Historical And Radio-Archaeological Perspectives On The Use Of Radioactive Substances By Ernest Rutherford

Interim Version 1, December 2008

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Summary

This report is an interim supplement to “Perspectives on Radioactive Contamination in the Rutherford Building” which formed appendix H in Churcher et al (2008) “Possible health risks due to ionising radiation in the Rutherford Building at the University of Manchester”. Its aim is to collect together for the first time all the available historical evidence relating to the use of radioactive substances by Ernest Rutherford during his research career spanning 1897 - 1937 and beyond. The work is incomplete and much further material remains to be uncovered and collated, but the picture which has emerged is already sufficiently well developed for some general conclusions to be reached which are of interest to all concerned with continuing radioactive contamination in the Rutherford laboratories. The conclusions may be summarised a follows:

(1) at Montreal, Rutherford's laboratory became contaminated initially without his being aware of it, the primary source of this contamination being the escape of radium emanation, i.e. radon (Ra222) which distributed long-life active deposits (Pb210/Po210);

(2) at Manchester between 1903 and 1907, early work with radium by Arthur Schuster and his associates may have produced some contamination prior to Rutherford’s arrival;

(3) at Manchester between 1907 and 1912, although aware of the problem of contamination, the precautions Rutherford put in place were inadequate and the Manchester Laboratory became contaminated -- probably due to accidental breakage of radon tubes, spillage of solution and the handling of contaminated apparatus -- to the extent that a new extension had to be built in 1912;

(4) at Manchester after 1912, it was intended that physics rooms in the extension should remain uncontaminated, but it is unlikely that this goal was achieved;

(5) at Cambridge, stricter precautions were adopted and the contamination was probably more limited;

(6) at all three laboratories, the radioactive substances used, and therefore the potential contamination, were not confined to products of the radium decay series, but included also radionuclides from the actinium and thorium series;

(7) the contamination found in these laboratories should be regarded as a form of archaeological data, for the invaluable information it provides to the history of science, and not treated solely as a problem of health and safety; a thorough consideration of the health and safety issues should, in turn, be informed by a full consideration of the historical and radio-archaeological facts.

Preface

The initial impetus for this work was the discovery in 1999 of radioactive contamination in the Coupland Building (formerly the Schuster Building and now the Rutherford Building) which historically was occupied by Physics from 1900 until the 1970s, including 1907 - 1919 when the Laboratory was directed by Ernest Rutherford. At the time of the discovery of contamination, I was a Lecturer in Perception in the Department of Psychology which then was located in the Coupland Building. Although I was working as a psychologist, my first degree was in theoretical physics, and so I took a particularly keen interest in this matter. Along with my colleagues Mr Churcher and Dr O'Boyle, I became intrigued by the origin of the contamination. It became clear that here was an archaeological site, containing radio-archaeological remains of considerable importance for the history of science.

The laws enunciated by the early pioneers of radioactivity had a profound effect on all the sciences, not least astronomy, geology and archaeology, as well as, of course, physics and chemistry, and on wider society through the influence of nuclear weapons and energy. The traces of activity they left behind are therefore valuable sources of information about a remarkable period of history. Each contamination event, like the formation of a fossil in palaeontology or an artefact in archaeology, is a record of the daily activity of the pioneers. In conjunction with existing historical information these radioactive 'artefacts' may be used to piece together for posterity a picture of the laboratories as they were 100 years ago. The scientists and their activities have become objects of study in themselves, a programme of study aided by the very laws which they uncovered. Like fossils and artefacts, the 'radio-artefacts' are also subject to decay, depending on their time-constant, and so it is important that the short-life radio-artefacts are recovered before their activity sinks below the background.

Motivated by such thoughts, I embarked on an enquiry into the historical origins of the contamination, independent of the work which went into the main body of our report “Possible health risks due to ionising radiation in the Rutherford Building (formerly Coupland Building 1) at the University of Manchester” (Churcher et al., 2008), and carried out some analyses of the radiological data which we had received at the time of the report. Some of this historical and analytical work appeared in that report. Since the report was submitted in June 2008, I have made further progress in uncovering the history. Although there remains a considerable amount more work to be done, given that the matter has now been taken up by the University of Manchester and has become public, causing some alarm among former occupants, it seems appropriate that an interim supplementary report be expedited. It is hoped that the information contained herein will assist the independent review which has been initiated, and will be of interest to the past and present occupants of Rutherford's laboratories.

It is a matter of regret that I did not carry out this work at an earlier time. Unfortunately at the time we started our investigations, Mr Churcher and Dr O'Boyle were taking retirement and I was taking sabbatical leave in Australia. It is unfortunate that we were unable to have any influence on the radiological and remedial work carried out in the

Coupland Building. In treating the issue of contamination as purely one of health and safety, many valuable archaeological data have been lost, including data on the precise location and radiochemical composition of each of the contamination events. Other important data have not been collected. For example, a radiochemical analysis of substances dissolved in the mercury found in the radium room (2.62) would give important clues as to the experiments carried out in this room. An analysis of the proportion of isotopes of stable lead to radiolead (e.g. Pb210/Pb206) would allow estimates of dates and quantity. It should be added to the list of regrets the unfortunate fact that during the refurbishments of 2006 a number of the archeological sites within the Rutherford Building were destroyed, most significantly the magnificent lecture theatre on the top floor. Constructed in 1900 it had survived practically unchanged for over 100 years.

In addition to the loss of data, a radiological survey which was properly guided by the historical data would be likely to be more successful in locating contamination, including any contamination of relevance to health and safety, and in the interpretation of complex spectrographic analyses. In other words, without knowing in advance precisely what substances were used, the chemical procedures used to isolate them and their possible locations any survey would be running blind. It is to be hoped that any further radiological survey work at Manchester and the other laboratories will correct this deficiency.

Another source of regret is that we did not immediately take the advice of Professor Robin Marshall FRS who in 2003 recommended that we contact Samuel Devons, a former student at Cambridge in the last two years of Rutherford's life. Devons was probably the last of Rutherford's research students who worked with radioactive materials in the Cavendish at Cambridge, before the era of particle accelerators made the materials obsolete, and he then went on to succeed Rutherford as Langworthy Professor at Manchester from 1955-1960. As he took a keen interest in the history of science, including recording an interview with William Kay the Laboratory Steward at Manchester (Hughes, 2008), Devons would have been an invaluable source of information. At the time of the discovery of the contamination in 1999, at least three of Rutherford's former research students were still alive, including M Oliphant (1901-2000), TE Allibone (1904-2003) and S Devons (1914-2006), but the small window of time available for us to contact these last of Rutherford's ‘boys’ was rapidly closing. In December 2006 with Devons’ passing, the opportunity to interview him was, sadly, lost.

Although the loss of information by the ending of this generation of physicists is keenly felt, we are fortunate in that they left behind many writings on Rutherford's life and work and their time working with him as colleagues and students. I have found these to be extremely helpful, in particular Oliphant’s 1972 “Recollections of the Cambridge Period” and Devons' numerous historical pieces, not least his 1991 Rutherford Memorial Lecture “Rutherford and the Science of His Day”. The fact that they lived as long as they did would need to be taken into account in any overall assessment of possible risks to health from occupancy of the Rutherford laboratories. Just before the contamination was discovered, I occupied as an office room 2.62 which was the probable location where

Rutherford kept his radium between 1907 and 1919 and where the experiments with Thomas Royds were carried out in 1908. I felt privileged to be able to work in a room which had once been used by Rutherford and it has been a source of inspiration. In the light of the information I have uncovered since the discovery of contamination, I do not have any undue anxiety concerning my health, although I remain of the view that it is important that a thorough, independent expert epidemiological study is carried out to resolve the remaining uncertainty concerning possible health risks.

In deciding on the structure of the report I have been guided by the words of John Cockroft in his 1953 Rutherford Memorial Lecture when he said “The history of Nuclear Physics is very largely the history of Rutherford and his schools”. The first part of the report then is based around Rutherford’s career and his three schools at Montreal, Manchester and Cambridge. A matter of some concern is the fate of Rutherford’s inventory of radioactive substances, not least after his death in 1937, and for this reason I have included sections on this for each of his laboratories. As will be apparent, the impact of both of the World Wars is a factor which cannot be ignored and this is included for the Manchester and Cambridge Periods. In the second section, I give data and analysis from remedial work carried out at Manchester from an archaeological perspective, although some of this material has already appeared in Appendix H of Churcher et al (2008). At this time I have not been able to obtain details of the Montreal or Cambridge radiological work.

In putting together this interim report, I have made use of a wide variety of historical sources which include the biographies, correspondence, reminiscences and memorial lectures, text books and official university documents, including website material. At Montreal I should acknowledge help from Professor Jean Barrette curator of the Rutherford Museum, the director of the Macdonald Library (formerly Macdonald Physical Laboratory) for access and allowing me to take photographs, and members of the McGill archive for their assistance. At Cambridge I should acknowledge the help that I have received from current and retired members of the New Cavendish Laboratory and occupants of the Old Cavendish Laboratory in the Department of Social Psychology at Cambridge. At Manchester I should thank John Ponsonby for reading through an early version and for correcting some errors in the draft and to the Manchester archivist James Peters for his help. I have also received much help from John Churcher, particularly his archival work at Manchester, and Donald O'Boyle for reading various drafts of my reports. The translation of Geiger’s note to Chadwick was done by Chris Lee. I am grateful also to the UK Atomic Energy Authority for carrying out a search of their archives for me.

Neil Todd

7th December, 2008

CONTENTS

I HISTORICAL PERSPECTIVES

Rontgen's discovery of X-rays in 1895 had a profound effect on the development of physics, leading Henri Becquerel in 1896 to the discovery of uranium rays and JJ Thomson in 1897 to the discovery of the electron. Rutherford's first period at Cambridge (1895-1898) coincided with these remarkable discoveries and it was during this time that he made his first investigations of radioactivity and its ionising effects. He spent the next four decades working with radioactive substances until his death in 1937. This period in the history of science, and the great advancements in our knowledge associated with it, has been described by historians as the second scientific revolution. According to Lawrence Badash:

"After the scientific revolution of the seventeenth century came another in the 1890s. This second revolution, mirroring the increased pace of life, changed the face of science in little more than a generation, in great contrast to the one hundred and fifty years that spanned the contributions of Copernicus, Kepler, Galileo, Descartes, and Newton." (Badash, 1969)

At the centre of the revolution was Rutherford himself whose own career spanned this critical period. After Cambridge, Rutherford was appointed to a Chair in Physics at McGill (1898 - 1907), during which he articulated the theory of successive transformations with Frederick Soddy. Following this as Langworthy Professor at Manchester (1907 - 1919), his tenure oversaw a very considerable period of expansion in research in radioactivity with assistance from a number of students and co-workers, including Royds, Geiger, Marsden, Hevesy, Chadwick, Darwin, Bohr and others. The whole modern nuclear and atomic conception was founded, culminating in the first artificial transmutation in 1919. From 1919, this work with radioactive substances continued at Cambridge including scattering of alpha-particles to probe the nucleus, transmutation by bombardment with alpha-particles and also work on the nature of radiations. This led to the discovery of the neutron by Chadwick in 1932, culminating, shortly after Rutherford's death in 1937, in the discovery of nuclear fission in 1939 and ultimately leading to the nuclear bomb and the nuclear energy industry.

The aim of Section I of this report is to put together all of the historical information relating to Rutherford's use of radioactive substances, and, in particular, information relating to contamination and the events which led to the contamination of his laboratories.

I.1 The first Cambridge Period 1895 - 1898.

As noted above, Rutherford's first period at Cambridge (1995-1898) coincided with the discoveries of X-rays, radioactivity and the electron. Although initially interested in Herzian waves, in continuation of his work in New Zealand, Rutherford was soon drawn into the work of JJ Thomson on the ionising effects of X-rays, and then to the ionising effects of uranium and uranium rays (Devons, 1991). He quickly discovered the complexity of the Bequerel rays and coined the terms 'α rays' and 'β rays' to describe the strongly ionising and easily absorbed vs the weakly ionising and more penetrating radiations. Samuel Devons (1991) writes evocatively of this discovery

"Virtually from their birth, and christening by Rutherford, he would adopt the α rays as his cherished own. And they would remain his cherished companions throughout almost the whole of his research" [Devons 1991]

I.1.1 The Cavendish Laboratory 1874 - 1896.

The 'New Physical Laboratories' of Cambridge, also known as the Cavendish Laboratories after its benefactor, were opened in 1874 and directed by Maxwell until his death in 1879. He was succeeded by Lord Rayleigh until 1884 when JJ Thomson became the Cavendish Professor. The original 1874 building (see Appendix B1) comprised a ground, 1st and 2nd floors, and also an attic and basement. The layout is somewhat complicated by the fact that the porters lodge lies below the slope of the 1st floor lecture theatre but is raised above ground. Also, above the stairwell lies a third floor comprising a set of attic rooms grouped into an external tower.

A good account of the Cavendish Laboratory prior to the arrival of Rutherford is given in "A History of the Cavendish Laboratory 1871-1910" published in 1910 to commemorate the 25th year of JJ Thomson as Cavendish Chair. This also gives a description of the 1896 extension south along Free School Lane.

In 1893 the houses along free school were assigned as a site for the extension of the Cavendish Laboratory... In view, however, of the financial position of the University, they recommended that the ground floor only should be built at once, and that the two upper floors should be left for future construction...

The large ground floor room, now used for medical students and for the more elementary course for Part I of the Natural Sciences Tripos, was then built by Mr Sindall of Cambridge, from the designs of Mr WM Fawcett. The small lecture-room and the private room for the professor were added at the same time...

The extension was first used in the Lent Term of 1896,...

I.1.2 Use of radioactive substances at the Cavendish in 1898

Table 1. Rutherford's Cavendish Inventory of Radioactive Substances

Uranium Series	Thorium Series	Actinium Series
U metal (1897 - 1898) U Nitrate (1897 - 1898) U Oxide (1897 - 1898) U Potassium Sulphate (1897 - 1898)	Th Nitrate (1898) Th Sulphate (1898)	

During his first period at Cambridge Rutherford wrote only a single paper reporting the use of radioactive substances "Uranium radiation and the Electrical Conduction Produced by it" submitted on September 1st 1898 and published in the *Philosophical Magazine* in January 1899 after he had arrived in Montreal. The study made use of four different preparations of uranium, including the uranium metal, all in powdered form. During the experiments reported the radioactivity of thorium was discovered and he quickly acquired thorium compounds for use in this work. Table 1 abive gives a list of the substances used. At this time the actinium series had not been discovered.

The work was almost certainly carried out in the Maxwell wing of the Cavendish and quite possibly in one of the rooms used by JJ Thomson. From 1895 - 1898 there are several references to room use in his letters.

Rutherford to his Mother

1895. "I work on the third floor in the laboratory and have a few fellows in adjoining rooms for company."

From the 1874 plan (see Appendix B1) is likely that he was working in either the "Optics Rooms" or the "Radiant Heat" room.

Rutherford to Mary Newton

15 January 1896. "I started at work at once in the Lab on my electric waves and made my first experiment on long distance transmission of signals without wires. I set up the vibrator in the Prof's room at the Cavendish and my detector a 100 yards away in Prof Ewing's Lab,...

My next experiment will be, I think, from the tower of the Cavendish to St John's tower nearly a mile away."

In the 1874 a room on the second floor is designated as the Professor's Private Room, but in the 1910 account, the Preparation Room is also designated as the "Professor's Laboratory". The "tower" is clearly marked on the 1874 plan. There are several rooms at the top of the tower, including the one he would later use as the Radium Room.

In a letter to Mary Newton in February 1896 he gives a brief mention of the opening of the 1896 extension at which he presented a paper "Experiments with Herzian Waves". In his publication of June 1897 "A magnetic detector of Electrical Waves" submitted in June 1896, he refers to experiments being carried out "on the top floor of the Cavendish".

At about this time he switches from radio waves to start working with Thomson on X-rays

24 April 1896. "I am working with the Professor this term on Rontgen waves."

This work on X-rays led to the publication of three articles on the ionizing effects of X-rays and the nature of the ions, the last of which submitted on July 19 1897, followed by an article on the ionising effects of ultra-violet light submitted on February 21 1898. In July 1898 the Curies announced the discovery of polonium and it is about this time, according to Eve (1939), that he extended his work on the ionising effects of radiation to radioactive substances. Wilson's (1983) view is that actually Rutherford had started working with uranium in 1897 (he submitted a report to the Commissioners of the 1851 Exhibition scholarship in June 1897 stating he had begun work with uranium).

I.1.3 Work at the Cavendish with radioactive substances 1898-1919

Although Rutherford departed for Montreal in September 1898 work with radioactive substances continued at the Cavendish. Some of this work was done by RJ Stutt (1875-1947), the fourth Baron Rayleigh. His first paper making use of radioactive substances was in 1900 “The behaviour of the Becquerel and Rontgen Rays in a magnetic field” and subsequently published as many as forty articles in the next ten years on subjects related to radioactivity. This included for a short time work with Harriet Brooks who had worked with Rutherford at Montreal on radium emanation. During 1899 - 1906 he mainly worked in the Cavendish or in a laboratory at his family home. In 1908 he was appointed to physics chair at Imperial College. JJ Thomson also did some work with radioactive substances during this time, including with Walter Makower as his research student on diffusion of radium emanation.

I.2 THE MONTREAL PERIOD 1900 - 1907

The following is from the McGill University Website:

Rutherford's research at McGill covered every aspect of radioactivity, including the nature and properties of the 'emanation' (radon) produced by radium and thorium, the heating and ionization properties of the radiations, the charge and nature of the α, β and γ rays, excited radioactivity, and elucidation of the three natural radioactive series (uranium-radium, actinium and thorium). During his nine years at McGill, Rutherford published 69 papers, either alone or with a second author. The latter group included graduate students, demonstrators and professors at McGill and (after 1903) graduate students and post-doctoral scientists from several countries outside Canada. These collaborators published some 30 independent papers on various aspects of radioactivity, mostly on topics suggested by Rutherford and under his general guidance.

The most significant collaboration was between Rutherford and Frederick Soddy, a young English chemist who was appointed Demonstrator in Chemistry at McGill in 1900. The collaboration between Rutherford and Soddy lasted only 18 months, from October 1901 to March 1903, but resulted in nine important papers, including "The cause and nature of radioactivity," published in two parts in 1902.

Other than Soddy, the most important of Rutherford's collaborators were Arthur Stewart Eve, an English physicist; Howard Barnes, a young Montreal physicist; Howard Bronson, an American physicist from Yale; Tadeusz Godlewski, a physical-chemist from Cracow (Poland); and Otto Hahn and Max Levin, both physical chemists from Germany.

I.2.1 The Macdonald Laboratory

The following information relating to the Macdonald Building has been obtained from the McGill University Website:

The Macdonald Physics Building was constructed in 1893 by Sir Andrew Taylor, who designed several of the University's projects of the 1890's, and his partners at that time Morley Hogle and Huntley Davis. It was a gift of Sir William Macdonald, the donor of many other edifices on campus including Macdonald Engineering, Macdonald Chemistry, and the Old Student Union (now the McCord Museum). As with many of his other projects, Taylor took into account the function of the building before its ornament, though the latter was not ignored. Knowing the nature of Physics experiments and the current needs of the field, he built the entire edifice using only wood, masonry, and copper, bronze and brass for the nails and fixtures. No iron or steel was used throughout, even in the radiators, to keep magnetic interference at a minimum. The interior is of heavy brick and is constructed in large arches, many of which have since been filled in. Many labs and much apparatus were originally provided for the study of electricity, light, heat, and the elements.

At the Formal Opening held on February 24th, 1893, a commemorative booklet was published which gave a description of the Macdonald Laboratory. On the basis of this booklet and the current floor plans it has been possible to reconstruct the layout of the laboratory (see Appendix B2). The north end of the first three floors were primarily devoted to research, including a Magnetic Laboratory on the basement floor, and Electrical Laboratory on the 2nd floor and a Heat Laboratory on the 3rd floor. The first two floors also allowed a number of private research rooms, and it is likely that Rutherford worked in these. At the south end of the building was located the large Lecture Theatre on the 3rd and 4th floors, supported by a Preparation Room and two

Apparatus Rooms. The 4th floor was primarily devoted to teaching and on the 5th floor there was a large Elementary Laboratory. The building was heated by a set of boilers in the basement and ventilated by a 5 HP fan in a tower structure.

I.2.2 Acquisition of radioactive materials in Montreal

Between 1898 and 1907 Rutherford acquired radioactive substances from a number of sources. Before leaving for Canada in1898 he put in a request for uranium and thorium oxide through the Cavendish. He arrived in Montreal in September 1898. His impatience to get hold of these materials is indicated in a letter of 24th October 1898 to "Hayles of the Cavendish urging him to send the preparations ... as soon as possible, together with the account which would be settled on their arrival." In December 1901 he wrote to William Crookes requesting pure thorium nitrate from Knofler of Berlin. His notebooks of March/April 1902 indicate "new radium from Paris arrives", suggesting that he had received a number of consignments of radium. From his publications with HT Brooks some details of these can be found. In 1903, as detailed below, through Soddy he discovers Giesel of Bruswick is selling radium bromide and obtains about 100 mg in total funded by a Macdonald grant. On Otto Hahn's arrival in 1905 preparations of radiothorium from Ramsay and actinium from Giesel were added to his supplies. Table 2 below gives a summary of Rutherford's Montreal inventory of radioactive substances.

Table 2. Rutherford's Montreal Inventory of Radioactive Substances

Uranium Series	Thorium Series	Actinium Series
U Ox (Schuchrart 1898) U Ox (Eimer and Amend NY, 1898-1902) Ra Cl2 (Estler and Geitel 1900) Ra Cl2 (P de Haen, Hannover, 1901) Ra salt (Paris, 1902) Ra Br2 (Giesel 1903) Radiolead (Boltwood 1904) Polonium (1902)	Th Ox (Schuchrart 1898) Th Ox (Eimer and Amend NY) Th Nitrate (Knofler 1901) Radiothorium (Ramsey 1905)	Actinium (Giesel 1905)

I.2.3 Use of radioactive substances and contamination events during the Montreal Period.

Rutherford's first work with thorium led to the discovery of thorium emanation (Rn 220) and the active deposit of thorium. (In parallel radium emanation (Rn222) and active deposits were discovered by Curie and Dorn). Fresh supplies of a substantial amount of thorium in 1901 enabled Rutherford and Soddy to determine that the emanation was an inert gas and that there was an intermediate substance, thorium X (Ra 224), which was the immediate source of the emanation, ultimately leading to their theory of successive transformation by nuclear disintegration (Rutherford and Soddy, 1902ab).

His earliest work with radium (Rutherford and Brooks, 1901) made use of impure and therefore weak sources, but he was able to make the first estimates of the molecular weight and diffusion properties of radium emanation. The acquisition of more concentrated radium preparations in 1901 allowed a more detailed investigation of the

nature of the radiations, the active deposit and decay products (Rutherford and Brooks, 1902). After the arrival of the Giesel radium in 1903, and up until 1907 when he left for Manchester, Rutherford's work was almost exclusively done using radium. All of his 1904 and 1905 publications were radium based. In the eleven 1904 publications he determined the heating effects of radium and characterised the nature of the slow transformation products (radium D, E and F). In the nine 1905 and nine 1906 publications his focus became more concentrated on the nature of the α-particle, including its charge, mass and velocity. As is documented below the arrival of the Giesel radium also led quickly to the contamination of the Macdonald Building.

A contamination event at Ramsay's Laboratory at UCL 1903

In April 1903, Soddy moved to London to work with Ramsay at UCL with a view to testing the hypothesis that helium was produced from radium. Up until this time, all of Rutherford's work had been done with only weak sources, primarily thorium compounds. This was to change in the summer of 1903 when Soddy discovered a shop in London, Isenthals in Mortimer St, which was selling radium bromide produced by Giesel of Brunswick.

