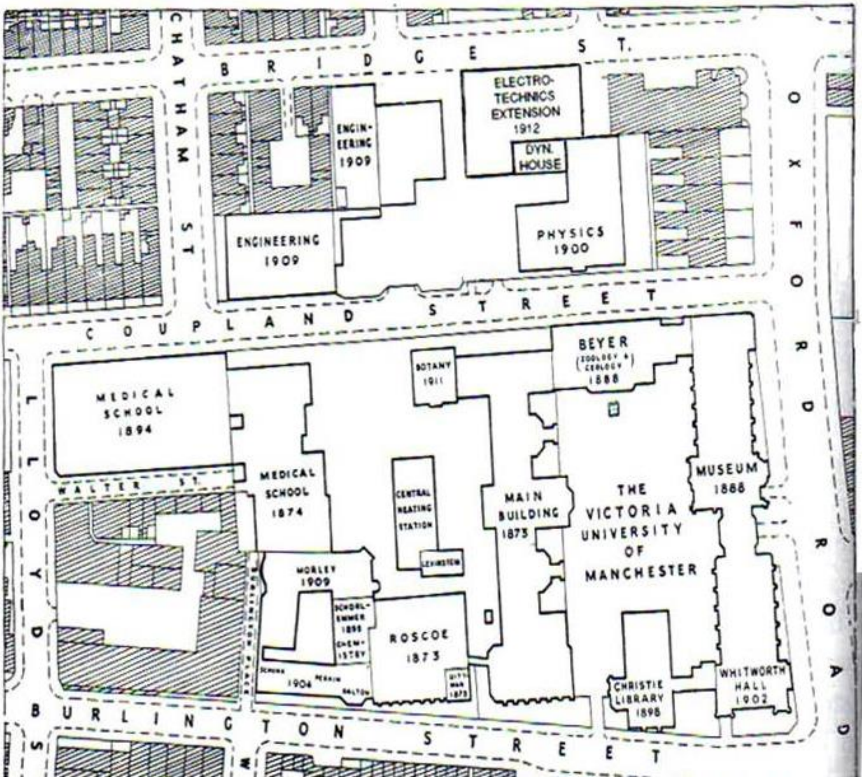


Figure 8. Campus Map from 1914 showing the relation of the Physics Department to the Medical School and Owens College Building.

5. The War Memorial, HGJ Moseley

Leaving from the front of the Owens Building into the quadrangle one can inspect the War Memorial to the fallen from the two World Wars. To the left of the lower of the brass memorial plaques commemorating World War I is a list of the dead from the Royal Engineers, which includes the name of 2nd Lieutenant HGJ Moseley who was killed at Gallipoli in 1915 (see right).

6. Archway to Coupland Street

From the quadrangle the tour goes past the Whitworth Hall (where in 1961 the Rutherford Jubilee was held) out along Oxford Road to the entrance to Coupland Street. On the left of the archway is a blue plaque commemorating Rutherford's Nobel Prize for Chemistry awarded in 1908 "for his investigations into the disintegration of the elements, and the chemistry of radioactive substances".

7. Foundation Stone of the New Physical Labs (old Schuster Lab)

After entering Coupland Street with a good view of the old Schuster Laboratory one might pause on the corner of the building at the location of the foundation stone laid in 1898. From this point there is a clear view of the four levels of the laboratory. Hans Geiger's laboratory room was located on this corner at the lower ground or basement level. Ernest Marsden probably carried out his alpha-scattering work in the room next door.

8. Main Entrance to the New Physical Labs (old Schuster Lab)

Proceeding along Coupland Street the next station is old main entrance to the old Schuster Laboratory (now Rutherford Building). It was at this location that many of the Physics Department photographs were taken. (See inside front cover – Ed.)

9. View of the South End of the Old Labs

At the southern end of the old Schuster Laboratory on Coupland Street is a vantage point from which a number features of the laboratory can be observed. These include at the top the bay window of Schuster's old Transit Room which was adapted by Rutherford for his Radium Room. To the right of the bay window stone platforms can be seen which were designed by Schuster to hold heliostats for directing light into the laboratory for spectroscopic analysis. For this purpose Schuster had set up a special room which housed a large Rowland Grating. A clear view can also be obtained of the entrance to the 1912 extension where the 1912 Departmental photograph was taken.