"Our trouble here was the same as in Montreal. We had a quite insufficient amount of radium for our investigations.

Then, by the most extraordinary chance, the whole future prospect was changed.... I was walking along Mortimer St off Upper Regent Street, in London one day when, casually looking through Isenthal's window, I saw advertised something I could not credit to be true: 'pure radium compounds on sale here'. ... I learnt from the salesman that Professor Giesel in Germany,..., had started manufacture of radium compounds on a commercial scale in the Chinin Fabrik at Brunswick. He used residues left after the extraction of uranium from the Pitcblende found in the old state silver mine of St Joachimsthal in Bohemia. Isenthal had quickly taken advantage of this supply.

At that time one could buy radium only from the French factory by favour of the Curies. Here it was to be bought in a London shop at some eight shillings a milligram of pure radium bromide. ....

I hurried back to UCL to tell Ramsay of my treasure. Looking at it in the dark with an X-ray screen would have convinced the investigator that it was genuine. Ramsay, to my absolute horror, stuck in a moistened platinum wire, removing a large fraction of my few milligrams and held it in a Bunsen burner to see if it gave the red carmine flame characteristic of radium free from barium. It was the only time I have seen that flame and I never want to see it again! It made me almost ill to see this treasure treated so profligately, besides permanently spoiling the laboratory for any delicate radioactive work. Ramsay at that time had little experience of radioactivity." [Soddy 1957]

Rutherford's discovery, via Soddy, of the Giesel radium

Rutherford visited Soddy in London in the summer of 1903. He took Rutherford to Isenthals where he purchased 30 mg of RaBr2.

"I told him immediately on his arrival at UCL about my find at Isenthals and together we lost no time in walking round to Mortimer St.

I must say he experienced the same astonishment and joy that I had experienced when confronted with radium bromide for eight shillings a milligram some weeks before. He was absolutely bowled over and

became as excited as a school boy over the coming holidays. With thirty precious milligrams of pure radium bromide we bounded back to Gower Street and we both immediately repaired to the dark room with some metal foils and a bit of X-ray screen.

The effect was terrific; it was like a person born blind suddenly being given sight, for though R had made a special study of the Becquerel rays, this was the first time he had ever seen them. All his work had been done by the ionization method with substances far too feebly radioactive to light up the X-ray screen. Now he had a visual demonstration of what he had found out in the dark - so to speak." [Soddy 1957]

After lending his 30 mg to Soddy for their helium experiments, he later took some of this back to Canada, although it appears that there were some problems with customs in New York. The radium was nevertheless forwarded to Canada and probably arrived in about August 1903. The first reference to the 30 mg is in Rutherford and Barnes (1903) dated October 16th. In 1903, a gift of 500 dollars was made from Macdonald for the purchase of 100 milligrams of radium from Dr Giesel of Brunswick. This was purified RaBr2 which contained 75% Ra. It is likely that this was ordered shortly after Rutherford's return to Canada that summer. The consignment would likely have arrived sometime towards the end of 1903. A reference is made to this in the 1902-1903 McGill Council Reports

"80 milligrams of this rare substance have been secured, the total existing amount being probably not more than one gram; and this will be employed for further research" [Cox, 1903]

I.2.4 Contamination of the Macdonald Laboratory 1904 - 1906

It is apparent that within a short time after the acquisition of the Giesel radium, Rutherford's laboratory became contaminated. According to Eve in about 1904:

"I was asked to make a sensitive, small capacity electroscope the gold leaf of which would remain charged for two to three days. This I failed to do. So Rutherford said: 'Lester Cooke used to make them; why can't you? Get Jost the mechanic to make you one!' So I went to Jost and repeated this. He said: 'If I could not make a better electroscope than Cooke, I'd shoot myself!' So he made a beauty to look at, but a bad one to go. Its leaf collapsed in twelve hours. This puzzled me. One night I could not sleep and got up in my diggings and made an electroscope of a tobacco tin, and amber mouthpiece of a tobacco pipe, and some Dutch metal foil; charged it with sealing wax and went to sleep. The leaf of this home-made freak remained open and charged for three days, and solved the problem. An electroscope made of material outside the laboratory would remain charged for 48 hours inside the laboratory, but all the material inside the building was contaminated and coated with active deposit including the slow period transformations of radium...Precautions were then taken to prevent the escape of radon which had been at the root of the mischief, hitherto unsuspected." [Eve, 1939]

The contamination is also referred to by Otto Hahn in "A Scientific Autobiography":

"Acting upon Rutherford's invitation, I travelled to America in September 1905....I called to introduce myself to Rutherford, and he showed me around the Macdonald Physics Building. His own laboratory and most of his co-workers were located in the basement of the Institute. ….

AS Eve investigated the gamma rays emitted by uranium and probably also by thorium. But the electroscopes that he built in the Institute were not so well insulated as they should have been. He took to building his instruments at home, because the Institute was already so contaminated with radioactivity that instruments for the detection of weak gamma rays did not work well. Nobody at that time was worried

about radioactivity as people are now. Rutherford once helped me with a measuring device that was not behaving properly, and in the process of correcting whatever was wrong, he made the instrument radioactive." [Hahn 1966]

Hahn also wrote about this in "My Life" published just after his death in 1968:

"I was allotted working-space in the cellar, where I was able to set up my electroscopes - and where I also had a space for chemical work at a considerable distance from the electroscopes. The institute was not particularly well-equipped for chemistry. There was only one 'chemist's kitchen' as they called it." [Hahn, 1968]

Also working in the cellar was Bronson on the decay-products of radium, McClung on beta rays and Eve on gamma-rays:

"Eve set up his electroscopes in his own flat, because in our laboratory they would inevitably have become contaminated with radioactivity and thus would have given wrong readings of the faint gamma rays from his preparations. I was better off. Ramsay had given me some highly active radiothorium and also two preparations of actinium that had been made by Giesel." [Hahn, 1968]

During Hahn's visit in 1905 he participated in the photographic session which led to the now famous photograph of Rutherford in his basement laboratory (Appendix B2):

"One day in Montreal a representative of Nature presented himself in order to take a photograph of the prominent scientist for this journal. The photograph was taken in the cellar of the laboratory where Rutherford's a-ray apparatus was set up. When the first negative was developed, the photographer was not satisfied with the result. His appearance was not elegant enough for the fastidious English public … So for the next picture I had to lend him my pair of detachable cuffs. But in the second photograph not enough of them was visible. However, in the third picture they showed up in their glory, and so in 1906 I had the proud satisfaction of seeing my 'detachables' immortalized in Nature." [Hahn 1962]

The photograph appeared in an article by Eve in the July 19th 1906 issue of *Nature*. It is of considerable interest because it shows that by 1905 Rutherford was keeping his radium in the same room as his experimental apparatus, although he has clearly adopted Ramsay's method of keeping it in a bulb evacuated by a Teopler mercury pump. The Manchester radium bromide apparatus (see Figure 1) would have looked very similar to this. The photograph also gives some clues to the location in the Macdonald Building.

Hahn left Montreal in the summer of 1906. Shortly after this Rutherford wrote to Boltwood and discusses the possibility that some actinium had been contaminated with radium.

Rutherford to Boltwood

10 November 1906. I live in dread of contaminating things but I don't see how it was possible in this case. This brings me to a note of warning. Keep all radium in quantity out of the SloaneLab as if it were the plague. You may keep a closed tube of Ba [barium] for the benefit of visitors containing a gram of the precious metal. My laboratory is in a perilous state for fine experiments and I see no hope of improvement."

It was about this time (August/September 1906) that communications took place between Arthur Schuster, Langworthy Professor at Manchester, and Rutherford concerning his possible succession to the Langworthy chair.

I.2.4 The Macdonald Laboratory after Rutherford and the fate of the Montreal radioactive materials

When Rutherford left Montreal in 1907, he evidently did not take his radium with him to Manchester as he complained to Ramsay when negotiating use of the Vienna radium that he had "barely 30 mg", but there is some evidence that he did take the actinium. As is pointed out by Wilson (1983) his first publications from Manchester were concerned with the relationship between actinium and radium and this could only have been done if he had transported the actinium from Montreal to Manchester. However, since most of the preparations remained it was possible for research to continue in Montreal making use of radioactive substances.

Howard Barnes 1907-1919

After Rutherford's departure, the Physics Department at McGill was run by Howard Barnes, who had worked with Rutherford on the heating effects of radium. Although it would appear that Barnes himself did not conduct experiments using radioactive substances, Eve continued to published on γ-radiation produced by radium C and other substances up to 1914. Thereafter, his publications were varied, and reflected an increasing interest in geophysics. JA Gray joined the department in 1912 and published articles up to 1922 on γ-radiation . During the War years, there was a great reduction in staff and Barnes carried a heavy workload.

A S Eve 1919 - 1935

After the War Eve took over from Barnes in 1919 and made efforts to rebuild the department after the war (Foster 1949). Among the new staff appointed was Etienne Bieler, who had worked with Chadwick at the Cavendish (Chadwick and Bieler, 1921) on collisions of a-particles with hydrogen. Also appointed was David Keys who had also worked at the Cavendish with JJ Thomson. Keys collaborated with Eve on geophysical problems. During this time "a fire broke out in the optics lab in December, 1924 causing $20,000 of damage but fortunately the edifice was rescued. In 1930, a meteorology station was added to the top of the building." According to Foster (1949), "the Department received a major shock from the sudden death of Bieler in Australia" when carrying out geophysical work in 1929. Eve retired to London in 1935 and was appointed Honorary Physicist to the Radium Beam Cancer Research Board. On Rutherford's death in 1937, Eve was persuaded to write the official biography "Rutherford, Being the Life and Letters of the Rt Hon Lord Rutherford".

After 1935

Some of Rutherford's equipment and personal effects were kept in a museum on the top floor of the Macdonald Building but these were moved to the new Ernest Rutherford Physics Building in 1982. According to the McGill website:

The Rutherford Museum contains a collection of the actual apparatus used by Ernest Rutherford when he was Professor of Experimental Physics at McGill, 1898-1907.....The formulate Museum also includes some photographs, letters, documents, and other materials relating to Rutherford's work. ... The period covered by this Museum was still within the age of 'Little Science.' A scientist would design the apparatus for an experiment and it would then be constructed in the machine shop. At the conclusion of the experiment the apparatus would be returned to the workshop, where it would be dismantled, since many of the components (such as brass plates, blocks of wax, glass tubing, etc.) could be re-used in later equipment. This was known as 'cannibalizing the apparatus.' This would normally have happened to Rutherford's apparatus, but for the foresight of his colleague Howard Barnes, who pointed out that Rutherford was a pioneer in a new field of science and, by 1900, was already world-famous: it would be a crime against posterity to destroy his apparatus. The equipment was therefore put away in a cupboard, where it remained, undisturbed, until the late 1930s.

With regards the building:

In 1941 a fifth floor was added. In 1982, Taylor's building no longer met the needs of the modern Physics department. It was at this point transformed into the Macdonald-Stewart Library Building of Physical Sciences and Engineering. Its sturdy structure has been well adapted to house many thousands of volumes and it is still regularly filled with physicists doing research.

I received a helpful communication from the museum curator Professor Jean Barrette:

“I do not know if there was research on radioactivity between Gray’s time and the beginning of research in Nuclear Physics with the McGill Cyclotron that began immediately after the war.

I learned a bit more about the decommissioning of the Macdonald Physics building. In fact it was done by the Canadian Army around the 60s as an exercise after it was found that there was scattered radioactivity in the building. It was at the time of the cold war and the Army took it as a kind of exercise. It would have been too expensive to have it done by a private company.

I do not know about all of Rutherford’s sources. We have in fact in the museum some of the samples he used. Most are samples used in experiments and that are no longer active. However some are Uranium sources that I found out are still active. I do not know about any of the other sources like the Radium he used. These may have been disposed of during the clean up.”

Among the twelve old radioactive materials in the Rutherford Collection, in addition to the uranium oxides, are a sample of Boltwood’s 1904 radiolead and various metal plates which were exposed to radium emanation.

I.3 THE MANCHESTER PERIOD 1907 - 1919

Rutherford arrived in Manchester in May 1907 and, during his Manchester period, he undertook studies using radioactive substances from all three natural decay series: radium (U238), actinium (U235) and thorium (Th232). His tenure oversaw a very considerable expansion in research in radioactivity, initiated in Canada, with assistance from a number of students and co-workers, including Royds, Geiger, Marsden, Hevesy, Chadwick, Darwin and others. This work at Manchester finished in 1919 when Rutherford was appointed to a chair at the Cavendish Laboratory in Cambridge, when he took with him his consignment of radium. Rutherford was succeeded in the Langworthy Chair by WL Bragg (1919 - 1937), PMS Blackett (1937 - 55), S Devons (1955 - 60), and BH Flowers (1961 - 1972). In 1967, the Department of Physics moved to a new building.

I.3.1 The Schuster Laboratory 1900 - 1912

The Manchester Physical Laboratories were designed by the architect JW Beaumont with close supervision by Arthur Schuster and they opened in 1900. A detailed account of the New Physical Laboratory is provided in a publication by the University of Manchester in 1906 in commemoration of 25 years of Arthur Schuster's Professorship (Schuster and Hutton 1906). A floor plan of the New Physical Laboratories as they were in 1900 is provided in Appendix B3 of this report. The building was constructed on four floors consisting of a basement, ground, 1st and 2nd floors. The ground floor was primarily devoted to electrical engineering and electro-chemistry, except for one room which was designated for "private research" and a workshop next door. The 1st floor was primarily devoted to elementary teaching of practical physics and included a general and elementary physics laboratory as well as specialised teaching laboratories for acoustics, optics and electricity and a "balance room" off the general laboratory. The 2nd floor and basement were primarily designated for research with named "research" rooms on the 2nd floor. The 2nd floor also housed a small and a large lecture theatre and an associated preparation room.

I.3.2 Radioactive Substances in the Schuster Laboratory

I.3.2.1 Acquisition of radioactive materials in Manchester 1903 - 1912

The first indication of the use of radium at Manchester is a receipt dated 27th October 1903 for 20 mg of $RaBr_2$ and made out to Arthur Schuster at his private address in Victoria Park. It was obtained from Chemists Armbrecht Nelson and Co of London at a price of 30 pounds for 5 mg. This acquisition was shortly after Schuster had attended the Meeting of the British Association held at Southport in October during which he participated in the crowded session on the nature of radioactivity and the origin of the heating effect of radium. Some time after this, Schuster obtained a further quantity so that a total of 60-70 mg of radium bromide was available:

"The discovery of the radio-active elements has opened up an entirely new field for scientific enquiry, and so great has been the influence of the investigations in this subject upon physical theories, during the last few years, that no physical laboratory could be considered complete without the means for carrying on

research in this branch of science. The department now possesses between 60 and 70 milligrams of the most active preparation of radium bromide. The greater part of this radium was purchased by Professor Schuster for the Laboratory from the proceeds of a course of four lectures on “Rays and Radio-Activity” given in October and November, 1903. With this large provision of material, experimental work is much facilitated.” [Shuster and Hutton 1906]

It is clear, however, that Schuster’s radium was insufficient for Rutherford, possibly because of its low purity, or possibly because it had already been committed to other experiments, and he set about acquiring further materials. Shortly after his arrival in Manchester in 1907, an additional amount of about 500 mg of radium bromide (equivalent to about 250 mg radium) was obtained on loan from the Vienna Academy (Rutherford and Royds, 1908). This assignment of radium compound arrived in January 1908. At about the same time, Rutherford also acquired from the Royal Society residues of actinium (Ac227) and polonium (Po210). In addition, in 1908-1909 he obtained amounts of thorium (Th232) and mesothorium (Ra228) compounds from Otto Hahn. He also acquired uranium and thorium compounds from his friend Boltwood. Table 3 below gives a summary of the history of acquisition of these substances.

Table 3. Rutherford's Manchester Inventory of Radioactive Substances

Uranium Series	**Thorium Series**	**Actinium Series**
U_3O_8 (Boltwood, 1908) Uraninite 1 (Joachimsthal, Boltwood, 1908) Uraninite 2 (Joachimsthal, Boltwood, 1908) Ionium (Boltwood 1909-10) 20 mg $RaBr_2$ 1 (Schuster 1903) 40-50 mg $RaBr_2$ 2 (Schuster 1903?) 500 mg $RaBr_2$ 3 (Vienna 1908) 7 mg $RaBr_2$ 4 (Vienna 1912) Polonium residues (Royal Society, 1907)	Th O_2 1(Boltwood, 1908) Th O_2 2 (Boltwood, 1908) Th salt (Hahn) Mesothorium (Hahn) (Ramsey 1905)	40 kg actinium residues (Royal Society, 1907) Actinium (Boltwood, 1909-10)

Residues from the Royal society 1907

In the 1907-1908 “Report on the Physical Laboratory” (University of Manchester, 1908), Rutherford notes the following:

“The Royal Society loaned to the Director for experimental purposes the residues of actinium and polonium from a large quantity of pitchblende. Methods of separation have been devised and are now in progress.” [Rutherford 1908]

Shortly after receiving the residues, he seeks the advice of Boltwood on chemical methods for processing this material.

Rutherford to Boltwood

28 July 1907. "By the way I have got polonium and actinium residues from the RS...The later is in the form of hydroxide 40 kilos in weight. ... Can you give me the benefit of your advice as to the best method of rapidly concentrating the actinium?... I shall probably have a chemist or two to turn onto it, keeping a close tag on things by radioactive and growing radium tests".

Rutherford to Boltwood

20 October 1907. "I am sending you 100 grams or so of residues for you to look at. The activity as wet paste is six times UrOx and when dry 70 times."

Boltwood to Rutherford

28 Nov 1907. "I want to thank you... in sending me the 184 grams of the RS 'Actinium' residues....It requires quite a stretch of the imagination to designate it as 'Actinium' though,..., it contains a good many other things radioactive and otherwise....The precipitated sulphides (lead, antimony, tin, bismuth, Ra D and Ra F), were filtered off ... The residue remaining weighted only a fraction of a milligram and had an activity equal to about one gram of uranium. The activity of this preparation appears to be due entirely to ionium, although I have not had it under observation long enough to be sure that there is no actinium..."

Rutherford to Boltwood

8 Nov 1908. "I note what you say re actinium. The stuff I've separated is not very active - about 400 (150 grams of it)."

450 mg Radium Bromide from the Vienna academy 1908

In the 1907-1908 “Report on the Physical Laboratory” (University of Manchester, 1908), Rutherford notes the following:

“The Vienna Academy of Sciences generously loaned to the Director radioactive material containing 450 milligrams of radium bromide. The use of such a large quantity of radium has proved invaluable for carrying out a number of important researches.” [Rutherford 1908]

On 5th October 1907, Rutherford had formally applied to the Kaiserliche Akademie der Wissenschaften of Vienna for a loan of "about half a gram of pure radium". He notes in the letter that the University at this time has "less than 30 milligrams of radium bromide" (that leaves 30-40 mg unaccounted for, presumably in use by Makower and co-workers). The Vienna Academy then arranged for Rutherford to share 250-350 mg with Ramsey in London. The well documented friction between Rutherford and Ramsey led to Rutherford being given a second loan.

Rutherford to Boltwood

24 November 1907. "This brings me to the Radium question. I think I told you the Austrian people promised me about half a gram of Ra. Apparently they changed their mind.... I believe they have nearly 3 grams in all and I don't blame them. Apparently Ramsey had been promised some too, so they finally gave us 250 mg $RaCl_2$ in common."

Rutherford to Boltwood

15 Feb 1908. "I feel considerably picked up as the Austrian Acad have kindly sent me some 7% Ra preparation containing about 500 mg $RaBr_2$. I am now quite independent of Ramsay and have got more than he has ...."

Rutherford, nevertheless, adopted Ramsay's method for storing radium in solution, an account of which is given in Ramsay (1908) and in Gray and Ramsay (1909), although it is apparent from the 1905 photograph taken in the Macdonald basement that he had already been using a similar set-up.

Samples of Uranium Oxide from Boltwood, 1908

Boltwood to Rutherford

11 October 1908. "I am enclosing with this letter a sample of the purest uranosouranic oxide (U3O8) made from uranium nitrate.... I also enclose a small sample of my No.2...uraninite...You will notice that it contains 6.1% ThO_2. I also send a sample of No. 5 uraninite."

Rutherford to Boltwood

7 March 1909, "Geiger is hard at work with your samples of Ur and other minerals"

Samples of Thorium Oxide from Boltwood, 1909

Rutherford to Boltwood

30th May 1909. "I am enclosing with this letter two samples of material the one sample of pure thorium oxide, just separated from thorianite. It has been completely separated from radium and other products of the uranium series except ionium and uranium-X. The thorianite was of the variety containing 78% of ThO_2 and 10% U. The thorium oxide should then contain ionium sufficient to contribute about 4.5% of total alpha activity when the thorium products have come into equilibrium, which will be about July 1st.....I am also sending you a small sample of thorite which is unique in that it contains only about 0.44% of Ur and 52% of ThO_2 (45% of thorium)...I hope that I am not sending these substances too late to be of use to Geiger in his counting experiments."

Since it is clear from this correspondence that these various substances were used extensively by Geiger, Table 4 below gives the key counting articles from this time.

TABLE 4: A sample of articles making use of substances for range and number of a-particles

Substance	**Article**
Uranium 238	Rutherford and Geiger (1910) Geiger and Nuttall (1911)
Thorium 232	Geiger and Marsden (1910) Geiger and Nuttall (1912)
Actinium 227	Geiger and Marsden (1910) Geiger and Nuttall (1912)

I.3.2.2 Radiochemical methods for the separation of the products of decay

In addition to the above counting experiments using the raw materials provided, it was necessary to carry out chemical procedures on the substances in order to separate out the products of decay: (1) to produce α-sources for scattering and transmutation

experiments, (2) to study the nature of the decay, and (3) to study radiations produced by the products of radioactive decay. A great deal of information on these can be obtained from texts written by Rutherford (1908, 1913) and Geiger and Makower (1913). The sources were mostly either radium emanation (radon 222) or radium C' (Polonium 214).

Emanation (Radon)

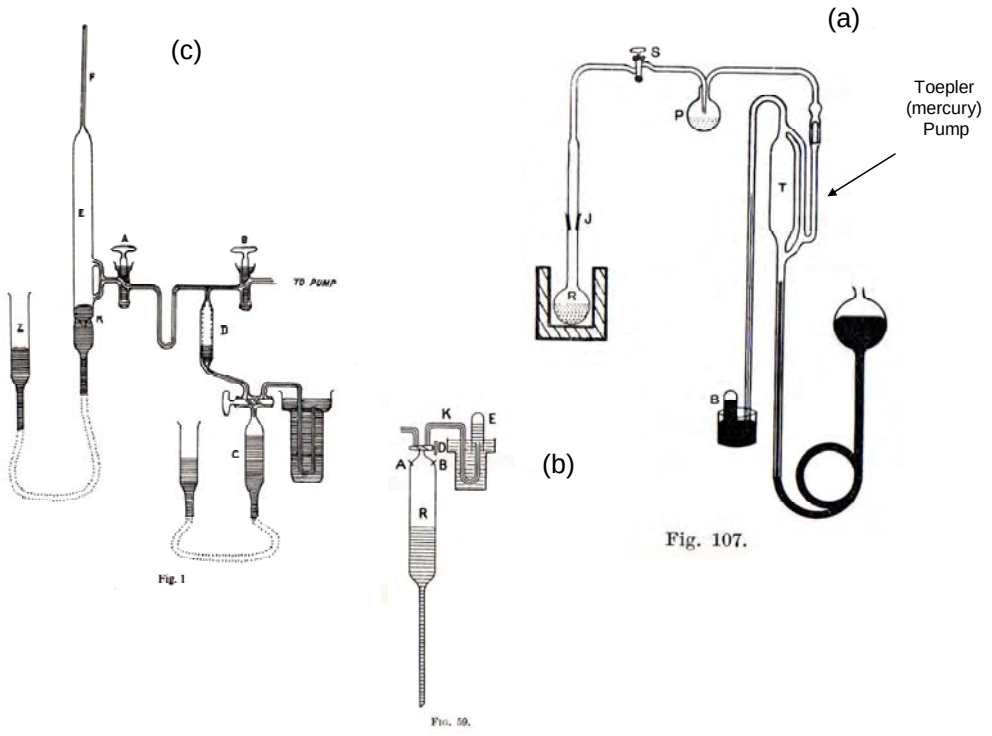

Figure 1. (a) shows the radium bromide apparatus where the radium (R) is kept in an HCl solution (Rutherford 1913). The whole apparatus is evacuated by means of a Toepler mercury pump (T) and the radon is drawn off over mercury into a small burette (B) using the method of Ramsay (1907). (b) shows the associated apparatus for sparking the unpurifed gas (Makower and Geiger 1912). (c) shows the apparatus for further purification and for compressing the radon into a 'radon tube' (Rutherford 1909).

The radium was kept dissolved in HCl and about 50 cc placed in a 100 cc bulb which was mounted inside a second strong glass vessel in case of an accidental breakage. This was surrounded by thick lead to absorb the gamma-rays. Under reduced pressure, the radium solution boils and emanation is carried off into a pump and into an inverted tube over mercury (see Figure 1a, but this omits the second strong glass vessel). The emanation was, however, impure because of other gases, notably hydrogen, oxygen and CO_2 produced by the decomposition of water in the solution and the effect of emanation on the grease used to seal the stop-cocks. In order to purify the emanation, it is transferred over mercury from the tube to a reservoir (see Figure 1b). A spark produced by an induction coil is passed through the gas in the reservoir to make the H and O_2 combine. This reduces the volume of gas to about one-fifth. The remaining gas was then exposed to caustic potash for some hours, to remove the CO_2 and H_2O vapour. The next stage of

purification involves condensing the gas in a U-tube immersed in liquid air (see Figure 1c). The purified emanation was transferred to the experimental emanation tube by means of a reservoir by raising the level of mercury. The experimental tube is then sealed off in a blow-pipe. In order to avoid further CO_2 from the tap grease, all stop-cocks are lubricated with phosphorous pentoxide. The emanation tubes produced in this way took considerable skill and were first used by Rutherford and Royds with the assistance of the glass-blower Otto Baumbach.

It should be clear from the above that in addition to spillage of solution there was a strong possibility of spillage of the mercury. Mercury pumps were widely used to evacuate the apparatus and the radon was transferred to other apparatus over mercury. Substantial quantities of mercury were indeed found in the Manchester radium room (see Section II).

It was also an inherently dangerous procedure due to the risk of exposure to radiation. Makower and Geiger caution:

"When using large quantities of emanation alpha-ray tubes should be handled with great caution, for they constitute a very powerful source of radiation, and if held in the hand too long may produce "burns" which are very difficult to heal. In all the manipulations involved in extracting the emanation and filling tubes with it, it is important to take precautions to prevent the escape of emanation as far as possible; for the emanation diffuses about and may contaminate electroscopes throughout the laboratory." [Makower and Geiger, 1913]

Radium C

The procedure for separating radium C was carried out in two steps. First, the active deposit was collected on a platinum plate (Figure 2). For small quantities this involved dissolving $RaBr_2$ in hydrochloric acid and making the solution positive. The deposit was collected on a platinum plate above the solution which is negative, in order to attract the +ve radon ions.

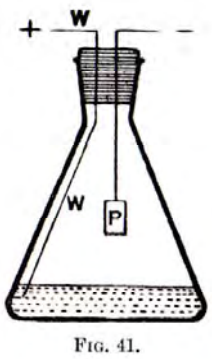

FIG. 41.

Figure 2. Apparatus for collecting the active deposit from radon gas above a solution of radium bromide (Makower and Geiger, 1912).

This procedure, however, had the potential for accidental escape of radon. Makower and Geiger caution that

"The manipulation should be carried out quickly to prevent the escape of emanation....When working with large quantities of radium this method of exposure is unsuitable, since it is impossible to prevent occasional

losses of emanation. The escape of any appreciable quantity of emanation should be avoided as it diffuses through the room and contaminates any measuring instruments which it reaches." [1913, p73]

The second step involved separation of the radium C from radium A (Po218) and B (Pb214).

"The platinum surface is washed with alcohol to remove traces of emanation and the deposit is dissolved in hot HCl. The solution is diluted and a nickel plate immersed in it. The solution is agitated and radium C deposited by electro-chemical action. The plate is then thoroughly washed with hot water to remove the solution adhering to it." [1913, p73]

Again, it is easy to see how contamination by the spillage of solutions could occur.

Actinium and Thorium C

For Thorium C (Bi212), the active deposit of thorium is collected on a platinum foil and dissolved in HCl. Thorium C is then separated by the same method as for radium C (Makower and Geiger, 1912).

Actinium C (Bi211) is also separated in a similar manner as for radium C (Makower and Geiger, 1913). The deposit is collected in an electric field on platinum. The platinum is then placed in boiling HCl to dissolve the deposit and the solution neutralised. A nickel plate is then placed in the solution for a few minutes and is then removed and washed with water. This procedure needs to be carried out rapidly as the half-life of actinium C is only 2.1 minutes.

Radium E

Radium E (Bi 210) is separated from D by electrolytic deposition on silver in an HCl solution of radiolead (Makower and Geiger, 1913).

Radium F

Usually obtained from an old radium D solution in which radium F has been allowed to accumulate. A polished plate of copper or bismuth is immersed in the solution for about one half an hour. This can also be used with a radium solution.

I.3.2.3 Experiments with radium at Manchester before Rutherford

Schuster's interest in radioactivity from 1903

It seems that Schuster had been inspired by his attendance at the 1903 British Association:

"The discussions at Southport must have greatly excited Schuster. For within the next few months he had written two letters to Nature concerning radium and presented a course of lectures on 'Rays and Radioactivity'." [Davies 1983]

It is apparent that Schuster had begun experimenting with radium within days of his acquisition of the 20 mg of RaBr2 on 27th October. The two letters, both entitled the "The heating effect of radium", are dated 5th and 19th of November and merited a reply by Rutherford and Barnes on December 10th 1903. In the second of the letters, Schuster describes the experimental procedure:

"A fortnight ago I wrote to you respecting the rise of temperature observed in radium compounds. I pointed out that the experiments of Profs Rutherford and Barnes seemed to show that the effect was largely due to the excited activity. I have since made a few experiments confirming that view.

Air charged with radium emanation was led through a tube in which I placed a thermal junction … The junction was left charged to a high negative potential during about ten minutes, then taken out and placed side by side with an unexposed junction … The two junctions at first seemed to be at the same temperature, but the exposed one began to become warmer almost immediately … The experiment was repeated with the same result … Experiments are now in progress to test the matter further." [Schuster 1903]

Research 1904-1905

There is no evidence, however, that that Schuster took this line of enquiry further -- at least, no further publications on this issue appeared. Nevertheless, Schuster encouraged research using radioactive substance by younger members of the department. In the 1904-1905 "Report on the Physical Department", for the University Council, Schuster notes:

"Mr Makower has begun a research on certain features of radioactivity." [Schuster 1905]

Walter Makower had joined the University as John Harling Research Fellow in 1905. Previously, he had graduated in chemistry from UCL (William Ramsey's Department) and then worked a research student under JJ Thomson at the Cavendish for his MA on the diffusion properties of radium emanation. The lag of a year or so between his acquisition of radium in 1903 and the initiation of a sustained programme of research may have been because prior to Makower there was no one at Manchester with experience of working with radioactive substances. Makower's work at the Cavendish would have benefited from the presence of Harriet Brooks who, after her early Montreal work with Rutherford, spent some time in Cambridge collaborating with Rayleigh.

The work referred to in the Council Reports appeared in the November 1905 edition of the *Philosophical Magazine* in an article entitled "On the Method of Transmission of the Excited Activity of Radium to the Cathode". The apparatus used by Makower in his 1905 experiment is shown in Figure 3 below. There are several features of this apparatus of interest. First, the radium bromide solution, the source of emanation, is directly connected to the main apparatus. This stands in stark contrast to Rutherford's set-up, as shown in Figure 1, where he kept the radium bromide solution completely isolated from the main experimental apparatus, the emanation being transferred in a burette over mercury. A second important feature is that the space above the radium solution was kept at atmospheric pressure by means of a capillary tube *c*. Makower states that the capillary was of sufficient length so that "the rate of escape of emanation from the bottle by diffusion was rendered small". However, we know from Rutherford's description of his radium bromide apparatus that the pressure above the solution would rise from the mixed

gases evolved (30 cc per week from 250 mg of pure radium). Thus, if the apparatus was left for any length of time, a pressure gradient would develop, and increase the rate of escape. Makower does not give a quantity of radium salt used, but refers to a "strong solution" and he had up to 70 mg available. From Rutherford's letter to the Vienna Academy in October 1907, in which he notes that the University has less than 30 mg, we may infer that Makower may have used up to 40 mg of salt, corresponding to about 30 mg of pure radium. This would yield about 4 cc of gas per week and we know that the apparatus was allowed to stand for several weeks until the concentration of emanation had reached maximum. A third feature is that in addition to the cathode becoming active, the containing vessel and all of the other apparatus would become active, including the McLeod pressure gauge and the pump. The experiments done using this apparatus would almost certainly have given rise to significant contamination.

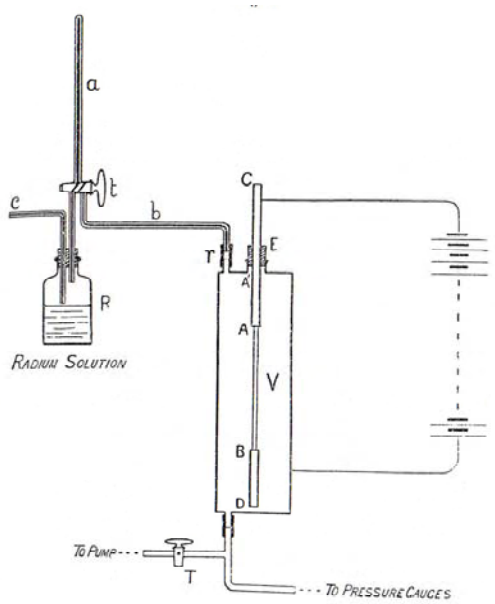

Figure 3. Makower's 1905 apparatus for inducing active deposit of radium emanation on a cathode.

Research 1905-1906

According to the 1905-1906 "Report on the Physical Department",

Mr Makower (John Harling Research Fellow) has completed his research on the mode of transmission of the excited activity of radium to the cathode. His paper on the subject is published in the *Philosophical Magazine*. During the session he has been engaged on an investigation on an investigation concerning the effect of high temperatures on the activity of radium emanation. A paper giving an account of the preliminary results has been published in the *Proceedings of the Royal Society*. … Mr Sidney Russ worked in conjunction with Mr Makower on the effect of high temperatures upon radium emanation. [Schuster 1906].

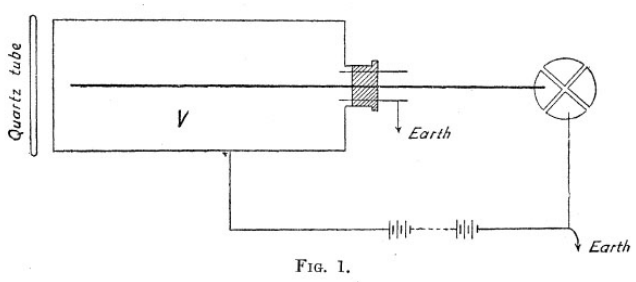

FIG. 1.

Figure 4. Apparatus used by Makower (1906) to investigate the effect of temperature on radium emanation. The emanation from 5 mg of radium was contained in a quartz tube and heated up to 1300 deg C.

Makower's 1906 heating experiment was submitted on 22nd November 1905 and published in March 1906 as "On the effect of high temperatures on radium emanation" in *Proceedings of the Royal Society*. The experiment involved sealing radium emanation from 5 milligrams of radium bromide in a quartz tube (Figure 4). The tube was connected to a bulb containing the radium and the apparatus evacuated to allow the emanation to diffuse freely. The tube was then immersed in liquid air to condense the emanation and the tube sealed using a blowpipe.

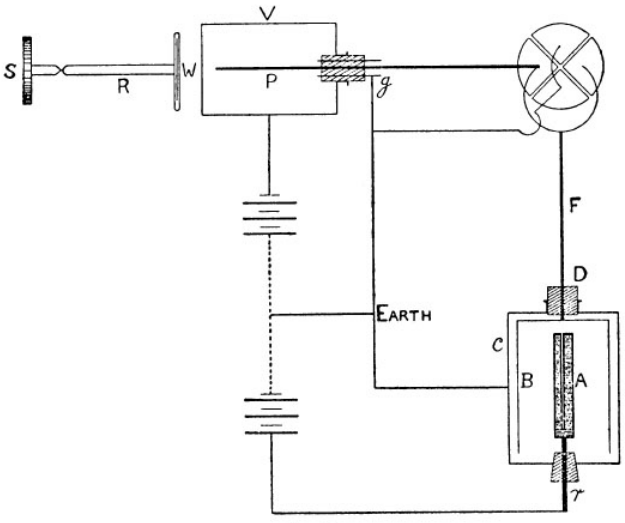

FIG. 3.

Figure 5. Apparatus used by Makower and Russ (1907) to investigate the effect of temperature on radium emanation using a differential method. The activity of wires W and r, which had been identically exposed of radium emanation, were compared when W was heated.

The follow-on experiment conducted by Makower and Russ used a more sophisticated differential apparatus. By this time, Makower was Assistant Lecturer and Sidney Russ was employed as Demonstrator of Physics. Their joint work on the effects of temperature were submitted on 10th November 1906 and published on May 14th 1907 as "On the effect of high temperatures on active deposits from radium" in *Proceedings of the Royal Society*. In the differential method, two platinum wires *W* and *r* were exposed to a "considerable quantity of radium emanation" for four hours. Wire *W* was then sealed in a quartz tube and subject to heating while the other wire *r* was kept at normal temperature. The ionising effects of these were compared by means of an electrometer.

Research 1906-1907

Schuster's last official report as Langworthy Professor was made in the 1906-1907 "Report on the Physical Department" (University of Manchester 1907):

"Mr Makower completed his work on the effect of high temperature on the radium emanation, and begun a research on the effect of electric fields on the active deposit of radium at high temperatures.

Mr S Russ worked in conjunction with Mr Makower in the first of the above investigations, and is at present investigating the effects of low pressure on the distribution of radio-active deposits. …

Mr Thomas Royds (Graduate Scholarship 1906) carried out a practical determination of the resolving powers of a spectroscope with wide and narrow slits, and extended the study of the constitution of the spark by photographing spectrum on a revolving film. …

Mr William Wilson (Third Year Honours student) studied the rate of decay of the active deposit of radium.

I have been chiefly occupied with a theoretical calculation … and with some experimental work on the effects of pressure on radio-activity." [Schuster 1907]

This last report is interesting for a number of reasons, not least that it indicates that Thomas Royds was already developing an interest in spectroscopic work, which may have been carried out in the Grating Room (2.60/2.61) or the Optics Room (1.53). It also shows that Schuster himself had been continuing research with radium. This work was published in *Nature* as "On the influence of pressure on radio-activity", July 1907:

"I have, during the last eighteen months, been engaged in an investigation on the effects of pressure on radio-active phenomena. In designing the apparatus necessary for the purpose, it was necessary to consider that if any change in the rate of production of the emanation occurs through pressure, effects would not be noticeable at once, as a new state of equilibrium would only be reached after several days. Similar considerations hold if any of the slowly decaying products is affected. A special pressure pump was therefore constructed according to the designs of Mr. J. E. Petavel, and this pump allowed me to keep up a pressure of about 2000 atmospheres almost indefinitely without sensible leak. The time of the experiments was not, however, extended beyond four or five days. The results have been entirely negative, and I estimate that a change in the activity of one-third per cent, would have been noticed.

During the course of the investigation several fictitious effects made their appearance, and it was the elimination of these which necessitated a gradual improvement in the methods of observation and took up the greater part of the time occupied in the experimental inquiry.

In addition to the help of Mr Petavel which has already been mentioned, I have had the assistance of Mr. Makower in the early stages of the work. The final experiments were conducted by my assistant, Dr. Hans Geiger." [Schuster 1907]

The work done by Russ had initially been done in collaboration with Makower, but later Russ continued this work alone. This was published in an article, "The Distribution in Electric Fields of the Active Deposits of Radium, Thorium and Actinium" read on March 13th 1908, which was only a few weeks after the Vienna radium arrived at Manchester. Only in the latter stages did Rutherford have a direct input to this work.

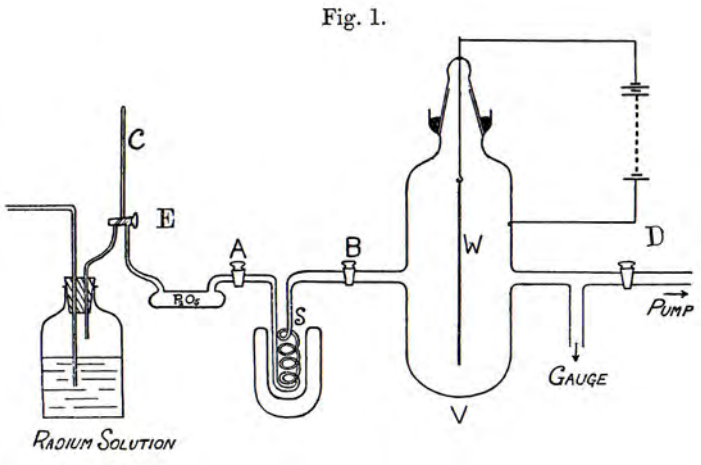

Figure 6. Apparatus used by Sidney Russ to measure the distribution of active deposit in an electric field. This included a P_2O_2 tube for drying and a condensing coil immersed in liquid air.

Figure 6 above shows the apparatus used by Russ for this purpose. It is highly likely that the radium solution, and indeed the bottle in which it was kept, was the same as that used by Makower. There were, however, a number of new features. The capillary tube which connected the radium bottle to the atmosphere was inserted below, rather than above, the surface of the solution. This would have reduced venting of emanation, but if the pressure was allowed to build over several weeks, there was a danger that radium solution itself could be forced out of the capillary. The apparatus also included components for purifying the gas, a P_2O_2 tube and condensing coil immersed in liquid air.

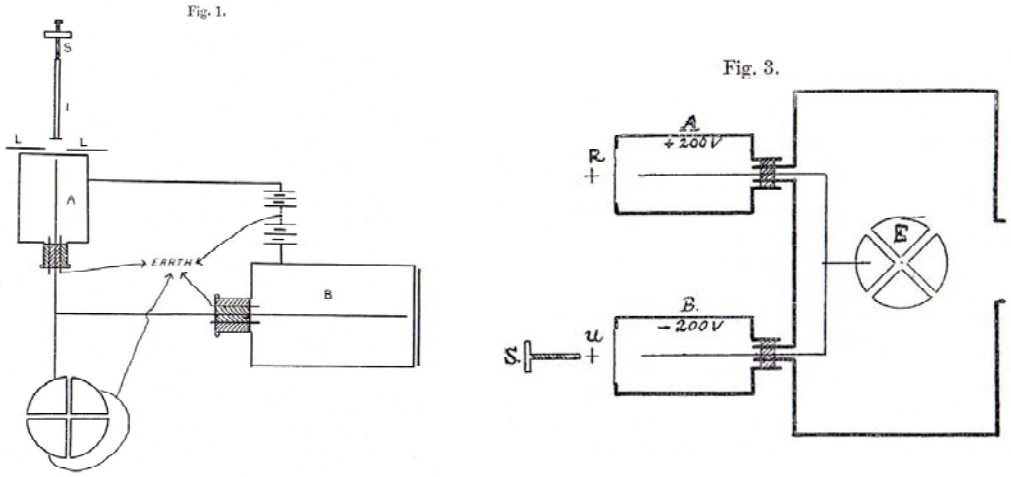

Figure 7. Apparatus used by Wilson and Makower (May 1907) (left) and Geiger (April 1908) (right) to balance the ionisation currents from two sources. The sources (R and u) were mostly radium C and were openly exposed during the experiment. Geiger's experiment also made use of 5 mg of radium bromide

In addition to collaborating with Russ, Makower also worked with W Wilson, who carried out experiments to measure ionisation currents from two sources. Makower and Geiger must have been collaborating on this as Geiger published a paper about a year after Makower using a very similar apparatus, as shown in Figure 7 (right). The sources

were primarily radium active deposit and would have been prepared using the apparatus as shown in Figure 2. Geiger's experiment also made use of 5 mg of radium bromide in a quartz tube. (This 5 mg source was used in other experiments, including those by Russ and Makower.) In addition to the spillage of solution and the release of emanation in the preparation of the sources, the fact that the sources were exposed would likely have given rise to further contamination.

Research 1907-1908 and the transition to the Rutherford Period

Rutherford gives an account of the completion of the above work in the first of his reports in the 1907-1908 "Report on the Physical Department":

"Mr Makower continued his observations on the effect of temperature on radioactive products, …

Mr Russ investigated …the distribution of the active deposits of radium and actinium …

Mr Royds, Beyer Fellow, continued his work upon the constitution of the electric spark , the results of which have been published in Philosophical Transactions of the Royal Society. He assisted Professor Rutherford in the purification of radium emanation and in the determination of its spectrum. …" [Rutherford 1908]

It is clear that, from 1903 onward and by the time Rutherford had arrived, a significant amount work using radium had been in progress at Manchester. Given the above descriptions of the experiments, it is almost certain that there would have been some contamination in the Schuster Laboratory at this time. There is a hint of this in the following letter to Eve written shortly after Rutherford's arrival in Manchester.

Rutherford to Eve

June 11, 1907. "I have been in Manchester since my arrival & have got pretty well settled down in the Lab. I have rigged up the emanation electroscope & my actinium solution and hope to get a reading of all of them this week. … The lab itself has only a small workshop… Just alongside, however, is a regular workshop under the charge of Cook – formerly Dewar's assistant in the Royal Institution, which has a contract with the University … This, I think, will prove invaluable as not only is he skilled in all pressures and big work but has three or four first class mechanics to turn in work in a hurry. He made me an α-ray electroscope which has an extraordinarily small natural leak, so I have hopes to avoid all contamination in his shop – I made a γ-ray electroscope of moderately low leak. Also, by the way, my emanation electroscope when refitted up gave .16 divs natural leak – it was 0.15 in Montreal, so you see there is a fate about the numbers."

I would interpret this as indicating that Cook's workshop, removed from the Schuster Laboratory, was uncontaminated at the time of writing. However, materials within the main building had already become contaminated, to the extent that electroscopes constructed from these materials showed the same leak as those from the Macdonald Laboratory. This interpretation is supported by the following passage from Makower and Geiger's (1913) text book in section 19 on the "Natural Leak of Electroscopes".