10. The old Ground Floor Lab

This completes the tour of the external part of the buildings and on entering the buildings one can assemble in old Ground Floor Laboratory from Schuster's time which had been used by Rutherford (see Figures 10 and 11) and now renamed the Rutherford Room. The room contains some exhibits of apparatus and the bench used by Rutherford to carry out the transmutation experiments published in 1919. The bench is still slightly radioactive from radium.

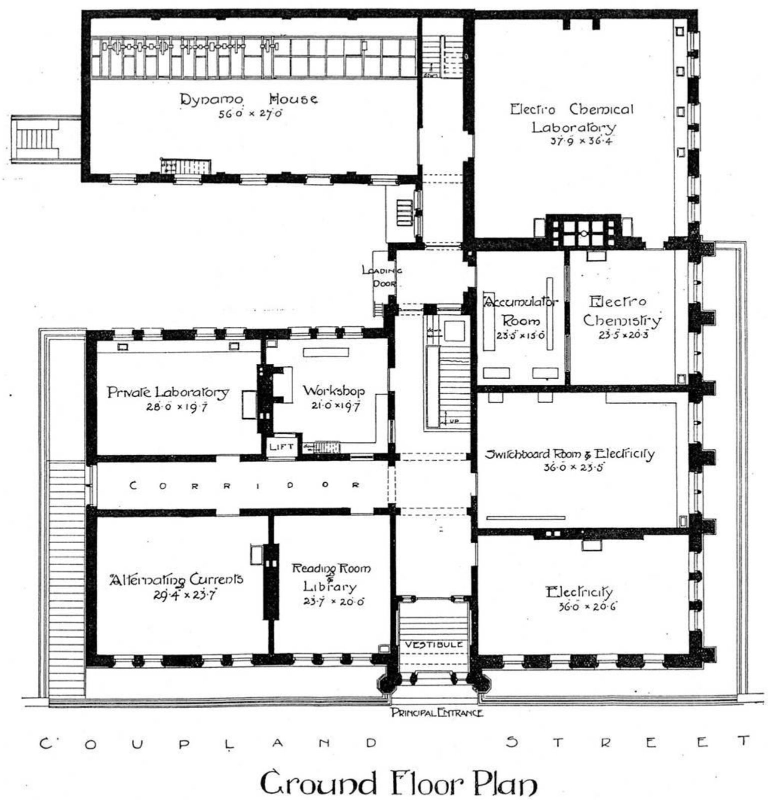
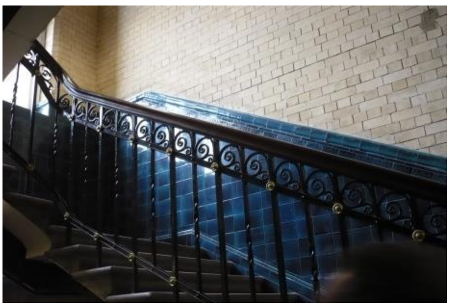


Figure 10. Plan of the ground floor of the New Physical Laboratories (from Schuster and Hutton (1906) with permission from Manchester University Press).

11. The Staircase



From the Rutherford Room one can pause on the ground floor at the base of the staircase which runs from the basement up to the top of the building. Rutherford’s private office was located on the first floor at the staircase end of the building. We can infer from Marsden’s recollections that he met Rutherford in the landing just below his office to tell him of the results of his wide-angle alpha-scattering experiments. It was these results which led Rutherford to deduce his scattering law in the winter of 1910. A short excerpt of Marsden speaking in 1961 describing these events still exists.

Figure 11. The old Ground Floor Laboratory now called the Rutherford Room.

12. John Hopkinson Memorial

Continuing on the ground floor and moving into the part of the laboratory which had been the John Hopkinson Memorial Wing. Hopkinson had been an outstanding engineer and physicist but was tragically killed along with three his family in 1898 in a mountaineering accident. In the corridor there is a stone plaque dedicated to him. The site of the 1900 quadrangle can also be seen from this location. It was built on in 1919 as part of an expansion after World War I.

13. Blackett's Cosmic Ray laboratory

On the right proceeding along the John Hopkinson Memorial corridor was the site of the Electrochemistry Laboratory from Schuster's time. This was requisitioned by PMS Blackett for a Cosmic Ray Laboratory in 1937 when he succeeded the Langworthy Professorship. It was in laboratory where Rochester and Butler discovered strange particles in 1947.

14. The Old Dynamo Hall

The final station of the tour is the old Dynamo Hall, now a student Common Room. This room was designed to house a number of AC and DC electromagnetic devices powered by a gas turbine.

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