"If the insulation of the leaf is good and the apparatus is otherwise working satisfactorily, the leaf will not move more than about a tenth [0.1] of a division per minute … If the natural leak is much higher than this, the sulphur insulation should be cleaned …; and if this is not effective in reducing the leak …, the inside of

the electroscope should be cleaned to remove any adhering radio-active matter. It may happen that the natural leak is increased by the presence of radium emanation in the room, which must then be thoroughly ventilated." [Makower and Geiger 1913]

I.3.2.4 Use of alpha-particle sources 1908 - 1919

TABLE 5: A sample of articles making use of α-sources from radium

α-source	publication	source strength
radium (Ra226)	Geiger (1908) Rutherford and Geiger (1908)	5 mg
radon (Rn222)	Rutherford and Royds (1909) Geiger and Marsden (1909) Geiger and Marsden (1913) Rutherford and Robinson (1914)	140 millicuries 20 millicuries 100 millicuries
radium C (Bi/Po214)	Rutherford and Geiger (1908) Geiger and Marsden (1909) Geiger and Marsden (1913) Rutherford (1919abcd)	 30 - 80 millicuries 5 to 80 millicuries
radium F (Po210)	Rutherford and Geiger (1910)	

As noted above, a primary use for radium during the Rutherford period was for sources of α-particles, either from a radon tube, or from metal plates coated with radium C or F. At Manchester, most sources were of the first two kinds. Table 5 above gives a sample of publications from the Manchester period which use α-sources. Although the sample of articles in Table 5 is far from complete, it does include some of the key papers of this period. We can see that both radon tubes and radium C sources were commonly used. Radon had the advantage that large strength sources could be produced which would last for a few days. For radium C+C', with a half-lives of 20 mins and 160 microseconds respectively, the experiment had to be prepared quickly and the sources were of low strength, but the individual α-particles had a higher energy than α-particles emitted by radon. Radium F at this time was not commonly used. The fact that generally two strengths of radon sources were used suggests that there were two sets of radium bromide apparatus in use, the stronger source (100 - 140 millicurie) being the Vienna radium and the weaker (20 millicurie) being from the original Schuster radium used by Makower.

I.3.2.5 Radiochemical Work before and after the extension in 1912

TABLE 6: Sample of radiochemical work before and after 1912

Series	Before 1912 (in the shed)	After 1912
Uranium-radium	Boltwood (1911)	von Hevesy and Putnoky (1913) Russell and Rossi (1912)
Thorium		Darwin and Marsden (1912)
Actinium	Boltwood (1911) Geiger (1911) von Hevesy (1911)	Marsden and Wood (1913) Marsden and Perkins (1914)

In addition to counting and scattering experiments, a considerable amount of radiochemistry was carried out on all three series. Before 1912, some of this was done in

a shed outside the main laboratory, and after 1912 in a chemical laboratory attached to the extension. Table 6 above shows some of the publications on the chemical work conducted before and after 1912. In the samples given, Boltwood (1911) separated out actinium (Ac227) and ionium (Th230) from the Royal Society residues during his visit in 1909-1910. The ionium was later made use of by Russell and Rossi (1912).

I.3.3 Room Use in the Schuster Laboratory

I.3.3.1 The Radium Room

Makower and Geiger (1912) recommended that a special room be set-aside for the handling of radium:

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

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

Rutherford (1913) provides similar recommendations:

"In a laboratory in which radio-active experiments are constantly made, it is desirable that all sources of active matter should be kept in sealed vessels, in order to avoid possible radio-active contamination due to the distribution of radio-active material. This is especially important with a substance of a high activity like radium. The presence in a closed room of an unsealed capsule containing a few milligrams of radium salt, on account of the escape of the emanation, is sufficient in the course of a day to increase greatly the spontaneous leak of neighboring electrometers and electroscopes..... In many laboratories, the radium emanation is now used in the place of radium itself for many experiments. It is important that this emanation should be kept in sealed vessels, and the work of transference should be done in some part of the laboratory where any accident involving the escape of emanation shall not lead to the contamination of the main part of the building." [Rutherford, 1913, pp112-113]

It is clear from the above that the view at this time was that the ideal location of the radium room should be at the top of the building. Rutherford attempted to keep the radium clear of his main experimental work by keeping his radium in a room on the top floor some distance away from his main research rooms on the ground floor and basement.

In an interview with Devons (Hughes, 2008), William Kay gives a strong clue to the location of the radium room:

"Well, the radium room was right at the top at the far end. That's where we kept the radium. That's where he did all his production of emanation-rays, in there with Boltwood. That's where all the glass apparatus was, but the other room, where we did all the atom work was right at the bottom, a room on the ground floor. And of course, the rooms was all over the place, you see, and Moseley did all his work in the room underneath that, you see." [Hughes, 2008, p102]

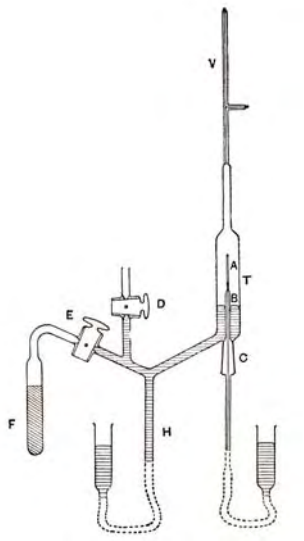

Figure 8 shows the apparatus used by Rutherford and Royds (1909)

We may be confident of the location of the radium room to which Kay refers to in this case, as this was also the location of the Rutherford and Royds (1909) experiment on the helium nature of the alpha particle. This room is located at the west end of the 2nd floor on the north side and was designated as a “Transit Room” in 1906. The contemporary number is 2.62 and the room was marked by a plaque on the wall commemorating the Rutherford and Royds (1909) experiment. The apparatus for this is shown above in Figure 8, from which it should be apparent that there was a distinct risk of mercury spillage, in addition to that from the radium bromide apparatus. In this room, quantities of mercury were found under the floor boards in 2000 (see section II).

Although it seems clear that 2.62 was a main site of storage of radium, there is sufficient ambiguity in other recollections from Geiger and Moseley to suggest that there may have been a second site (and we know that Makower and Russ used a bottle of solution before the Vienna radium arrived). Geiger recalled:

“When I look back on the five years which I spent with Rutherford as a young physicist in Manchester, many delightful impressions spring to mind. I see his quiet research room at the top of the physics building, under the roof, where his radium was kept, and in which so much well-known work on the emanation was carried out. But I also see the gloomy cellar in which he had fitted up his delicate apparatus for the study of the a-rays. Rutherford loved this room. One went down two steps and then heard from the darkness Rutherford's voice, reminding one that a hot-pipe crossed the room at head level, and that one had to step over two water-pipes... There was also a cheerful room upstairs, in which we all met for a cup of tea in the late afternoon.” [Geiger, 1938]

Geiger’s phrase “quiet research room at the top of the physics building under the roof” could be consistent with the Rutherford & Royds Room or it could also be consistent with use of the rooms above the Preparation Room, e.g. the Map Room (see Appendix B2), which could be construed as an “attic”, as in the following by Moseley :

Moseley to his Mother

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

There is, however, an ambiguity which makes precise localization difficult. Strictly speaking, between the ground floor and the 2nd floor there are four flights, two flights per level (if a flight is taken to be an uninterrupted series of steps). There is also a single flight to the basement and a single flight from the Preparation Room to the Chart Room. If his research room was on the ground floor, three flights would only take him half-way between the 1st and 2nd floors. If his research room was actually on the basement floor (as implied by Kay), and by "flight" he meant the sequence of steps connecting one floor to the next, then three flights would take him to the 2nd floor. The term "attic" is also consistent with room 2.62, as the rooms on the second floor do not have a flat ceiling, i.e. are under the roof.

Nevertheless, the separate location of the radium room at the top of the building, and the research rooms on the ground and basement meant that during an experiment, it was necessary to transfer the active source from the top to the bottom of the building. This is clear from the above description by Moseley in the letter to his mother, which was written during an experiment on the nature of β-particles produced by the decay products of radium (Moseley, 1912, "The Number of β-particles emitted in the transformation of radium", P R Soc 87, 230-255). It is clear from the above that Moseley prepared his source in the upper part of the building and then ran down the stairs. It is not clear whether he was holding the source in his hands while running.

In spite of the ambiguity in Moseley's letter, there is still a lot to be learned from it, in addition to the fact that the sources were transported between floors during the experiment. (An interesting conjecture put forward by John Churcher is that the sources may have been transported to the lower floors via the lift. This shaft extends from the basement to the top floor.) The sentence, "At present beta-ray experiments which must be got through while my supply of emanation lasts", in conjunction with the description given in his 1912 article, tells us that he had drawn off (or had drawn off for him) a quantity of purified emanation from the radium room and had put it into a small tube which would be active for a few days, during which he had a lot experiments to do. The next sentence, "The experiment is now clamoring for attention, and I must go to it" probably refers to the fact that radium B+C would reach equilibrium with the emanation within about five hours after the emanation had been extracted, so that he was waiting for the decay products to reach equilibrium while writing the letter. The apparatus for his experiments is shown below in Figure 9. In this apparatus, the emanation tube was placed inside a paper tube.

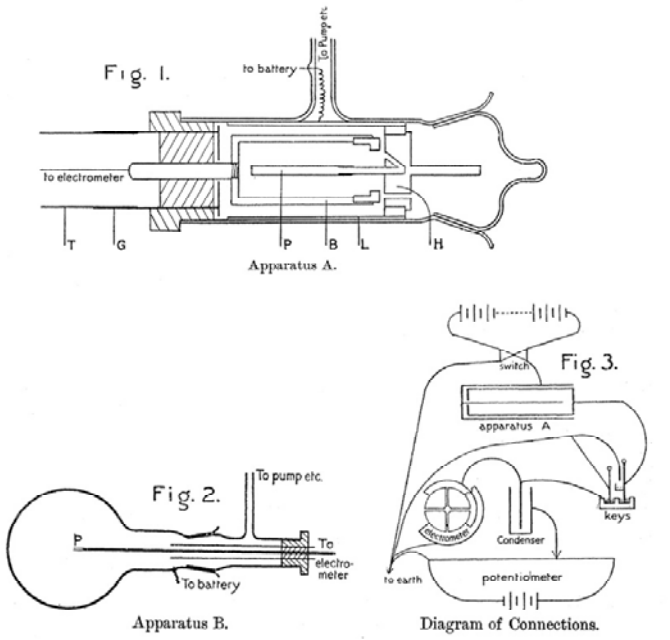

Figure 9. The apparatus used by Moseley in 1911-1912, either on the ground floor or the basement of the Rutherford Building, to investigate beta-rays. The sources contained in the tube (P) were the active deposit of radium emanation and were prepared at the top of the building. Radium B+C take about five hours to come into equilibrium with the emanation.

Moseley's comments about the heating are also of interest. It can be seen from the floor plan (Appendix B3) that the coal-fired boiler room was in the basement on the north-east side. This would have been producing a tremendous amount of heat locally as well as transmitting heat through the hot piping. Thus, his experience of a "Laboratory so steam heated that even with coat off it is hardly bearable" would be consistent with the occupation of a basement research room.

I.3.3.2 The Radioactivity Training Laboratory

In addition to the radium room, an important feature of the Manchester set-up was the radioactivity training laboratory.

Marsden (1949) recalls:

"Rutherford arrived at Manchester ....and I well remember a sort of inaugural discussion and meeting at the Physical Colloquium with A Schuster, JJ Thomson and Rutherford present, three giants all beaming and smiling in happy reunion.

I was then a callow youth in the second year of my honours degree. The arrival of Rutherford decided my fate - and what a spur of energy he was! I quickly ran through all the practical exercises in electricity and magnetism and optics etc., and then proceeded as the first of the guinea-pigs in those beautiful experiments in radioactivity drawn up by Rutherford and Geiger, and afterwards published by Makower and Geiger. We constructed our own electroscopes and obtained first hand acquaintance with the absorption and other properties of the alpha, beta and gamma-rays, and with the radioactive transformations of radium emanation and its products - and similarly with thorium and actinium."

A copy of Makower and Geiger's book can be found in the store of the John Rylands Library at Manchester. The inside front cover has Makower's name written in ink, from which it might be inferred that it was his personal copy. It was obviously a well-used laboratory book as some of the pages are stained from spillages of substances. Naturally, I took the precaution of having it checked for contamination and was relieved to note that the beta/gamma count was not higher than background. The pages which were stained were also tested for alpha contaminants and again proved negative, although not every page was tested.

It would appear that all newcomers to the Manchester Laboratory (including the theoretical physicists) were routinely put through the course. Niels Bohr recalls his arrival at Manchester in 1912:

"Naturally, to trace in every direction the consequences of the discovery of the atomic nucleus was the centre of interest for the whole Manchester group. In the first few weeks of my stay in the laboratory, I followed, on Rutherford's advice, an introductory course on the experimental methods of radioactive research which under the experienced instructions of Geiger, Makower and Marsden, was arranged for the benefit of students and new visitors. However, I rapidly became absorbed in the general theoretical implications of the new atomic model…." [Bohr, 1958]

Bohr's disinclination to get involved with the experimental work is evident in a letter to his brother.

Niels to Harald Bohr

May 27th, 1912. "...but I hardly have time to concentrate on such things...when I am at the Laboratory all day, which is absolutely necessary. You ask about the work in the laboratory. It is really going quite well. Unfortunately, I must say right off that I'm not yet sure how much will come of what Rutherford has put me on..."

Robinson recalls that the training laboratory for work on radioactive substances was also used as the tea-room:

"I am sure that the laboratory tea-table, situated in the radiation training laboratory, was far from the least important bench in the laboratory. Rutherford provided tea and biscuits every day, and nearly always attended himself, sitting at the table, with the rest of us perched on stools and the neighboring benches." [Robinson, 1943]

Robinson's recollection of the radiation training lab doubling up for the tea-room, in conjunction with Geiger's (1938) recollection that "There was also a cheerful room upstairs, in which we all met for a cup of tea in the late afternoon", would suggest that the training lab was either on the 1st or on the top floor. An inspection of the floor plan in Appendix B3 suggests that this could be located in the 2nd floor "Apparatus Room" or the 1st floor "Electricity Room", as these both had plenty of benches for people to sit at. There are arguments for and against either of these locations, but only the 1st floor room had sinks, i.e. a source of water for making tea, and adjoined the elementary laboratory, which would be consistent with it being used as a teaching room. Other evidence in favour of the 1st floor is that for both the 1900 and 1912 conversazione (see Section

1.3.4.2), the reception and refreshments were held in the large Electricity Room (1.51) and the radioactive experiments in the adjacent room were essentially the same as those described in Makower and Geiger's (1913) book.

I.3.3.3 Use of rooms and accidents 1908 - 1913

As discussed above, it is almost certain that some contamination of the building had occurred before Rutherford arrived in 1907, from emanation escape, spread of active deposits and spillage of solution. It is likely that as well as isolating the Vienna radium as shown in Figure 1, Rutherford would have wanted the Schuster radium, as used by Makower and Russ, to be placed in a similarly isolated apparatus, in order to minimise contamination from emanation escape. In spite of Rutherford's best intentions, however, it is apparent that accidents happened between 1908 and 1912 which caused the Manchester laboratory to become further contaminated.

Rutherford and Geiger in 1908-1909

Rutherford to Boltwood

8 Nov 1908. "I quite agree with you that the bigger problems of radioactivity can only be solved by the people with lots of Ra but there is still lots to be done with homeopathic doses. As a matter of fact, it is not very easy to run expts in the same Lab on the large & the very small scale. I have avoided all contamination so far but occasionally somebody knocks over an emanation tube downstairs when the Laboratory hums like a beehive with excited workers wanting to know what had gone wrong with electroscopes. I work upstairs & everything goes up & not down & we seldom let any emanation loose."

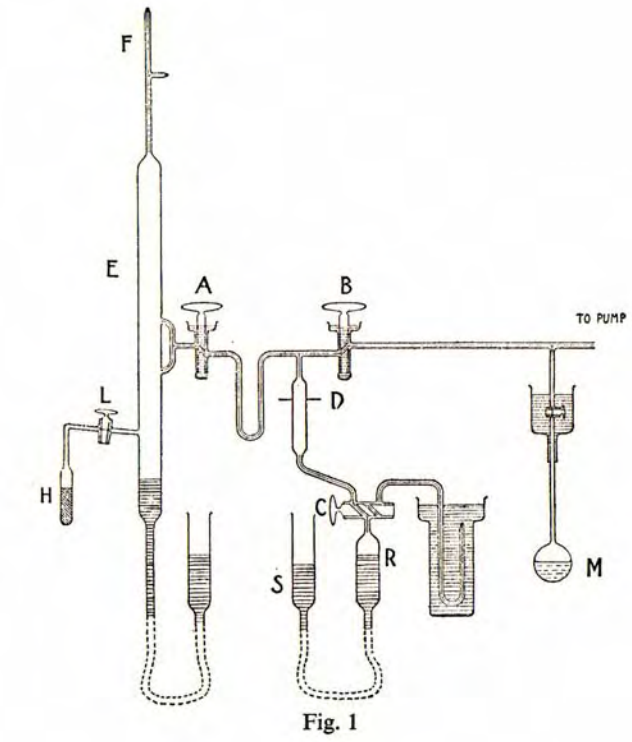

Figure 10. The Rutherford and Royds (1908) apparatus for measuring the action of emanation on water.

This incident raises important questions concerning the transport of how radon was transported in the building at the time. When Rutherford wrote “I work upstairs & everything goes up & not down & we seldom let any emanation loose.” he could simply have been stating his belief that the culprits for emanation release were at the bottom of the building. It may also reflect his beliefs about the properties and behaviour of radon in a building (I return to this issue in the discussion). At the time of writing this, Rutherford would have been working on the 2nd floor with Thomas Royds. His paper on “Spectrum of the Radium Emanation” had been published in August 1908, his paper “The action of the Radium Emanation upon Water” was published in November 1908 (see Figure 8 above) and his famous paper with Royds “The Nature of the α-Particle from Radioactive Substances” (see Figure 10) was submitted on 13th November, five days after his letter to Boltwood referred to above. Despite the fact that Rutherford was working with large quantities of emanation, he seems remarkably confident that he had not been responsible for significant amounts of emanation release. Judging from publications, the only other workers using emanation at this time were Geiger, Makower, Russ and possibly Marsden, who would have been working mostly in the basement. Geiger, as we see below, gives a different version of these incidents in his (1938) recollection of the Manchester laboratory:

"I always like to recall another little episode, which occurred at the time when much work was being done in the laboratory with sources of radiation consisting of extremely thin tubes filled with emanation. It was necessary to exercise great care lest any of this emanation should escape, for it spread rapidly throughout the building, and by virtue of its activity made experimental work an impossibility for periods of many hours. In his typically drastic manner, Rutherford had threatened the severest penalties for offenders in this manner. One day I noticed that it had become impossible to use an electroscope in my room, where I had fitted up the first counting experiments for Rutherford, and before long other research workers emerged from the neighboring rooms with the same sad story. We were not long in discovering that that the emanation had come from Rutherford's own laboratory, where at that moment he was actively engaged with his experiments."

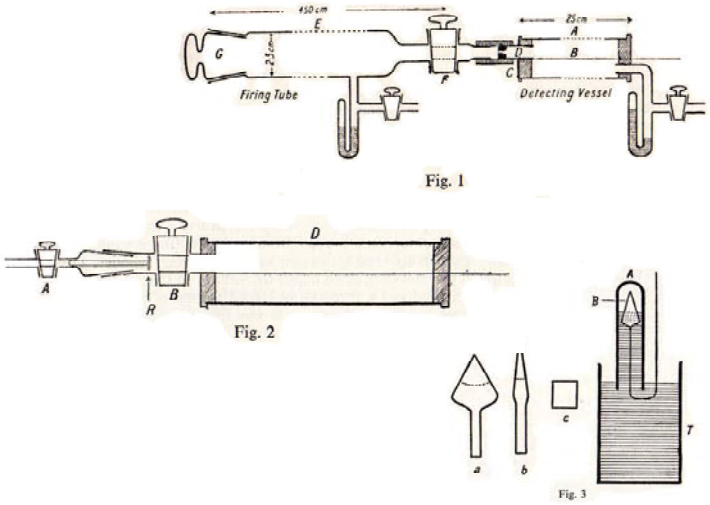

Figure 11. Geiger’s apparatus used in the early (1908) counting experiments using the very first “Geiger Counter”. These were most likely carried out in the basement at the same time as Rutherford was working with Thomas Royds on the 2nd Floor.

Geiger notes that this incident occurred during the period when he had set up the early counting experiments, which date from 1908. His article, “An Electrical Method of

Counting the Number of α-particles from Radioactive Substances" was received on July 17th 1908 (see Figure 11 above). Thus, his recollection probably corresponds to the same time as Rutherford was working with emanation on the top floor. These experiments used a large number of sources, including radium, radium products, uranium, thorium and actinium. The radium C sources were obtained from emanation kept over mercury. Thus the potential for contamination was significant, as Geiger himself notes:

"A lot of time was lost also because we worked with Ra B + C as a source of radiation, and these preparations, as only gradually became clear, gave off emanation and contaminated the apparatus." [Geiger 1937, from a personal note to Chadwick]

The basement was the only level which was devoted entirely to research, so that for Geiger to have had many neighboring rooms containing research workers during the above incident, he would most likely have been in the basement. The famous photograph of Rutherford and Geiger was taken in 1912 and was almost certainly taken in the "Liquid Air Room", as indicated in Appendix B3. Also, we know that, during the 1912 Conversazione, Geiger's demonstration of atom counting was in the basement. It is possible that the 1908 experiments were also done in this room. Geiger's neighbours at this time would have included his collaborators Walter Makower and Sidney Russ, who probably used their radium bromide apparatus in the basement before the new regime in which the radium was kept isolated using the Ramsay method in an upper room.

Geiger also indicates in the passage quoted in 1.3.3.1 that Rutherford used a

"gloomy cellar in which he had fitted up his delicate apparatus for the study of the α-rays. Rutherford loved this room. One went down two steps and then heard from the darkness Rutherford's voice, reminding one that a hot-pipe crossed the room at head level, and that one had to step over two water-pipes". [Geiger, 1938]

Inspection of the floor plan in Appendix B3 suggests that this room was the "Spectroscopic Research" room in the basement. There are indeed two steps down from the basement level and it is adjacent to the boiler room from which there would have been emerging hot pipes. It is also on the north side of the building and would have been gloomy.

Marsden

During the 1907-1908 academic year, the first of the physics undergraduates went through the new radioactivity training course. Some of brightest students were then recruited into Rutherford's team, including the young Ernest Marsden who graduated with a 1st class degree in 1909. Marsden's 1909 experiments on α-particle scattering carried out with Hans Geiger led to Rutherford's discovery of the nucleus. Marsden describes how he informed Rutherford of the results:

"I remember well reporting the result to Rutherford a week after, when I met him on the steps leading to his private room, and the joy with which I told him that the effect seemed to vary approximately as the 3/2 root of the atomic weight and not as a square root.... Unfortunately I had to report an exception - silver. I had borrowed a coin of allegedly pure silver from a Russian scientist (Antonoff) working on electrochemical

effects, and at that time did not realize that he had contaminated the surface with polonium." [Marsden 1949]

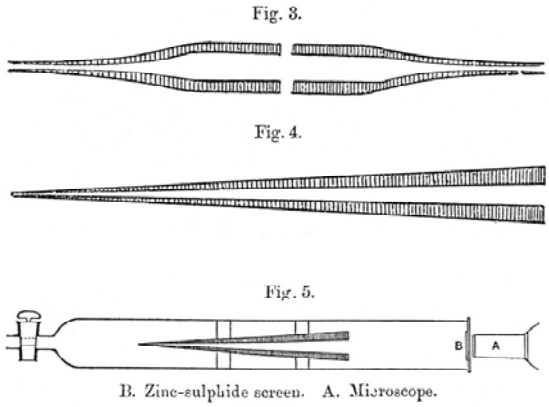

Figure 12. Apparatus used by G.N. Antonoff in "Radium D and its Products of Transformation"

G.N. Antonoff can be seen standing next to Marsden in the 1909 photograph of the Physics group (Appendix C). His article, "Radium D and its Products of Transformation" was published in the June 1910 edition of the *Philosophical Magazine*. Antonoff obtained radium D from old radon tubes which had been used to study the decay of emanation, the shapes of which are shown in Figure 12 (3,4). These were opened, either but cutting in half or by removing the mica window, and α-particles were counted by the scintillation method. Antonoff also carried out some radiochemical procedures using old radium solutions. Given the above methods used in this work, one wonders what other surfaces the Russian contaminated with polonium in addition to those of the silver coin he loaned to Marsden.

Marsden subsequently participated in a series of experiments to test Rutherford's new nuclear model. Marsden recalls this period as follows:

"The work established the theory on a sound basis. It involved counting by eye by the scintillation method one by one over a million α-particles. When I look back and consider, in the light of modern knowledge of safety standards, the nearness of our heads and bodies to the large sources of emanation and the time of exposure to radiation, I marvel that it did us so little harm." [Marsden, 1954]

Moseley

Moseley to his Mother

Oct 1910. " I am suffering from an instrument whose tricks drive me wild. I cannot get it to behave rationally, and meanwhile no experiments can start. I am to work with my apparatus in one table, and the measuring electrometer on another table 12 foot away, to avoid as far as possible the disturbance due to the Ra emanation I will use. The two will be connected by a wire which has to run inside a vacuum to avoid leakage by the way."

Nov 13 1910. "My work is going through much tribulation. On Thursday I at last induced my apparatus to stay at a pressure of 1/400 mm...Then I started my experiment, but a glass tube of thickness much less than tissue paper filled with Ra emanation chose to break off its stalk inside, and everything had to come to pieces to get it out. Fishing for a thing that breaks at a touch was too risky to be tried, for to let emanation loose upon the Laboratory is a capital offence."

28 July, 1912. "I am hard at work trying to get finished and get away from here. It is high time I got away from here as I am breaking all my apparatus, a sure sign that it is time for a holiday. ... I am trying to find the potential to which radium hung up in a vacuum charges itself. The radium gives off beta-rays and positive electricity is left behind which accumulates until a spark passes through the vacuum and discharges it. So far I have managed to get to 160,000 volts, but I have not yet had an experiment which consents to work properly. Usually something breaks or goes wrong at the critical moment, which is a nuisance as it takes 24 hours continuous labour getting the vacuum alone."

7 May, 1913. "The work is going on the whole very well, but at times it makes us tear our hair. Just now a horrid fellow has polluted the atmosphere with radium emanation, and so work is impossible."

I.3.4 Extension of the Manchester Laboratory 1908 - 1912

As a result of the early work before Rutherford, and of a sequence of accidents which took place in the four years after Rutherford had acquired the Vienna radium, the entire Laboratory eventually become permanently contaminated. The extent of the contamination was such that it became necessary to find new rooms away from the contaminated main building and, in addition to overcrowding, this was an argument used by Rutherford and Schuster in persuading the University to fund an extension to the main laboratory in 1912.

I.3.4.1 Planning for the 1912 Extension

The main laboratory had already become greatly pressed for space by 1908 due to the massive increase in the number of research students, which Rutherford makes clear in the 1908-1909 report:

"The increase in the number of research students and the extension of the practical work for the more advanced classes [the radiation training lab] have made great demands on the space of the laboratory. The building is at present unduly crowded, and the present accommodation in Physics is inadequate both for teaching purposes and research. It will be remembered that the laboratory is only partly devoted to Physics proper; one floor [the ground floor] is set aside for Electrical Engineering, and the space occupied by this department is now required to provide for the natural expansion of the teaching and research in Physics.

On account of the restricted space available for research it was found necessary to remove the liquid air plant from its original position in one of the research rooms [the liquid air room in the basement, G05] to the basement under the dynamo room, and this has avoided the danger and disturbance arising from the running of this machine in a room occupied by several experimenters." [Rutherford 1909]

It is clear, then, that the extension was at least two years in the planning so that the contamination problem was probably already apparent in 1910, if not before.

From the Report of the Physical Laboratory Extension Committee:

21 July 1910. Tentative plans for the proposed extension were presented and discussed. Resolved: that a meeting of the committee be held on the 26th at 4pm, and that Mr Beaumont be invited to attend.

26 July 1910. Resolved: that that Mr Beaumont be instructed to prepare plans, after consultation with Professor Rutherford and Dr Beattie, to shew how the land can be most profitably appropriated for necessary extension and the requirements of the Physics Department.

Rutherford to Boltwood

14 Dec 1910. "As to the Lab, things are going well. We are going to have the extension for the Electrical Engineering at the back of the dynamo house, a new lecture room for Physics, and I have also got another floor of about five rooms for special research as well as a small Chemical Laboratory to be built outside, with a draught cupboard and other accessories, to await your next arrival."

1 Feb 1911. "Estimates and tenders are at present being prepared for the extension of the Physics, and I hope the matter will be finally settled in a month or two."

15 Feb 1911. "Those old buildings at the back and in front of the Physics are coming down preparatory to a new erection."

16th May 1911. "Our new building is going up apace, and we expect to be in it in October."

In the 1910-1911 "Report on the Physical Department", progress in the building of the extension is noted, as is the contamination in the main building:

"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." [Rutherford 1911]

I.3.4.2 The Opening Ceremony on March 1st 1912

In a University document to accompany the new extension, "The Physical and Electrotechnical Laboratories of the University of Manchester", Arthur Schuster wrote:

With the steady increase in the number of research students, it has become 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 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....

In addition to the difficulty already mentioned of avoiding the 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.....

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.

This was also described in *Nature* (1912) by Schuster:

"The steady growth of the department and the increase of the number of those engaged in original investigation have, in recent years, placed great pressure on the space of the laboratory. This was emphasised by the nature of many of the researches in radio-activity, in which large quantities of radium are employed. The effect of the γ-rays, which are able to traverse the walls and floors of the laboratory, disturbed the measurements of the workers not only in the immediate vicinity, but also in neighboring rooms. In order to provide additional space, the Council of the University decided to remove the department of electrical engineering from the physical laboratory proper and to locate it in a new building. In these new engineering laboratories, part of the first floor, containing six research rooms, has been set aside for physics, while a small electrochemical laboratory has been erected outside for work on radio-active substances. The physics department has thus the use of the space formerly occupied by electrical engineering [on the ground floor]. The addition of a number of new research rooms for physics, removed some distance from the main physical laboratory will prove of great advantage for the purpose of original investigation, especially for radio-activity and allied subjects. It is intended to keep the new laboratories uncontaminated by radio-active matter, and they will be employed mainly for the more delicate measurements."

At the ceremony on March 1st 1912, a brochure was handed out to visitors which gave a description of exhibits and demonstrations on display throughout the original laboratory and the extension. The ceremony started on the 1st floor in the Electricity Room (1.51) in which there were refreshments (probably the same room used as the laboratory tea room and radioactivity training lab). We can be fairly sure of this because the same room was indicated unambiguously for the 1900 conversazione. Among the exhibits, the work using radioactive substances was well represented, mostly all on the 1st floor, and included the following.

“Room 1”, most likely the large Electricity Room (1.51), used for:

“**Refreshments.**”

“Room 2”, most likely the Balance Room (C1.10), contained:

“**Radioactive Minerals and Radioactive preparations. New Radioactive Minerals** lent by Professor MARKWALD, of Berlin.”

“Room 3”, most likely the Elementary Laboratory (C1.09), contained a number of general physics exhibits, including colour photography, gyroscopes, heat insulation, and

“**Effect of Radium Emanation on Bacteria**. Exhibited by Dr S. Russ.”

“Room 4”, most likely the small Electricity Room (1.52), contained the following exhibits which all made use of electrical effects:

"**Radioactive Exhibits.** A number of working experiments illustrating the methods of measurement employed in radioactivity and the properties of the radiations.
Types of electroscope used for measurement.—The great penetrating power of the γ-rays. – Separation of radioactive matter by the principle of recoil.—The magnetic deflection of β-rays.—Methods of estimating small quantities of radium, illustrated by the electrical effect due to the radium which has been formed during the last few years from the element ionium. The radium clock.

Magnetic Storms (due to tramway currents)."

"Room 5", most likely the Optics Room (1.53), contained the following exhibits which all made use of optical effects:

"**Radioactive Exhibits.**
Alpha-ray Tubes Containing Emanation. The glass walls are so thin that the a-particles escape and produce brilliant phosphorescent effects on certain materials
The Range of the Alpha-rays. Illustration, by phosphorescence, that the a-rays have a definite range in air.
The Condensation of Emanation by Liquid Air.
Production of Helium by Radium. The spectrum of a tube filled with helium which has been grown from radium during the last year will be shown.
A Method of separating Helium. Experiment to show the presence of helium in the gases drawn off from radium. The use of cocoanut charcoal immersed in liquid air as a method of purification of gases.
Radioactive Shadows. Illustration by phosphorescent methods of the distribution of the radiation from a thin film of radioactive substance.
Experiment to show the Presence of a New Substance in the Thorium Emanation (Thorium A) of Mean Life one-fifth of a Second.
Phosphorescent Effects produced by Actinium and Thorium Emanations. The thorium emanation is derived from a large quantity of radio-thorium [Th228] (kindly lent for the purpose by Sir JAMES MACKENZIE DAVIDSON). The characteristic properties of this emanation are clearly shown with this very active material.
Experiments with Scintillations. Exhibit of scintilloscopes lent by Mr. F.H. GLEW. Scintillations produced by the actinium emanation. 'Double' scintillations from the emanations of actinium and thorium."

"Room 6", most likely the General Physics Room (1.54/55), contained the following apparatus commonly used in radioactivity (as well as many other general pieces of apparatus not listed):

"**Exhibit of Apparatus** by the CAMBRIDGE SCIENTIFIC INSTRUMENT CO., LTD.
Wilson Tilted Electroscope.—Wilson Simple Micro-Electroscope.—Universal Portable Electrometer.—String Electrometer.—Dolezalek Electrometer.—Apparatus for Radio-activity Measurements. …"

"Room 14" in the basement, most likely the old Liquid Air Room (CB05), contained the only other radioactive exhibit:

"**Counting of Atoms of Matter**, by Dr H. Geiger.
Each α-particle from radium in passing into the apparatus produces a visible movement of the electrometer."

In the 1911-1912 "Report on the Physical Department", an account of the opening was given:

"The new extension of the Physical and Electrotechnical Laboratories was completed early in the year. The new building was opened on March 1st by Dr Arthur Schuster FRS … A well attended reception and soiree were given in which the main Physical Laboratory and the new additions were opened to visitors. A large

number of interesting experiments and exhibits were shown by staff and students of the Laboratory … The laboratory was thrown open the following day to students of the University … and to others interested, and a number took advantage of this opportunity of viewing the numerous exhibits and experiments. A pamphlet was circulated at the opening of the laboratory giving an account of the history of the Department of Physics and Electrotechnics and a description of the new buildings." [Rutherford 1912]

I.3.5 The radiochemical laboratory attached to the extension in 1912

Radiochemistry before 1912

As noted above, with the large amount of substances available, not least the Royal Society residues, it was necessary to carry out chemical procedures to isolate the various components. For this reason, Rutherford was very keen to have his friend and chemist, Boltwood, come and work at Manchester.

Rutherford to Boltwood

8 Nov 1908. "Why not come over next year and put in a year's work with me? I will give you the run on the radium & the actinium we have just separated from the RS residues."

It was recognised early on that chemical work was impossible to carry out without some contamination and for this reason it was considered good practice to do this work outside the main building. In the 1908-1909 "Report to the Physical Department", it was reported that a special room had been set-up:

"A small room in the sheds outside the laboratory has been fitted up and utilised as a laboratory for chemical work on radium and other radioactive substances. Experience has shown that such work should be carried out on outside the walls of a Physical Laboratory in order to avoid the possibility of radioactive contamination. It will probably be found necessary in the course of the year to fit up another room for the same purpose." [Rutherford 1909]

The same report also noted that Bertram Boltwood was appointed John Harling Fellow and we can be sure that Boltwood carried out much of his work in the shed, in addition to his work in or next to the radium room. A photograph of Boltwood and colleagues posing outside the shed in 1910 can be seen in Appendix C1. Unfortunately, the 1909-10 "Reports on the Physical Department" appear to be missing, but Boltwood's work was referred to by Schuster in the 1912 account of the laboratory which notes that in addition to the Vienna radium,

"The Laboratory has also the use of the ionium and actinium separated in the Laboratory by Professor Boltwood from residues loaned by the Director of the Royal Society". [Schuster and Hutton, 1906]

This work was published in the *Proceedings of the Royal Society* under the title "Report on the separation of Ionium and Actinium from certain residues and on the production of helium by ionium", received on 4th February, 1911. This publication provides a considerable amount of detail on the amounts and natures of the substances, and the procedures adopted to process them:

"The material consisted of certain substances separated from 500 kg of pitchblende residues purchased by the Royal Society from the Vienna Academy of Sciences, and treated at the works of the Armet de Lisle at Nogent-sur-Marne, in France, for the removal of the radium contained in them. The operations to be described were carried out on that portion of the residual material returned to the Royal Society as "actinium residues". [Boltwood 1911]

It is apparent from a footnote from Rutherford in Boltwood (1911) that some work had been done prior to the arrival of Boltwood. Rutherford had carried out some initial tests on the "actinium" residues in 1907 but, due to the large amount of material involved, 21.2 kg of wet paste, he contracted to have the large scale work of separation done by Mr H C Greenwood at the works of Thomas Tyrer and Co in London. The procedures carried out by Greenwood resulted in 160 g of dried precipitate and this was the initial material which Boltwood received:

"The various operations described above up to this point were carried out either by, or under the direction of, Prof Rutherford and Mr Greenwood. The first material placed at my disposal consisted of the precipitate … [which] when dried weighed 160 grm. Its activity was about 20% of the total activity of all of the substances which had been separated from the original material [21.2 kg wet paste]. …

Owing to the presence of fluorine, the decomposition of the precipitate was extremely difficult, but was finally accomplished by heating the material with concentrated sulphuric acid. …

The final material obtained in this manner consisted of pure white thorium oxide and weighed 1.8 grm. It was highly radioactive, because of the ionium it contained, and had an activity about 3000 times that of an equal weight of uranium oxide. Two thin films of this material, …, were prepared and the number of α-particles emitted by these were kindly counted for me by Dr Geiger. … The amount of ionium present with the thorium was therefore equal to the amount in equilibrium with 5.3 mgrm of radium." [Boltwood 1911]

Boltwood (1911) then described the procedures and outcomes of his attempt to extract actinium from the residues:

"A sample of the original [21.2 kg] "actinium residues" had been tested and found to contain a considerable proportion of actinium, but very little actinium, if any, had been separated with the … [160 g] precipitate which contained the ionium. An effort was made therefore to discover what had become of the actinium. It has been noticed … that the precipitate of ammonia is very uncertain ... It therefore appeared highly probable that the actinium present in the original "actinium residues" had remained in solution after treatment with ammonia … The residue of ammonia salts (denoted ... as "residue B") …
was carefully examined … [and these tests] indicated the presence of some permanent radioactive constituent having chemical properties similar to those of actinium. The total weight of "residue B" was about 18 kilogrammes …" [Boltwood 1911]

After some further chemical procedures, 10 g of precipitate were formed:

"The [10 g] material obtained in this manner was only slightly radioactive when first prepared, but its activity increased rapidly and at a rate corresponding to the recovery of activity by an actinium preparation from which the radio-actinium [Th227] and actinium X [Ra223] have been separated. After about four months its activity was over 20,000 times that of an equal weight of uranium oxide … The relative amount of actinium present in this material was … roughly estimated to be equivalent to … 30 mgrm of radium …" [Boltwood 1911]

In summary then, the 20 kg of "actinium residues" supplied by the Royal Society were processed to produce 1.8 mg of thorium oxide, which included about 5 millicuries of

ionium (Th230) and 10 g of preparation which contained 30 millicuries of actinium (Ac227).

1912 Chemistry Laboratory

As part of the 1912 expansion, and for the reasons given above, a special external room was built to house a chemical laboratory in the new extension. The planning for this probably goes back to 1910 at least.

From the Report of the Physical Laboratory Extension Committee:

18th Oct 1910. The plans for the proposed Physical Laboratory Extension were considered. It was suggested … that small sheds for Electro-chemical work, and for special experiments should be erected on the vacant plot of land between the proposed extension and the Dental Hospital Boundary

In Shuster's 1912 account:

"A small Chemical Laboratory has been erected outside for chemical work on radioactive substances....Outside, in a yard adjacent to the north wing, a small chemical Laboratory for radioactive work has been erected. In this yard is also a small shed for open-air electrochemical experiments, besides several store rooms". [Shuster 1912]

Rutherford to Boltwood

18th March 1912. "The new laboratory looks very well ... and the new Physical rooms are already proving very useful. I have a little Chemical Laboratory attached, which is now being used by Russell..."

In the 1911-1912 “Report on the Physical Department”:

“The small Chemical Laboratory, which was attached to the new extension, has already proved of great utility for carrying out the chemical work of separation of very highly radioactive substances.” [Rutherford 1912]

Among the most active radiochemists during this period were G von Hevesey who published five papers during 1911-1912, and who made heavy use of the actinium and electrochemical methods. He published four papers during 1912-1913, including work on uranium diffusion. At this time, several experiments were carried out using Boltwood's ionium. In addition to Russell and Rossi (1912), who provided further evidence for the chemical identity of ionium and thorium (contributing to the enunciation of isotopes by Soddy), Chadwick also carried out some work with Russell on the radiations from ionium (Th230) and radiothorium (Th228). (Chadwick was to make use of Boltwood's ionium 30 years later in his work related to the nuclear bomb).

In the 1912-1913 “Report on the Physical Department”:

“The small Chemical Laboratory has been in constant use during the year for the separation of radioactive materials, while the new research rooms allotted to the Physical Department have proved of great advantage for special investigations.” [Rutherford 1913]

About a year after the chemical laboratory was opened, an unfortunate incident took place, as reported by Moseley.

Moseley to his Mother

29th July 1913. “Rutherford left on Sunday and most of the research men followed immediately. There are still 6 of us left in the Lab however... A terrible thing happened to one unfortunate. He was lent a valuable preparation of actinium to purify chemically. After much purification the final solution had just been boiled down and tested radioactively. Alas he has purified the actinium all away, and now it is down the sink.”

It is interesting to speculate who the 'unfortunate' individual was. From the 1913 and 1914 reports, it is apparent that the following individuals were working with actinium: Marsden, Perkins, Walmsley, Wilson and Wood. In the summer of 1913, there was a meeting of the British Association in Birmingham and it is likely that Marsden attended, which might suggest one of the others as the culprit responsible for flushing away Boltwood's actinium.

It should be clear that the potential for contamination in this laboratory was very considerable, as is made clear by Rutherford in his 1913 text:

"It is highly important not to perform chemical work with strong preparations of radium in a laboratory used for radio-active measurements, for general experience has shown that it is almost impossible to avoid a permanent radio-active contamination of the laboratory in consequence. Such work should be done in a building outside the main laboratory."

I.3.6 Work carried out in the 1912 extension, 1st floor

Rutherford to Boltwood

18th March 1912. “The new laboratory looks very well ... and the new Physical rooms are already proving very useful. ...The new Museum building is pretty well up, and the new archway over Coupland street improves the appearance of the Laboratory very much.”

12 June 1912. “The new rooms in our Laboratory are proving very serviceable as they have a low natural leak.”

By “low natural leak”, Rutherford meant that, at that time, the rooms were free from contamination. In a room that was contaminated, a charged electroscope would 'leak' very rapidly, as was the case in the Macdonald Laboratory, and in the main laboratory.

In the 1911-1912 “Reports to Council”:

“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.” [Rutherford 1912]

The 1900 building had become so contaminated that the elevated background activity made some work impossible or difficult and this would have been particularly true for

beta and gamma-ray measurements. It was in 1912, shortly after the opening of the new extension, that Rutherford took a strong interest in the beta and gamma spectra in a paper entitled, "The Origin of β and γ Rays from Radioactive Substances" 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 work at the Schuster Laboratory and it would almost certainly have been carried out in the six rooms of the 1912 extension. The principal workers 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.

H Richardson - Analysis of the gamma rays (1913a,b,c)

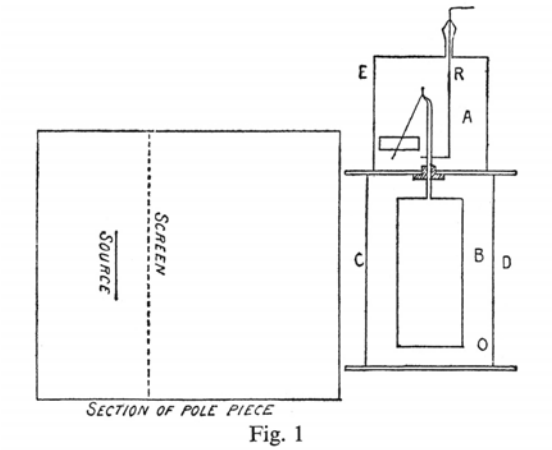

Figure 13. The apparatus used by Rutherford and Richardson 1913 to analyse gamma rays. The effect of ionization is measured by an electroscope.

Rutherford and Richardson published three successive articles examining the gamma-rays produced by radium (B+C), radium (D+E) and thorium and actinium products. The apparatus used for these experiments is shown in Figure 13. 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). This work of chemical separation would almost certainly have been done in the chemical laboratory attached to the extension. Transportation of these substances would therefore have taken place from the chemical room into the yard, into the ground floor corridor, up the central stairwell to one or more of rooms A to F on the 1st floor.

E N da C Andrade - Gamma-ray spectroscopy (1913, 1914ab)

Rutherford and Andrade published three papers using the method of crystallography to obtain the wavelengths and spectra of the gamma rays from radium products. The apparatus is shown below in Figure 14. 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 Harold Moseley.

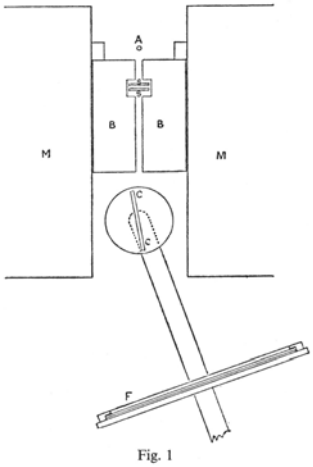

Figure 14. The apparatus used to measure the wavelength of gamma rays in 1914.

H Robinson and WF Rawlinson – Beta ray spectroscopy (1913, 1914).

Two papers were published in 1913 and 1914 concerning the measurement of the velocity of groups of beta-particles from radium products and also secondary beta rays excited by gamma rays. The apparatus used for these experiments is shown in Figure 15. The sources used were radon tubes and radium B+C active deposits.

It should be clear from this review of these three experiments, most likely carried out in the 1912 extension, that there was quite some risk of contamination, either by transport up from the chemical laboratory, the breakage of radon tubes or the spread of active deposit from instrument contamination or on hands and cloths.

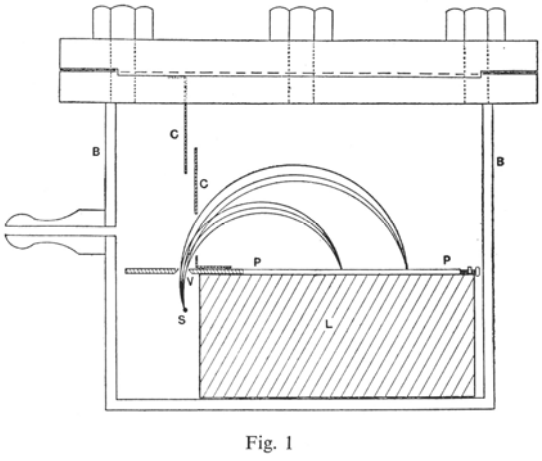

Figure 15. The apparatus used to measure the velocity of beta-particles.

I.3.7 The impact of WWI on the Manchester Laboratory

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. The impact of WWI can be gauged by the effect it had on the number of publications on radioactivity from the Manchester group, as shown in Table 6.

Table 6. Number of publications by Rutherford's group at Manchester.

year	publications
1907-8	17
1908-9	17
1909-10	
1910-11	28
1911-12	29
1912-13	34
1913-14	31
1914-15	22
1915-16	8
1916-17	3
1917-18	3
1918-19	4

There had been a steady increase from 1907, reaching a crescendo in 1913-1914. Some work was sustained in 1915 by staff, and the British Association was held at Manchester. According to the 1914-1915 "Report on the Physical Department":

"The meeting of Section A of the British Association was held in the Laboratory, which was thrown open to visitors. A collection of radioactive minerals and of original apparatus employed in radioactive researches was displayed. …

Owing to enlistment and other causes connected with the war, the number of research students was greatly reduced. A number of researches, however, have been carried out, chiefly by members of staff." [Rutherford 1915]

Thereafter, there was a significant drop in output which never recovered during Rutherford's tenure. In the 1915-16 "Report on the Physical Department":

"Owing to the pressure of the war, the number of research students in the Laboratory was much decreased, and the energies of the staff were partially or wholly taken up with special war investigations." [Rutherford 1916]

An account of this period is given by Bohr:

"The outbreak of the first world war brought about an almost complete dissolution of the Manchester group, but I was lucky to remain in close contact with Rutherford who in the spring of 1914 had invited me to succeed Darwin in the Schuster Readership of Mathematical Physics. On our arrival in Manchester in early autumn,..., my wife and I were most kindly received by the few of our old friends who remained in the laboratory after the departure of colleagues from abroad and the participation in military duties by most of the British. ...

Rutherford himself was soon drawn into military projects, especially concerning the development of methods of sound tracing of submarines, and teaching of students was almost entirely left to Evans, Makower and me. Still Rutherford found time to continue his own pioneer work...." [Bohr, 1958]

During his stay (1914 - 1916), Bohr attempted to measure the spectrum of mercury to test some ideas about the excitation of atoms by electron collision.

"...Encouraged by Rutherford, Makower and I planned experiments to investigate this point, and an intricate quartz apparatus with various electrodes and grids was constructed with the help of the competent German glass blower in the laboratory...Rutherford had tried to obtain permission for the glass blower to continue his work in England in the war time, but the man's temper, ... releasing itself in violent super-patriotic utterances, eventually led to his internment..... Thus when our fine apparatus was ruined by an accident in which its support caught fire, there was no help to reconstruct it, and Makower shortly afterwards volunteered for military service, the experiments were given up. ... I have only mentioned our fruitless attempts as an indication of the kind of difficulties with which work in the Manchester laboratory was faced in those days....

A terrible shock to us all was the tragic message in 1915 of Moseley's untimely death in the Gallipoli campaign..." [Bohr, 1958]

Despite these difficulties, Rutherford continued research with radioactive substances almost single-handedly, leading to his publication in 1919 of a quartet of papers which included his work on artificial transmutation by bombardment with alpha-particles. This work was done either in his ground floor room or in the basement underneath, with the assistance of William Kay. When interviewed by Devons, in the section of Hughes (2008) on the disintegration of nitrogen (p. 111), Kay gives some clues. Devons asks "He used to have a room downstairs?" to which Kay replies "It was done underneath the room there. Yes, No.9, I think it was, or No. 15....". If the current numbers coincide with Kay's recollection, then this would seem to point to the CB09 in the basement. CB15 in the basement was the Student Cloakroom and was still used as a toilet during the occupation by Psychology. A basement room would, however, be inconsistent with the location of the blue plaque in G55/54 commemorating the artificial disintegration of nitrogen.

Without the help of the glass-blowing skills of Baumbach, it would have been difficult for Rutherford to produce radon tubes and this may have been a factor in his decision to make extensive use of radium C. An additional explanation is given by Rutherford in the first of the 1919 papers:

"While the use of α-ray tubes as an intense source of radiation has many advantages, it has the drawback that the α-radiation is heterogenous arising from the three products radium A, radium C and the emanation. In addition it is difficult to make α-ray tubes of uniform thickness whose stopping power is less than two centimetres of air. For these reasons, I have discarded the use of α-ray tubes and have conducted the majority of the experiments with a homogenous source of radiation, consisting of the active deposit of radium." [Rutherford 1919]

Rutherford to Bohr

9th December 1917. “I occasionally find an odd half day to try my own experiments ... I am detecting and counting the lighter atoms set in motion by α-particles ... I am also trying to break up the atom by this method. In the one case, the results look promising but a great deal of work will be required to make sure. Kay helps me and is now an expert counter.”

Rutherford to Bohr

17th November 1918. “I wish you were here to discuss the meaning of some of my results in collision of nuclei. I have got some rather startling results, I think, but it is a heavy and long business getting certain proofs of my deductions. Counting weak scintillations is hard on old eyes, but still with the aid of Kay I have got through a good deal of work at odd times the past four years.”

After the Armistice in November 1918, some of the old workers drifted back to Manchester. Marsden made a brief visit and helped Rutherford complete the transmutation work before returning to New Zealand. Chadwick also returned to Manchester at this time. According to Massey and Feather,

“Naturally he went to Manchester, and was fortunate to be offered a job by Rutherford who was short of staff. This gave him the opportunity to regain his health ... while at the same time participating in some of Rutherford's experiments on artificial disintegration by α-particles.” [Massey and Feather, 1976]

During the spring of 1919, negotiations took place which resulted in Rutherford's appointment as Cavendish Professor to succeed Thomson.

Rutherford to his Mother

7 April 1919. “You will have received the news that I have been elected to the Cavendish Chair of Physics held by Sir JJ Thomson... It has been a difficult question to decide whether to leave Manchester.... I was appointed on April 2 ..., but I must finish out the terms work in Manchester...”

Communication also resumed with Geiger at this time.

Geiger to Rutherford

18 May 1919. “I take the opportunity to write you a few lines just to say that I am well, up and at work again. I need hardly say that all that has happened these last four years has had no influence on my personal feeling to you and I hope, dear Prof. Rutherford, that you still take an interest in your old pupil who keeps his years in Manchester in pleased memory.”

In July (June?) 1919 Bohr made another visit to Manchester:

“Rutherford was at this time almost alone in the laboratory, and as told by his letters, the only help in his fundamental researches, apart from Marsden's short visit, was his faithful assistant William Kay..."

Rutherford to Geiger

14 June 1919. "I have kept in touch as far as possible with my old researchers during the War and am glad to know that most of them are safe and sound. The research men here are very scattered, but Robinson and Florance have returned to their teaching duties. ... Our greatest loss was Moseley who was killed in 1915 in Gallipoli. We are intending to erect a memorial tablet to him in the Laboratory. ...

We are all feeling very rusty scientifically after the war, and it will be some years before we can get going properly, for apparatus is very dear and difficult to get. ... Robinson is gradually regaining his interest... Marsden is now in New Zealand again. Russell is a lecturer in Sheffield. I saw Bohr for a few days recently on his way to attend a conference ..."

I.3.8 Transportation of radioactive materials and apparatus to Cambridge 1919

Mark Oliphant, in his 1972 book, describes how Rutherford arranged for the training of his new Cambridge assistant GR Crowe and for the transportation of his radium to Cambridge:

"Following an interview with R ... he was appointed from June 1919.... One of his first tasks was to go to Manchester to learn how to handle and prepare radioactive sources from radium in solution. The glassware was discoloured and embrittled by exposure to radiation, but it was dismantled, packed, and re-erected under Rutherford's supervision in a small isolated "Tower" room in the Cavendish, without incident. R had evaporated the radium solution to dryness in Manchester, and he put it into solution again in the Cavendish. From then on Crowe regularly pumped off the radon and prepared from it the great variety of radioactive sources required, working under the general supervision of Chadwick, who had accompanied R from Manchester...." [Oliphant, 1972]

It is of interest to note that three pieces of the Manchester glass apparatus have been preserved and are on display at the Cavendish museum. These are the Rutherford and Gieger (1908) apparatus for measuring the charge carried by the α particle, the Rutherford and Royds (1909) apparatus for identification of the α particle as helium, and the Rutherford and Robinson (1914) apparatus for measuring the charge-to-mass ratio e/m of the α particle. It is almost certain that Rutherford transported these pieces to Cambridge at the same time as the radium apparatus, as most of the glass-ware was kept in the radium room at Manchester. According to Norman Feather's biography:

"He brought with him a considerable amount of apparatus from Manchester in a form ready for use, he brought the large quantity of radium lent him by the Academy of Sciences of Vienna in 1908, he brought with him one of his research students, James Chadwick, … and he would have brought with him Kay, his laboratory steward, also, had he not given way chiefly on a domestic issue … [Feather, 1940]

It is quite likely that much of the "considerable amount" of Manchester apparatus can be seen in the photograph taken in the early 1920s of Rutherford's Laboratory room in the Cavendish (Appendix B5).

I.3.9 The Schuster Laboratory after Rutherford 1919 - 1968

After Rutherford's departure in 1919, William Kay and a small number of lecturing staff from his original group remained at Manchester, including H Robinson. However, Robinson left Manchester in 1920-21 to join Rutherford at Cambridge. DCH Florance shortly after departed for Victoria University in New Zealand. Of Rutherford's original workers, only JM Nuttall (and William Kay) were to stay at Manchester.

1.3.9.1 WL Bragg 1919-1937

Bragg had been appointed to a chair in Manchester with the influence of vice-chancellor Professor Henry Miers, a Mineralogist. An account of Bragg's time at Manchester is given in Phillips (1979):

"Despite Miers's support, Bragg's early days in Manchester were not easy. Most of the other professors were relatively old - Horace Lamb .. had preceded WH Bragg in Adelaide - and they were used to dealing with Rutherford who has made the Physics Department world-famous. Bragg took over at a difficult moment. During the war most of the staff had been away on war work and the teaching had been continued by E.J.Evans and N Tunstall. When Bragg joined the Department in the autumn of 1919, he brought with him R.W. James and E.C.S. Dickson. H. Robinson (with D.C.H. Florance) had returned a little earlier so that he had at the beginning of a nucleus of sound-rangers to support him. ...

The first priority was to organize the teaching and Bragg at the age of 29 was very conscious that he had had essentially no previous experience that was relevant to elementary teaching - even as an undergraduate. The beginnings were disastrous. Many of the undergraduate were returning ex-servicemen and they had no mercy on the novices. Tunstall remembered that there were 'rowdy, boisterous goings on in the lecture room particularly when medicos were being lectured to. One could hear this not only on the same floor but in the laboratory under the large lecture theatre and there was visible evidence in the fact that panels of the benches were kicked into matchwood during lecture periods taken by Bragg, James and Dickson'. In one dramatic episode a student set off a firework under the reading desk and Bragg boxed his ears. To make matters worse anonymous letters began to arrive, addressed to the vice-Chancellor and others, in which Bragg and his young colleagues were accused of incompetence with evidence quoted that was clearly based on detailed knowledge of events in the Department. Bragg was brought close to the edge of breakdown but recovered when the letters began to attack his father and Rutherford and when his research began to flourish again. But he was deeply scarred and it took him a year or two for him to gain confident control. Miers gave him what support he could and noted laconically in his diary at the end of 1924: 'there was a plague of letters at the University against certain members of the Professorial staff. But these ceased with the disappearance of one of the Junior staff to another post (with his wife).'".

Bragg's research though "had a more promising start" and he quickly set up the laboratory for work using X-ray analysis. Although there was quite a large group of theoretical physicists at Manchester, including Neville Mott, Hans Bethe and Rudolf Peirls, who later contributed to the development of the nuclear bomb, in the absence of any interest in experimental nuclear physics or access to the radioactive substances which Rutherford had taken to Cambridge, work using radioactive substances effectively came to an end at Manchester at the start of the Bragg period. The only minor exception to this was the occasional paper by J Nuttall, appointed Assistant Director of Physics in 1920, who did some work on secondary beta-rays from X-rays.

A fair amount of building work went on during Bragg’s time, largely due to the massive (threefold) expansion in the number of students in 1919-1920, and many research rooms were turned over to teaching, including some old teaching rooms previously colonized by Rutherford for research.

In the 1919-1920 “Report on the Department of Electrotechnics”:

The gas engine and shafting have been removed from the dynamo house basement which will be used as a much needed extension to the laboratory accommodation. Part of the new building now being erected between the dynamo house and the Physics laboratory will also be available for this purpose. [Beattie 1920]

In the 1920-21 “Report on the Physics Department”:

The new workshop has now been completed and equipped. It is situated on the ground floor between the Electro-technics and the Physics Building. [Bragg 1921]

In the 1928-29 “Report on the Physics Department”:

Plans have been prepared for the additional accommodation which is to be built for Physics on a site adjoining the Engineering block. The new building will provide lecture rooms and laboratories … as well as space for the Department of Crystallography and additional research rooms. [Bragg 1929]

In the 1929-30 “Report on the Physics Department”:

The Physics Extension planned last year is now being built and it is hoped that it may be opened in time for the session 1931-32. [Bragg 1930]

In the 1930-31 “Report on the Physics Department”:

This year is marked by the opening of the new Physics extension. The building, which adjoins the Engineering block, contains a Lecture room and large laboratory … It also houses the Crystallographical laboratories … and it is intended that by degrees all the crystallographic research work will be grouped together in this building. [Bragg 1931]

In the 1931-32 “Report on the Physics Department”:

A feature of the year was the opening of the new Physics building by Lord Rutherford. In his address Lord Rutherford reviewed the history of the laboratory, and his fascinating informal account was greatly enjoyed by an enthusiastic audience. The new building has served its purpose most successfully during the year and had relieved the former congestion. [Bragg 1931]

There were no other major building projects, other than minor room changes, e.g. the old Observatory (beekeepers) at the top of the building was turned over to become a student Common Room in 1933. A Differential Analyser was erected in the basement in 1935 under the direction of Professor Hartree, who became the first Chair in Theoretical Physics in 1938.

1.3.9.2 PMS Blackett 1937-1953

Blackett’s first “Report on the Physics Department” for the year 1937-1938 was the last before the war. Some room related items were reported :

“A room on the first floor of the old building has been converted into a Departmental Library, for the use of staff and students. …

The old workshop on the ground floor has been made into a Steward’s office and store for Mr Kay

A room on the ground floor has been converted into a laboratory for Third year Honors students.

The old electrochemistry laboratory on the ground floor has made into a research laboratory for Cosmic Ray work and the large magnet along with other apparatus has been installed and is now fully working.” [Blackett and Hartree, 1938]

An account of Blackett's tenure at Manchester is given by Bernard Lovell (1975) :

"In the autumn of 1937 he [Blackett] succeeded W L Bragg as Langworthy Professor... Under Bragg the research in the department had almost entirely concentrated on X-ray crystallography. Within a few months of Blackett's arrival all crystallographic personnel had disappeared. Sweeping changes occurred. William Kay, the steward who had worked with Rutherford and who was regarded as an institution, working on the top floor, was installed in a room adjacent to the entrance to the laboratory. There could have been no more dramatic illustration of Blackett's dynamic impact than in this cataclysmic change of more than a quarter of a century of tradition. He initiated a departmental library, painted out the dark brown walls, shifted the workshops and seized large adjacent territories for the installation of the magnet and cloud chamber which arrived with J G Wilson and A H Chapman....

Of the original members of Bragg's staff only Tolansky effectively survived to carry on his existing researches. J.M. Nuttall and E C Scott-Dickson were there to take the brunt of the senior and junior teaching respectively. D R Hartree, the Professor of Applied Mathematics, was reappointed to a Chair of Theoretical Physics, which Blackett soon persuaded the University to create. Of the young people Blackett found Lovell and Rochester recently appointed as Assistant Lecturers in the department and in 1938 L Janossy, as well as J G Wilson, came from Birkbeck.

With remarkable speed Blackett created a major research centre for cosmic rays in the department. At various times in the next year or so he had in the department ....many distinguished visiting scientists - among them .... Heisenberg.... Blackett himself continued to work on the momentum spectrum. Janossy constructed a large and complex Gieger counter system and studied showers of the penetrating component with Ingleby and the photon component and cascade theory with Rossi. Rochester worked on the proton component. Blackett dispatched me to Birkbeck to take over the small automatic chamber... When I brought this to Manchester Blackett made me design a magnet and set me to study the showers produced by the mesotrons...."

It is clear from Lovell’s account and a look through the Reports to Council that there was no work carried out making use of radioactive substances during the Blackett period. Blackett’s own work with cosmic rays did not require radioactive substances (although significant advances were made in the discovery of new elementary particles), but by this time anyway radioactive substances had become obsolete for use as sources of energetic particles.

Blackett’s second published report appears after WWII in 1948, by which time Experimental Physics and Theoretical Physics have been split into separate departments. William Kay retired in 1946 and was awarded an honorary MSc by the University. Blackett’s last Report was given in 1952, the same year that Astronomy formed its own department under the Professorship of Zdenek Kopal. The following two years were transitional, with caretaker reports for Experimental Physics given in 1952-53 by JM Nuttall and in 1953-54 by GD Rochester. During the transition, many of Blackett’s co-workers joined him at Imperial College or moved on. Rochester took up a Chair at Durham Colleges in 1954-55.

1.3.9.3 S Devons 1955 - 1960

With the arrival of Samuel Devons in 1955 as Langworthy Professor, there was a renewed interest in nuclear physics at Manchester. Devons was probably the last of Rutherford's research students who worked with radioactive materials in the Cavendish at Cambridge, before the era of particle accelerators made the materials obsolete. (Indeed, in the 1974 account of the Rutherford era at Cambridge, Devons gives a very graphic

description of work in the radium room.). On looking through Devon's publications from this period, it is apparent that he had been interested in the decay of light nuclei after bombardment with accelerated protons. On his arrival, there was some momentum in this work from Cambridge and Imperial College, but there is no evidence from his papers that he carried out any experimental work at Manchester himself. Undoubtedly, it would have been a priority for him to develop experimental facilities for nuclear physics at Manchester and it is clear that he set about this with some vigour.

In his first Report for 1954-55, there was nothing to report in the way of buildings or new projects, but there was a continuation of publications in cosmic rays and astronomical physics. His second Report in 1955-56 marked a new era at Manchester, however. Under the heading of "Staff Changes" Devons reported:

"Dr J.M. Nuttall, who had been a member of staff since 1920, and Assistant Director of the Physical Laboratories since 1921, retired in September 1955."

It is worth noting here that in Nuttall's first publication in 1911, co-authored with Hans Geiger, the relation between the range α-particles and period of transformation (now known as the Geiger-Nuttall Law) had first been observed. This work was carried out in the same basement room (G05) in which Rutherford and Geiger were photographed in 1912, as shown in Appendix B.

Under the heading "Research" Devons was able to report:

"A major part of the activity has been the preparation of two pieces of equipment for research in nuclear physics. The first of these, the high voltage generator, will be housed in the new building in Ackers Street. The building is largely completed, and installation of the machine has begun. It is hoped that research work in the laboratory will begin in the autumn term 1956. The Department has received grants from the DSIR both for the high voltage generator itself, and for the experimental equipment for use in conjunction with it. The second major piece of equipment which is being designed in the Department is a linear accelerator for use with heavy nuclei. This work has been made possible by support from the Atomic Energy Authority and the DSIR." [Devons 1956].

Thus, in the same year that particle accelerator technology arrived, the last link with the Rutherford period at Manchester was broken. During that same year, speakers at the colloquia included H.A. Bethe and W Heisenberg. Bethe had participated in the Manhattan Project, while Heisenberg was associated with the German nuclear effort.

In the 1956-57 Report under "Research":

"The high voltage generator in the new building in Ackers Street is now completed and is being used for research in nuclear physics. A smaller machine has also been assembled and housed adjacent to the Schuster Building.

Work on the construction of the linear accelerator for heavy ions is continuing. This is now housed in the converted factory building in Oxford Road. Substantial grants have been received from the DSIR for continuation and expansion of this work. In addition support has been provided by the continuation of agreements with the Atomic Energy Authority.

Research in the field of cosmic radiation is being brought to a finish. In its place experiments in high energy physics will be developed in the laboratory, and eventually completed by using large machine facilities available in other laboratories, both in this country and at CERN, Geneva." [Devons 1957]

In the 1957-58 Report under "Research":

"Research in nuclear physics continued with the recently completed high voltage generator in Ackers Street. The running costs are being financed by a two-year extension grant from the DSIR.

A grant of £240,000 has been received from the DSIR to finance the continued development of the linear accelerator for heavy ions which is being built in the factory building in Oxford Road

Research in the field of cosmic radiation was brought to an end during the year 1957-58. In its place work is being developed in π meson physics, with the use of the synchrocyclotron at Liverpool University." [Devons 1958]

In the 1958-59 Report under "Research":

"During the year more buildings were added to the high voltage generator site, increasing the experimental area on the machine and improving general laboratory accommodation. Plans were made to install several spectrometers in the machine area …financed by the DSIR. Existing research programme in Nuclear spectroscopy continued.

Work in π meson physics continued, with the use of the synchrocyclotron at Liverpool University.

A group was formed to discuss the possibilities of constructing a high energy machine in collaboration with other Universities. Reports were made to the National Institute for Research in Nuclear Science, and tentative plans were made for the future participations by the Department." [Devons 1958]

This was the last official Report given by Devons as his tenure at Manchester was cut short after he resigned in 1960, when on sabbatical leave at Columbia. This was, I understand, after a disagreement with the University over the financing of the LINAC but details of this incident are still confidential. It seems a pity that after four years of development that Devons did not see his projects come to fruition. That same year, 1960, the first of many publications reporting experiments with nuclear reactions appeared from Manchester, the first since 1919. It is perhaps no accident that these first reactions were done using accelerated helium nuclei (He^4 or He^3), i.e. artificial α-particles. Devon's machines continued to operate for the next 20 years and were only decommissioned in the 1980s. The Universities Research Reactor at Risley started operations in 1962 (it was decommissioned in 1996) and it would seem likely that Devons must have been involved in the initiation of this project. Shortly after Devon's departure, William Kay died in January 1961.

1.3.9.4 Nuclear Physics at Manchester 1960-1967

Devons was succeeded in 1961 as Langworthy Professor by BH Flowers, a theoretician who had studied with Rudolf Peierls at Birmingham. For two years, Flowers gave the reports for both Experimental and Theoretical Physics. Thereafter, and before Physics moved to the new Schuster Building, the Reports on Experimental Physics were given by a series of interim Heads of Department.

BH Flowers 1960 - 61

In 1959-60:

"The first stage of the Heavy Ion Linear Accelerator was brought into operation (energy 1 MeV per nucleon). The studies of nuclear reaction mechanisms, coulomb excitation, internal pair formation and nuclear resonance fluorescence on the electrostatic generators were continued. A slow beam pulse and a time to pulse height converter were constructed to measure the half-lives of short-lived beta emitters. Work on ($\alpha\gamma$) reactions started. … The work in π mesons at Liverpool University was concluded." [Flowers 1960]

In 1960-61:

"The prestripper stage of the Heavy Ion Linear Accelerator has been used successfully in experiments on the scattering of lithium ions and on the $C^{12}(C^{12}\alpha)Ne^{20}$ reaction. The studies of nuclear reaction mechanisms, coulomb excitation, internal pair formation, nuclear resonance fluorescence and ($\alpha\gamma$) reactions on the electrostatic generators were continued. … Planning for experiments in the Liverpool Tandem Accelerator has begun, since it is expected that a Manchester team will have an appreciable fraction of the available time on this new machine. …Work on hyperfine structure of transuranic elements in the infra-red has been continued in collaboration with Harwell." [Flowers 1961]

During 1961, a conference was held at Manchester celebrating the 50^{th} anniversary of the nucleus. An outcome of the conference was a book "Rutherford at Manchester" edited by J.B. Birks and published in 1963:

"The fiftieth anniversary of the publication of Rutherford's 1911 paper announcing the discovery of the atomic nucleus was celebrated by an international conference on low-energy nuclear physics from September 4^{th} – 8^{th}. The conference was attended by more than 400 nuclear physicists from all over the world, including Sir Ernest Marsden, Sir Charles Darwin, Professor E N Andrade and Professor Niels Bohr." [Flowers 1961]

H.E. Hall and E.B. Paul 1961-1964

In 1961-62:

"The second and third stages of the Heavy Ion Linear Accelerator have been installed and commissioning of the complete accelerator should be complete before the end of 1962. This will be the only heavy ion accelerator outside the US and will be a major addition to the Department's equipment. The large electrostatic generator has continued to be the main research tool and reached 6.8 MeV during the year. A stripper for producing 10 MeV helium beams is being installed … Work with the Liverpool Tandem Accelerator, which began operating at the beginning of 1962, has been started and a modified negative ion source for heavy ion acceleration has been developed at Manchester. Approval for the construction of a 4 GeV electron synchrotron in the Manchester-Liverpool area was recently given. …

Amongst many experiments using the electrostatic accelerators or nuclear reaction mechanisms and nuclear structure, the following may be noted. Using the reaction $B^{11}(t,p)B^{13}$ the decay properties of B^{13} have been clarified. The first two excited states of P^{31} have been exited by resonance fluorescence. …" [H Hall & EB Paul, 1962]

In 1962-63:

"The Heavy Ion Linear Accelerator came into operation at full energy in April 1963. Three alternative beam lines into three experimental areas are in operation and experiments are under way. Experiments on the 2 MeV and 6 MeV Van de Graaff accelerators have continued and about one quarter of the running time of the 12 MeV Tandem Accelerator at Liverpool is used by this Department.

Experimental programmes include:

1. A study of the exited states of O^{19} and O^{20} using tritium induced reactions…
2. Studies of reactions induced by He^3 bombardment of carbon
3. Study of the $C^{12}(O^{16},\alpha)$ reactions. …

A High Energy Physics group has been studying the behaviour of sonic spark chambers … Such detectors will be used in an experiment on K meson interactions using the 7 GeV proton synchrotron of the Rutherford Laboratory …" [H Hall & EB Paul, 1963]

In 1963-64:

"The low energy nuclear physics group have been using the Heavy Ion Linear Accelerator, the 6 MeV Van de Graaff and the Liverpool Tandem, in the continuing programme of research into nuclear structure and dynamics. This work has been supported by annual grants totalling about £100,000 from the DSIR. It has been found that the energy of the Linear Accelerator can be varied in a unique and simple way, which greatly extends its potential usefulness. A facility allowing the 6 MeV Van de Graaff to be pulsed has been commissioned, which opens up new areas of investigation in neutron physics.

The high energy physics group have been actively engaged in experimental work using the recently commissioned 7 GeV proton synchrotron Nimrod at the National Institute Rutherford Laboratory. … A complex system of sonic ranging spark chambers (developed at Manchester) , photographic spark chambers and neutron counters is used to study the short lived particles. …" [H Hall & EB Paul, 1964]

J.C. Willmott 1964-1968

In 1964, J C Willmott was appointed Chair in Nuclear Physics.

In 1964-65:

"The low energy nuclear physics group have continued their investigations of nuclear structure and dynamics using the Heavy Ion Linear Accelerator, the 6 MeV Van de Graaff and the Liverpool Tandem. This work has been supported by the SRC with grants totalling amounting to £150,000 for the current year. … Much interest in the Department has developed in states of high angular momentum in both light and heavy nuclei. Several nuclei have also been investigated using the linear accelerator which were previously unknown.

The high energy physics group have completed their programme on the 7 GeV proton synchrotron at the Rutherford Laboratory, and are now actively engaged in preparing experiments to be done at the 4 GeV electron synchrotron now under consideration at Daresbury. This machine is expected to be operating in the late summer of 1966. This work is supported by funds from the NIRNS." [H Hall and JC Willmott]

In 1965-66:

"The low energy nuclear physics group have continued their studies of nuclear structure and dynamics using the Heavy Ion Linear Accelerator, the 6 MeV Van de Graaff and the Liverpool Tandem. Some use has also been made of the PLA at the Rutherford Laboratory. This work has been supported in part by the SRC, with grants amounting to £135,000. … Work on nuclear structure of medium weight has been greatly

stimulated by collaboration with the theoretical department. In the heavier nuclei, studies are continuing of states with high spin and of neutron deficient nuclei.

The high energy physics group has been preparing an experiment on the photoproduction of K mesons. This will be carried out on the electron synchrotron at Daresbury Laboratory of the SRC. …" [H Hall, JC Willmott and P R Murphy]

In 1967, JC Willmott succeeded BH Flowers as Director of the Physical Laboratories at Manchester.

In 1966-67:

"The low energy nuclear physics group have continued their studies of nuclear structure and dynamics using the Heavy Ion Linear Accelerator, the 6 MeV Van de Graaff and the Liverpool Tandem. Some use has also been made of the PLA at the Rutherford Laboratory. This work has been supported in part by the SRC, with grants amounting to £150,000. Evidence is beginning to build up for the existence of collective effects in the region of mass 40. Studies of isomeric states in the mass 70 region is giving us basic information on the shell structure in that region. A considerable amount of work is being done with heavy ions as projectiles and germanium counters as detectors, which is generally proving to be a very powerful technique.

The high Energy Physics Group has been carrying out research on NINA the 5 GeV electron synchrotron at the Daresbury Nuclear Physics Laboratory. The synchrotron started operating in December 1966. An array of scintillation detectors and wire spark chambers is being tested … They will be used in conjunction with a large magnet to detect K mesons produced by bombardment of a liquid hydrogen target with high energy photons. …" [JC Willmott?, 1967]

Although not reported in the Experimental or Theoretical Physics sections, in the Astronomy section the move to the new building was noted, thus bringing to a close nearly 70 years of occupation of the Schuster Laboratory:

"The most important event in the departmental history of last year was its removal from the old Schuster Laboratories to a new building providing ampler home for all branches of physical sciences at the University. The move itself occurred in December 1966 and provided us with long-desired accommodation appropriate to the present size of the Department." [JC Willmott? 1967]

Summing up the developments since Devons introduced his programme for the rebirth of nuclear physics at Manchester, within the Manchester Campus itself three machines were constructed: the Heavy Ion Linear Accelerator on Oxford road, a large 6 MeV Van de Graaf accelerator at Ayers Street and a smaller 2 MeV Van de Graaf accelerator adjacent to the old Schuster Laboratory, apparently this was located on the east end of the Schuster Building. A variety of other machines were also used in sites outside of Manchester, including Liverpool, Daresbury, Harwell, the Rutherford Laboratory and CERN. There is no evidence of the use of radioactive substances as sources for nuclear experiments, although some heavier nuclei were used as targets and most of the reaction products were radioactive. Undoubtedly, there would have been some local contamination in the areas occupied by the machines. There is no evidence, however, of any major nuclear physics programme within the old Schuster Laboratory itself, although it is quite possible that some of the developmental work took place in this building.

1.3.10 General Remarks on Radioactive Contamination in the Schuster Laboratory.

Looking back at the 67-year occupation of the Schuster Laboratory by the Department of Physics since the official opening on June 29th 1900, it seems quite clear from the available evidence that research using radioactive substances was essentially limited to the first two decades. To be more precise, it was limited to the period between Schuster's first acquisition of radium bromide in October 1903 and Rutherford's dismantling of his radium bromide apparatus in 1919. It is almost certain that all of the contamination found in the Rutherford Building since 1999 originated from this period, 80 – 100 years after it was deposited.

A question which is natural to ask is why has the contamination remained *in situ* for this time? It is not possible to answer this question with any certainty, but it is possible to answer the question whether the occupants were aware of the radioactive contamination. We know for a fact that the contamination in the 1900 building was known about by Rutherford and Schuster because there is plenty of documentary evidence in the form of letters and formal reports to the University between 1908 and 1913. Rutherford probably knew about the contamination deposited from 1903 shortly after he arrived in 1907 when he found that the natural leak on his a-ray electroscope was about the same as in the Macdonald Laboratory.

It is quite likely that Bragg knew about the contamination, but we should bear in mind the effect of the trauma of WWI and the immediate demands of the Department with the expansion in the number of students in 1919-1920. Nevertheless, although the experimental procedures used by the X-ray crystallographers did not make use of radioactive substances, some of their apparatus probably would have been sensitive to a high gamma-ray background, not least as some decay processes which result in gamma-rays also produce X-rays. Certainly, any photographic procedures would have been susceptible to an elevated background. Those members of his staff who were working on secondary beta-radiation from X-rays would also have had this problem. The same is true of the work done during the Blackett period. Any apparatus designed to detect cosmic radiation, such as a cloud chamber triggered by a Geiger counter, would also be highly sensitive to a high background due to radioactive contamination. Thus, Bragg and Blackett would probably have experienced the very same problem which Rutherford used to argue for the 1912 extension. This may explain why the X-ray crystallographers moved *en masse* to the 1930 extension and why Blackett set up his lab in the old Electrochemistry Lab. What was the problem with the basement research rooms? We should also bear mind that William Kay was still a member of the Department until 1946 and J M Nuttall until 1955, both of whom had participated in the contaminating experiments before 1919.

However, with the departure of Blackett in 1953, followed by many of his co-workers, Nuttall's retirement in 1955 and the phasing out of cosmic ray research within the Schuster Building in the late 50s, the last personal links with the memories of pre-1919 were broken and there was no large-scale use of apparatus within the building which would be sensitive to contamination. Added to this, it is quite likely that Samuel Devons

had a fairly relaxed attitude to contamination, given his experience of the radium room at the Cavendish (see section I.4). It is probable that many of the Manchester physicists shared a similar attitude, as some do today. This attitude is reinforced by the widely held view is that there was no epidemic of radiation related illness in the cohort of physicists made up of Rutherford's many co-workers and students.

There is some anecdotal evidence of awareness of contamination in the basement from the late 50's. Also, according to a private memoir, in the early 60s E.B. Paul discovered that he had been exposed to radiation in his offices in the Schuster Building, which were then vacated until they had been replastered and repainted, presumably in order to remove contamination. However, whatever concerns there might have been during the occupation of the old Schuster Laboratory by the Department of Physics, we have no documentary evidence of any systematic survey carried by the University.

I.4 THE SECOND CAMBRIDGE PERIOD 1919 - 1937

From 1919, Rutherford's work with radioactive substances continued at Cambridge including scattering of alpha-particles to probe the nucleus, transmutation by bombardment with alpha-particles and also work on the nature of radiations. The year 1932 is widely held up as the *annus mirabilis* of the Cavendish, with the discovery of the neutron by Chadwick and the first artificially produced nuclear reaction by Cockroft and Walton.

I.4.1 The Cavendish Laboratory 1907 - 1937

After the 1896 extension a second extension took place in 1907. This is described in "A History of the Cavendish Laboratory 1871-1910":

While the undergraduate class work continued to extend, the growing number undertaking original experimental investigations soon made the pressure for room and apparatus acute. The need of further extension was accordingly noted in the Professor's reports for 1903 and 1905.

In 1906, Lord Rayleigh, who was Cavendish Professor from 1879 to 1884, and to whom the Nobel Prize for Physics had been awarded in 1904, offered to use £5000, the greater part of its proceedings, in building or helping to build a new wing of the Cavendish Laboratory, …

The new extension at once became practicable. The Museums and Lecture Rooms Syndicate recommended … that the University should adopt Professor Thomson's suggestion and assign as a site for the building the frontage to Free School Lane, on the north side of the existing laboratory. …

On November 22 a syndicate was appointed to obtain plans and estimates. … Accordingly the report appeared on February 21. Mr WM Fawcett who had designed the original building, had prepared a plan for a new extension, which provided a large basement and a number of small rooms on the second floor for research, together with a large lecture-room to seat 120 students, a library and chemical room, and a room for demonstrators, on the first floor.

I.4.2 Radioactive Substances in the Cavendish Laboratory

I.4.2.1 Acquisition of radioactive materials in Cambridge

When Rutherford arrived in Cambridge in 1919 there would have been in the Cavendish already preparations of uranium and throrium. We know that he brought the Vienna radium from Manchester down to Cambridge. At this time he was involved in an exchange with the government over possession of the radium. According to Chadwick

"Rutherford's remarkable work in Manchester was made possible by the personal loan of some 250 mg of radium by the Vienna Academy of Sciences. After the war, when he had taken his radium with him to Cambridge, he resisted attempts to confiscate it as enemy property and arranged for its purchase, an act which rescued the Radiuminstitut of Vienna from dire poverty and which earned him the life-long gratitude of its Director Stephan Meyer." [Chadwick 1974]

As a result of these exchanges he also purchased another 10 mg of radium bromide from Vienna. In addition to the radium is likely that he also brought to Cambridge Boltwood's actinium and ionium preparations. Evidence in favour of this view is that Chadwick

makes use of the ionium in 1942 (see Section I.4.7). The fate of the polonium residues is unknown, but it is possible that it was returned to the Royal Society. In the early 1920s Rutherford acquired via the Medical Research Council about 500 mg of radium bromide so that by the time of his death he had about 1000 millicuries of radium source in total. Several other preparations were obtained during this period, including radiothorium and protactinium. Also during the Rutherford period at Cambridge, Norman Feather from his time at John Hopkins in Baltimore 1929-30, acquired a substantial amount of polonium from Dr F West who had charge of five grams of radium.

"West handed over to Feather about 300 of these 'dead' bulbs containing in all perhaps 100 millicuries of radium D, E and F, and he took them to Cambridge in his luggage. ... "

A summary of substances acquired at the Cavendish is given in Table 8 below. These, of course, were additional to the substances already at the Cavendish and those substances which Rutherford took down from Manchester. A complete summary is given in Appendix A2.

Table 8. Radioactive Substances acquired at the Cavendish

Uranium Series	Thorium Series	Actinium Series
10 mg $RaBr_2$ 1 (Vienna 1921) 500 mg Ra salt 2 (MRC 1921) 100 milicuries Ra (D+E+F)	Radiothorium (McCoy, 1921)	Proactinium (1929)

I.4.2.2 Knowledge of the physiological effects and precautions

It is useful at this point to describe what was know at the time about the physiological effects of radiation and the precautions put in place to avoid them. Rutherford, Chadwick and Ellis (1930) give the following account.

"It was early observed that the rays from radium and other radioactive substances produce burns of much the same character as those caused by X-rays. Some time after exposure, there is a painful irritation followed by inflammation which last for some weeks. After continued exposure the skin may break, giving rise to sores which are difficult to heal.

On account of the small penetrating power of the α-rays, their effect is mainly confined to the skin exposed to the rays; but the effect of the more penetrating β rays extends much deeper, while the penetrating γ rays traverse the whole body....

It would be out of place here to describe the results of numerous experiments that have been made on the therapeutic effect of the radiations... It is desirable, however, to draw attention to the precautions that should be taken in the preparation and use of radioactive products ...

Reference should be made to the action of the β and γ rays on the eye, first noted by Giesel. On bringing up a radium preparation to the closed eye, in a dark room, a sensation of diffuse light is observed which increases with the intensity of the radiation. This appears to be due to the fluorescence produced by the rays in the eye itself. The blind are able to perceive this luminosity if the retina is intact... The γ rays for the most part produce the sensation of light when they strike the retina.

In counting scintillations, where strong sources of radium and thorium C are employed, ..., the intense β and γ rays produce a disturbing effect on the eye. ... To avoid this difficulty, it is desirable that the light emerging from the objective of the counting microscope should be bent through a right angle ... before

entering the eyepiece. This arrangement allows suitable screens of lead ... to be interposed between the source and the eye and the head of the observer, ... Experience had shown that counting under these conditions is much less tiring and more reliable than when the observer is exposed to the full intensity of the γ radiation.
For many experiments on the α, β and γ rays it is necessary to obtain strong sources of radium (A+B+C) on wires and plates and occasionally to use 'a ray tubes', in which almost pure radon is compressed into such a thin-walled glass tube that the a rays emerge freely into the air. For the preparation of such sources, it is desirable that the radium should be kept in solution and the radon pumped off at intervals and collected in a tube over mercury and subsequently purified to the degree required.

These operations should be carried out as expeditiously as possible before the β and γ rays from the radon and its products reach an appreciable value. There is little β and γ radiation for the first 10 minutes after the removal from solution, reaching half its maximum in 40 to 50 minutes. In the transfer operations over mercury, rubber gloves should be worn to protect the fingers from the small traces of the active deposit which are always present in the mercury through which the radon has bubbled. This prevents the irritation of the skin of the fingers by the a rays and keeps the hands free from radioactive contamination." [Rutherford, Chadwick and Ellis, 1930]

It is interesting to note at this point that these precautions were not followed by Rutherford's assistant Crowe. In the same passage as that quoted above from Oliphant goes on to describe the effect of exposure.

"In 1926 Crowe became aware that there was something wrong with the tips of his fingers, with which he handled radon tubes or manipulated nickel buttons through a mercury trough into radon collected in a glass tube. He had been given regular blood tests for the effects of whole body radiation, but apparently he did not obey the rules laid down for the preparation and manipulation of sources. In particular, he did not always wear gloves, preferring to use his bare fingers. From then, deterioration was rapid, his fingers and thumbs becoming horny and insensitive, and painful cracks appeared. Many skin grafts were made and a finger amputated. He was withdrawn from work with radioactive sources, but the damage had been done." [Oliphant 1974]

Undoubtedly, Rutherford, Chadwick and Ellis (1930) would have been aware of these effects on Crowe when they were writing their book. In addition to these immediate physiological effects of exposure to radiations, Rutherford at al (1930) also caution against the inhalation of radon

"The radium in solution should be surrounded by sufficient lead to absorb the greater part of the γ rays. The radium room should be well ventilated so that any traces of radon which escape into the air are rapidly removed. It is very undesirable to remain for long in a room in which free radon is present in appreciable quantity. During respiration, the radon enters the body and some of it is transformed *in situ*.

For these reasons, it is of great importance that all radium preparations should be kept in sealed tubes to prevent the escape of the emanation into the air, and that every precaution should be taken against the liberation of emanation in the various operations of preparing sources" [Rutherford, Chadwick and Ellis, 1930]

I.4.2.3 Radiochemical methods for preparation of sources

It is very likely that when students in the 1920's were training under Chadwick, and later Ellis in the 1930s, that the student texts would have included Makower and Geiger's (1912) book, as well as Rutherford (1912). Chadwick had in 1911 attended the

radioactivity course run by Geiger in Manchester. By 1930, many new procedures had been developed and a description of these is given in Rutherford, Chadwick and Ellis (1930). Many of the procedures are, of course, similar to those described by Geiger and Makower (1912) but with additional steps included. For example, for radon separation, a procedure to increase purity by heating with copper had been introduced. It is beyond the scope of this report to detail all of the procedures but some of the main ones are highlighted below.

Radon Sources

"In most physical laboratories the greater part of the stock of radium is kept in solution and the radon grown by the radium is collected from time to time as it is required to provide sources of radon or radium active deposit....

The radium solution, in weak hydrochloric acid, is contained in a glass bulb which may be connected through a stopcock to a Toepler pump. When it is desired to collect the radon the stopcock is opened and the radon, mixed with the gases formed by the action of the radiations on the solution, is allowed to expand into the pump, from which it is transferred to a burette or tube standing in mercury. The gases with which the radon is mixed consist mainly of hydrogen, oxygen, and ozone from the water of the solution, and CO2 (with perhaps some hydrocarbons) from organic matter such as tap grease, with traces of chlorine and helium. The volume of the electrolytic gases will depend on the amount of radium present and on the time which had elapsed since the last collection of radon. With a solution containing 250 mg Ra about 30 cc of mixed gases are produced in one week. The concentration of radon in the mixed gasses is therefore less than 10^{-5}.

The mixed gases are first transferred to a gas pipette and exploded by sparking to remove the hydrogen and oxygen. It is usually of advantage to add oxygen in order to remove completely any excess hydrogen. Excess oxygen is easily removed by means of phosphorous. The residual gases, now about 0.5 cc in volume, are then introduced over mercury into a small tube containing a piece of caustic potash to absorb the CO_2. If the radon is required for the purpose of preparing active deposit sources, no further purification will usually be required.

For the preparation of radon tubes it is generally sufficient to condense, by means of liquid air, the radon in the mixed gas partially purified by sparking and exposure to P_2O_5 and KOH, and to pump off the uncondensed gases. The radon is then allowed to expand and compressed by a column of mercury into a tube or bulb. It is however, sometimes necessary to prepare very small strong sources of radon and in such cases a higher degree of purity is required. The mixed gases, after sparking, are introduced into a purification apparatus, in which they are brought into contact with heated copper and copper oxide to remove hydrogen, oxygen, and any hydrocarbons. The gaseous products of combustion, CO2 and water, are then absorbed with P_2O_5 and KOH. The radon can then be condensed in a side tube... This method, if used with care , will yield radon of about 50 to 70 % purity, and it is a comparatively simple operation to compress 100 millicuries of radon into a volume of less than 1 c mm." [p559]

Active Deposit Sources

"Sources of radium active deposit are prepared by exposing a disk or wire to radon in a suitable vessel. Radium A, the first product ... is a solid and deposits on surfaces exposed to radon. Since the majority of recoil atoms of radium A are positively charged, the yield of active deposit can be increased by charging the exposed disk or wire negatively with respect to the surrounding surfaces. If the disk is exposed for a short time only, practically pure radium A will be obtained. To obtain A, B and C in equilibrium the time of exposure should be ... when no field applied, about 41/4 hours. ... when the disc is negatively charged equilibrium is attained after about 2 hours' exposure ... .

When the source of active deposit is required the radon is pumped off and collected over mercury. The disk is removed, washed in alcohol, and heated to about 400 deg C. in an evacuated quartz tube to remove any radon which may be occluded in the surface of the disk." [p560].

Several other methods are described including (i) condensing the radon onto a disk, (ii) using hydrochloric acid to dissolve the deposit, and (iii) introducing a thin wire into a radon capillary tube (iv)

Several methods are provided for the separation of the various products, including chemical, electrochemical, volatilisation and recoil methods.

radium C

"from a solution of radium (B+C) in weak HCl or HNO3 pure radium C can be obtained on a cathode if its potential be kept between -0.08 and -0.5 V with respect to the normal calmel electrode." [p554]

"A simpler method of obtaining pure radium C consists of dipping a polished plate of nickel into a solution of radium (B+C) in hot weak HCl. Nickel is less noble than radium C and the latter deposits on the nickel surface in a practically pure state." [p554]

"A partial separation of the bodies comprising the active deposits can be obtained by the effects of temperature, for the B bodies volatilise more readily than the A bodies and the A bodies more readily than the C bodies." [p556]

radium D, E and F

"If a quantity of radon is introduced into a sealed tube and allowed to decay, radium D together with ... radium E and polonium are found in a pure state on the walls of the tube. Old 'radon tubes' of this kind afford very convenient sources from which to obtain concentrated preparations of radium D, radium E or polonium (radium F)." [p552]

"The most important application of electrochemical methods is in the preparation of sources of polonium (radium F) from a solution of radium D. ... In a weakly acid solution of radium (D+E+F) the F ... will deposit when the cathode potential is less than +0.35 V. When the potential falls to -0.08 V radium E will also be deposited and at -0.5 V radium D will begin to deposit." [p554]

"Polonium and radium E can also be obtained from a solution of radium (D+E+F) in weak hydrochloric acid by dipping into the solution a plate of nickel" [p557]

I.4.2.4 Interaction of alpha-particles with matter: Transmutation and Scattering by alpha-particle including neutron sources

The following articles are included in this category: Chadwick (1920, 1926, 1930, 1932), Chadwick and Beiler (1921), Chadwick and Mercier (1925), Chadwick and Emeleus (1926), Chadwick and Gamow (1930), Chadwick, Constable and Pollard (1931), Chadwick and Constable (1932), Rutherford (1921, 1923, 1924), Rutherford and Chadwick (1921ab, 1922, 1924abc, 1925, 1927, 1929), Rutherford and Kempton (1934).

Further work is required here to analyse the sources used, but for those articles which are easily accessible in electronic form, Table 9 provides a summary. It is clear the use of radon tubes had fallen out of favor. For the early Cambridge work, which was a

continuation of the 1919 work, radium and thorium C sources were used. There is an interesting passage from a 1924 paper "Capture and loss of electrons by α particles" which indicates that uncovered radium C sources were a big problem.

"In these experiments it is very important to avoid contamination of the box and screen. This is very difficult to effect when an uncovered source is used. In a low vacuum traces of emanation are usually released from the source, and contaminate the whole box. In addition if the source is placed in the box soon after removal from emanation the recoil of radium B causes a distribution of radioactive matter. Even when the source is not introduced into the box until radium A had practically disappeared, there is still the possibility of contamination due to the beta-ray recoil of radium C from radium B. For these reasons it is essential that the source should be completely
covered in."

The significance of this is that any experiment using a bare active deposit source would also spread around radioactvity due to recoil. It would appear that Rutherford only fully realised this problem in 1924.

TABLE 9: Summary of α-sources used by Rutherford and Chadwick

α-source	**publication**	**source strength**
radon	Chadwick, Goldharber (1935)	Rn + Be, neutron source
radium C	Rutherford, Chadwick (1921) Rutherford, Chadwick (1922) Rutherford, Chadwick (1924ab)	40 millicuries
thorium C	Rutherford (1921) Rutherford, Chadwick (1921) Rutherford, Chadwick (1922)	
radium F	Chadwick (1930) Chadwick et al (1931) Chadwick , Constable (1932) Chadwick (1932) Rutherford, Kempton (1934)	Pt foil, 8 millicuries Pt foil, 5 millicuries Ag disc, 15 millicuries Ag + Be discs, neutron source 3 millicuries

For most of the Chadwick publications in the 30's a radium F(Po210) source was used, obtained on either a platinum foil by electrolysis of a (likely HCl) solution of radiolead (radium D+E+F) and concentrated by volatilisation, or on a silver disc deposited from an HCl solution of radiolead. Much of this was derived from Feather's 300 tubes donated by Kelly Hospital Baltimore. Rutherford and Kempton's (1934) source was prepared by Chadwick. Radium F had the advantage that it was more of a pure alpha-emitter with less gamma rays.

I.4.2.6 Analysis of radiations from Radioactive substance, including new methods for counting.

The following articles are included in this category: Chadwick (1923), Chadwick and Emeleus (1926), Ellis and Wooster (1927), Rutherford (1921), Rutherford and Chadwick (1924), Rutherford and Wooster (1925), Nimmo and Feather (1929), Rutherford et al (1930,1931ab, 1933), Rutherford and Bowden (1932).

Further work is also required here, but it is clear that work involving all three radioactive series was carried out in the Cavendish during Rutherford's period. From the volume of articles, it is also clear that the radiations from the C stage of the series were the most intensively studied. Thus, in addition to the chemical procedures for isolating radium C and F for alpha-sources, there would have been a significant amount of radio-chemistry carried out for the isolation of radium emanation, A, B, C and E, thorium emanation, A and C, and actinium emanation, A and C.

Table 10: Summary of studies on radioactive substances

	Radium	**Thorium**	**Actinium**
eman	Lewis, Wyn-Williams (1932)	Lewis, Wyn-Williams (1932)	Rutherford and Bowden (1932) Lewis, Wyn-Williams (1932)
A	Lewis, Wyn-Williams (1932)	Lewis, Wyn-Williams (1932)	Lewis, Wyn-Williams (1932)
B	Chadwick (1923) Rutherford, Wooster (1925)		
C,C'	Chadwick (1923) Rutherford, Chadwick (1924) Nimmo and Feather (1929) Rutherford et al (1930) Rutherford et al (1931a) Rutherford et al (1933)	Rutherford (1921) Nimmo and Feather (1929) Rutherford et al (1930) Rutherford et al (1931b)	Rutherford et al (1930) Rutherford et al (1931b)
D			
E	Ellis, Wooster (1927)		
F			

I.4.3 Room Use at the Cavendish Laboratory

I.4.3.1 The Radium Room

When he arrived in Cambridge in 1919, with 250 mg of radium from Manchester, one of the first things Rutherford would have needed to do would be to find a suitable location for the radium room and a site for the training of new students, as well as allocating rooms for research and space for postgraduate students to carry out their work. It is apparent that the Cambridge Radium Room was located in the Cavendish Towers, the position of which can be seen in Appendix B5.

Oliphant refers to the radium room in recalling a conversation that took place between 1922 and 1925.

"One day I had taken R up to the Radium Room so that he could assure himself that all was in order. We had at that time about 400 mg Ra in solution for the preparation of radon and active deposit sources. I remember well how, as we were coming down the stairs, I said that we did not have enough radium, so that I had to allocate sources very carefully to meet the demands; I said it was a pity that somebody or other had not made a gift to him a gram of radium, as the women of the United States had made to Madame Curie. His reply astounded me. It was 'Well, my boy, I am very glad nobody did. Just think: at the end of every year I should have to say what I had done with it. How on earth could I justify the use of a whole gram of radium?'. [Oliphant 1974]

Shortly after this incident, Rutherford did indeed obtain a further 500 mg radium.

A good description of the radium room is given by S Devons at http://www.phy.cam.ac.uk/history/years/rutherford.php.

"For the initial exercise in research, and especially for a more substantial piece of research that I later undertook (the resonant scattering of alpha particles), the crucial item was the Cavendish radium source. For decades this radium - there was approximately one gram of radium bromide in the Cavendish - had provided the basis for much of Rutherford's research, but now it was hardly in demand at all. Cockroft and others were busily exploiting the high voltage equipment he had built, and newer, better such equipment had been ordered from Philips in Holland. Rutherford had built for himself a smaller equipment of some 250 kV, which he and Oliphant used; a cyclotron had already been planned and construction was about to begin; Chadwick had left Cambridge and was busy with similar preparations at Liverpool. Sealed radium-beryllium sources were still used for the new neutron investigations, but the old treasure, the 1000 millicurie source - in solution - was freely available even to a humble graduate student.

"Milking" the radon emanation from the radium source was, wisely, not entrusted to students. This operation was presided over by Mr. Crowe, Rutherford's long time assistant, who constantly bore, in his gloved hands, a reminder of the price that could be paid for careless practice. Nevertheless, about once a week the emanation would be pumped off the radium source, and I was presented with a small glass capsule, precariously sealed off by immersion in a small mercury-filled crucible, containing several hundred millicuries of radon (I was strongly advised not to get "the stuff" on my skin, or in my lungs.)

Even stronger was the warning not to contaminate the laboratory. There was an elaborate ritual of wearing rubber gloves, of washing and scouring the hands and changing jackets on the way in and out of the small room (the "Tower") at the top of the Laboratory where the radium was housed. Inside the radium sanctuary itself, the residual activity was so high from the "contamination" everywhere and from the residues of innumerable sources of the past that it was difficult to charge up the gold-leaf electroscope (mounted on the wall) for long enough to measure, even roughly, the strength of a newly prepared source of some 100 millicuries. But then one could always estimate the strength of such a source by its smell!

Many experiments (including my own) had to contend patiently with counting rates of one or two a minute: imagine how easily they might be wrecked by even the minutest amount of contamination - even one microcurie is more than a million counts a minute, and I would be carrying around hundreds of millicuries. As long as the sources were "carefully" sealed up (in a glass test tube with rubber bung), and kept away from other people's apparatus, no-one appeared to mind - or to know - that I had a 100-200 millicurie source in my pocket. Nor was I myself unduly alarmed, when shortly after a visit to the "Tower" (where I spent a couple of hours each day), I found that by simply blowing on a Geiger counter, its register would rattle furiously or completely choke in the attempt to record the activity. After a day or two of radioactive abstinence my breath always returned to normal. For more than a year I enjoyed a virtual monopoly of the radium source - perhaps the first (and last) student to be so privileged."[Devons, 1974].

I.4.3.2 The Radioactivity Training Laboratory

The radioactivity training laboratory was also located at the top of the building, probably in the attic above the 1896 extension, as is testified by Cockroft, Oliphant and Devons.

"After two years of the Tripos I was accepted as a member of the laboratory and set to work in Chadwick's introductory training course. ... By this time in 1924, Rutherford's Cambridge Research School was well established. … At the beginning of the October term the problems were ready to be assigned to students after their initial training period in Chadwick's attic course." [Cockroft 1946]

"It was Chadwick who saw that research students got the equipment they needed, within the very limited resources of the stores and funds at his disposal. It was he who trained the raw recruits to research in a 'kindergarten' laboratory in the roof above Rutherford's office." [Oliphant 1974]
"New students were often anxious to start research right away, in the middle of the summer, and stayed around in Cambridge hopefully. Something had to be done for them. An attic room full of discarded or temporarily unwanted apparatus, mostly junk, was nicknamed the "nursery" and used as a breaking-in ground. I recall spending five or six weeks there, dusty and directly under the roof, which was hot even in an English summer, vaguely learning some experimental "techniques" and trying to construct or repair or improve a sort of string electrometer ionisation chamber arrangement." [Devons 1974]

I.4.3.3 Room use by Rutherford and co-workers in the Cavendish 1919 - 1937

In this section, I have put together all available descriptions of the use of the Cavendish Laboratory. Not all of it relates directly to the use of radioactive substances, but it does help towards putting together the jig-saw pieces of information necessary to create a picture of activity in the Cavendish during Rutherford's second period.

Rutherford's Personal Office

A description of Rutherford's personal office in 1927 is given by Mark Oliphant.

"I was told to wait outside his office ....In the passage, with uncarpeted board floor, dingy varnished pine doors and stained plastered walls, indifferently lit by a skylight with dirty glass, I found myself in the company of ...Cecil Eddy... and ETS Walton... When my turn came, I entered a small office littered with books and papers, the desk cluttered in a manner which I had been taught at school indicated an untidy and inefficient mind. It was raining, and drops of water ran reluctantly down the grime covered glass of the uncurtained window." [Oliphant 1974]

Aston's Laboratory in 'the Garage'.

According to Cockroft, as a result of the agreement between Thomson and Rutherford which they made after negotiations in 1919, Thomson occupied the ground floor of the Rayleigh Wing. Aston’s mass spectrometry work was carried out in this area.

"'JJ' retained the ground floor of the wing of the Cavendish built by Lord Rayleigh, a space always referred to as 'The Garage'. There he worked with his personal assistant Everett, ... Within the JJ domain worked Aston, his research on isotopes then coming into full flower.." [Cockroft, 1947]

Oliphant's (1974) description of his introduction to the Cavendish continues from the above meeting in Rutherford's office when he was instructed by Rutherford to make himself known to "Aston and JJ whom you will find working in the Garage or in nearby rooms.".

Oliphant was then given help in locating the 'Garage' by PMS Blackett and Dymond:

"They led me down the stairs to the open door of the large basement laboratory known as the Garage, and told me I would find JJ's set-up in the far corner, and Aston's in a room beyond." [Oliphant 1974]

Rutherford's Laboratory Room from the 1920s

Rutherford's own laboratory room at the Cavendish was almost certainly located in the Maxwell Wing. According to a personal communication from Gordon Squires, curator of the Cavendish Museum,

"Rutherford's laboratory room was on the ground floor of the Rayleigh [Maxwell?] wing. It is now two rooms, numbered 823 and 823A, at the east end of the passage running east-west in the wing, so it is just next to the Arts School."

The 1874 plans indicate that the room at the east end of the east-west wing was designated for "Magnetism" and originally contained an electrodynamometer and a magnetometer. The 1874 plan also describes the floor as being tiled, which can be seen in the photograph of Rutherford's lab on display in the Cavendish museum (see Appendix B5). The positioning of the window on the south side of the room is also consistent with the direction of light in the photograph.

Rutherford and Chadwick's Laboratory used to continue the 1919 work

Several accounts of the Rutherford and Chadwick experiments are given. Cockroft describes how after the final 1919 Manchester disintegration experiments this work was continued at the Cavendish.

"The work was taken up at once at Cambridge in Maxwell's old research room. Figure 4 [in Cockroft 1946] shows the apparatus he used with Chadwick. The alpha particles from the radioactive source passed through a brass chamber filled with nitrogen and other gasses. The protons were detected by ... a zinc sulphide screen." [Cockroft 1956]

A clue to the location of Chadwick's laboratory is given by Oliphant:

"When I arrived in Cambridge, Rutherford and Chadwick were still working together on the disintegration of light nuclei by bombardment with α-particles. They used a zinc sulphide ... working with dark-adapted eyes in an underground laboratory in the older part of the Cavendish. They were helped by Rutherford's assistant, George Crowe, who had prepared most of the radioactive sources under Chadwick's watchful eye. ... In a ground floor room, through which it was necessary to pass to or from the laboratory occupied by Rutherford and Chadwick, G.I. Taylor worked with a research assistant." [Oliphant, 1974]

According to Ellis:

"Counting the scintillations was difficult and tiring, and Rutherford usually had one or two of his research students to help him. The experiments started about four in the afternoon and we went into his laboratory to spend a preliminary half hour in the dark to get our eyes into the sensitive state necessary for counting. Sitting there drinking tea, in the dim light of a minute gas jet at the further end of the laboratory, we listened to Rutherford talking of all things under the sun". [Ellis, 1938]

At this point the laboratory steward Crowe would bring in the alpha source prepared in the radium room and the counting could begin. Chadwick described the counting procedure as follows:

"The normal procedure was for an observer to count for one minute (sometimes less), being relieved by another observer, and each observer might have up to 20 periods of one minute each during an experiment. The total duration of an experiment was limited by the decay of the active deposit source, as well as the fatigue of the observers." [Chadwick, 1974]

From the above descriptions it would appear that Chadwick's laboratory room from the earliest years of Rutherford's second Cambridge period, was located in the basement of the Maxwell wing.

Chadwick's Laboratory for Neutron Experiments

In Eve's biography, there is a letter from Chadwick to Rutherford dated 1924 which talks about a move to new rooms. With regards to the location of Chadwick's post 1924 laboratory, it would appear that it no longer exists. According to Gordon Squires:

"It was in a building known as the Drawing Office, which had been the Drawing Office of the Engineering Department before it moved to its present site in Scroope Terrace in 1922. The Cavendish Laboratory moved into the vacant set of rooms. However, this building was demolished in 1938 to make way for the Austin Wing."

The neutron source used by Chadwick was a radium F (polonium)/beryllium arrangement. As noted above, a common source of polonium was old radon tubes and for Chadwick's famous 1932 study, the polonium was derived from tubes obtained by Norman Feather, as noted above.

Cockroft and Walton's Particle Accelerator

Cockroft's earliest research at Cambridge was on properties of thin films and he worked in "a semi-basement room beyond the Part I Laboratory, adjacent to Physical Chemistry, which he shared with TE Allibone and ETS Walton." The earliest experiments to construct artificial accelerators were made by Allibone, including using a 300 kV Tesla coil to accelerate electrons.

"I remember Rutherford putting a crystal in the emerging electron beam and watching the bright fluorescence with joy. I wonder what dose of X-rays he received - we had no health physicists to look after us in those days." [Cockroft, 1953]

Soon after, Cockroft decided to build a machine for accelerating protons when theoretical developments by Gamow predicted that a few keV would be sufficient to penetrate the nucleus of light nuclei. He was joined by Walton who had been disappointed with earlier attempts to use induction. Cockroft and Walton's first attempt to bombard elements produced X-rays, but not the gamma-rays indicative of proton capture. In 1931, according to Oliphant:

"Cockroft and Walton had dismantled their apparatus, as the semi-basement laboratory had been transferred to the physical chemists. They moved to a much larger room, with a high ceiling, which had been a lecture theatre. This provided the opportunity to start again from scratch, using an ingenious voltage multiplying circuit which Cockroft developed..." [Oliphant, 1974]

Eventually, the following year on 14th April 1932, success was obtained when, on bombardment of a lithium target, α-particles were observed. This event marked the beginning of the era of particle accelerators (culminating in the Large Hadron Collider recently fired up at CERN) and the beginning of the end of the era of the use of radioactive sources in nuclear physics (see Devons' comments above I.4.3).

The location of the Cockroft and Walton experiment would have been close to Chadwick's new laboratory, as Cockroft recalls:

"Just before this great event in our lives, in a small laboratory round the corner Chadwick had discovered a new atomic particle, the neutron." [Cockroft, 1946]

This event was eventually to lead to the era of nuclear fission in 1939.

The Rutherford and Oliphant Laboratory Room

In his first five years at Cambridge, Oliphant worked on ions and separation of isotopes then, in 1932, he was asked by Rutherford to set up another version of the Cockroft and Walton accelerator.

"I designed and constructed a simple version ... for a maximum energy of 200 keV, and with an improved form of canal-ray tube, giving 100 μA or more of protons. This equipment was set up in the room next to that in which Rutherford and Chadwick had done most of their work on artificial disintegration with alpha-particles. Because of the low ceiling, it was necessary to use a horizontal accelerating tube. A brick wall was erected to separate the beam end of the equipment from the high voltage area. This served to reduce greatly the intensity of the X-rays in the observing region ...

We used magnetic analysis of our beam to ensure that we knew both the kind of bombarding particle we were using, and its precise energy. We were fortunate to have the help of Rutherford's personal assistant, George Crowe... He also prepared alpha-sources of polonium and thorium C', the particle energies of which were known accurately, to insert in place of our targets for calibration of equipment."

Location of other workers

During Rutherford's time, there was a continuous pressure of space particularly to find room for the steady input of research students. This apparently led to breach between Rutherford and Chadwick in 1923-24:

"We had a difference of opinion about how the lab should be run. I thought we were having too many students, because we did not have the room for them..." [Chadwick, from Wilson 1983]

It is likely that every available space would have had been the site of some research activity.

"The second decade of Rutherford's work in Cambridge opened with an intensive development of new laboratory techniques. In various remote corners and cellars, Wyn-Williams and his co-workers had been developing methods for the electrical recording of particles." [Cockroft, 1946]

Some clue to the location of research students can also be inferred from the photographs published in Cockroft's memorial. Figure 13 from Cockroft, shows Rutherford sitting on a stool talking to Kempton and Wescott, would indicate the ground floor of old Maxwell wing as a location, close to Rutherford's laboratory room (see Appendix B5).

Oliphant also recalls occupation of the top floor of the Cavendish.

"On the top floor of the old part of the Cavendish there were a number of small research rooms. The most prominent of those occupying these when I arrived in the Laboratory were N Feather, E.J. Williams and FR Terroux, each working with an expansion chamber. ... Many others occupied these rooms, but I saw less of them than I did of those nearer my own." [Oliphant 1974]

Norman Feather's presence in this area is of interest as he played an important role in the first recording of neutron induced reactions in 1932. It is apparent, however, that there was a problem of contamination here, according to Cochran and Devons.

"Feather used his cloud chamber to clinch Chadwick's discovery by recording the recoil of nitrogen nuclei following a neutron collision .... He thus become the first person to observe a neutron-produced disintegration, ... Somewhat later Dee used his 'clean' cloud chamber in CTR Wilson's laboratory (at some distance from the Cavendish, to escape radioactive contamination).... Chadwick, Feather and Dee published successive papers in the P Roy Soc..." [Cochran and Devons 1981]

Overview of Room Use at the Cavendish

From the brief survey of room use at the Cavendish by Rutherford and co-workers, some interesting patterns emerge. I many ways the set-up can be viewed as a recreation of Manchester, at least in the early years of Rutherford's second Cambridge Period. Like Manchester he had his private laboratory on the ground floor with the laboratories of his main co-workers in the basement underneath, including the early Chadwick and Rutherford laboratory and the Oliphant and Rutherford laboratory. His private office was on the first floor in both Manchester and Cambridge. The radium rooms were both at the top of the building, as were the training laboratories. As the Manchester and Cambridge laboratories filled up with research students, space became increasingly strained, resulting in major expansions, and workspace was allocated anywhere it could be found.

I.4.4 Extensions of the Cavendish

[to be completed]

I.4.5 The Cavendish after Rutherford 1937 -

[to be completed]

I.4.6 The impact of WWII on the Cavendish

At this time I have not had the opportunity to examine all of the relevant documents to properly cover WWII. For the purpose of this interim document, however, a brief account is given in Cochran and Devons' biographical memoir of Norman Feather.

During the war years Feather carried a heavy load of responsibility. He was the only member of the teaching staff of the Cavendish still in Cambridge, and in Bragg's absence was acting Head of Department. … Feather was also the senior member of the Cambridge group which reported initially to the MAUD committee and later to the Tube Alloys Directorate, responsible for British work on the development of nuclear energy and more importantly nuclear weapons. … Late in 1940 Bretscher and Feather wrote a report in which they pointed out that an isotope of the element 94 (for which Kemmer suggested the name plutonium) … should be even more fissile by fast and slow neutrons than U235, and its preparation would present none of the problems involved in the large scale separation of isotopes. They also pointed to the possibility of U233 which could be prepared from thorium. The direction of the Cambridge work was to a considerable extent determined by this paper. (It is scarcely necessary to point out that their predictions were correct, and plutonium has now become a household word.) Measurements on fission cross-sections by means of the high-voltage sets were begun in 1940; work was also done on the chemistry of neptunium and attempts were made to extract U234, … When the bulk of the UK effort was transferred to North America, it was thought to be important to keep some nuclear physics research continuing in the UK., and in this context for a time Feather was released from his teaching duties to concentrate on research. … Approximately thirty war-time reports were written by Feather (1942-1944); the more important were later declassified and published." [Cochran and Devons 1981]

During the war, Rutherford's substances were clearly still at Cambridge, as can be inferred by correspondence between Chadwick and Soddy:

Chadwick to Soddy

21st Oct 1942. "I write to inquire if you have a strong ionium preparation and if so whether you will lend it to me for some months. I require such a preparation for work which has a high military importance,... I must however, tell you that it would be necessary to mix with it, successively small quantities of light elements.... In the meantime I am borrowing a preparation from the Cavendish - one prepared by Boltwood in Manchester."

The reference to use of Boltwood's ionium supports the view the Rutherford had taken most of his Manchester materials, in addition to the radium, to Cambridge in 1919. Chadwick had worked with Boltwood's ionium with Russell in the Manchester chemical laboratory attached to the 1912 extension.

Chadwick to Soddy

28th Oct 1942. I understand your reluctance to part with your very special preparations of ionium, and I think that most of our work can be done with less concentrated material. Could you spare me 10 grams of your 4% material for a few months?

The experiment … is quite a simple one and is not a 'fool wild goose chase'. I want to know how many neutrons are produced by bombardment of certain light elements by the a-particles of ionium…. Boltwood's preparation is about 10% concentration, but the total quantity is rather small, less than 1 gram, according to my information from Cambridge.

I can, in course of time, get considerable quantities of material from Canada, but this would have to be worked up and the time factor is important..."

Soddy to Chadwick

5th November 1942. On going through my collection of radioactive materials at the lab, I find I was mistaken in supposing I had kept the Io-Th preparation from Carnonite. I seem to have retained only a 5 gram sample... I enclose most of this sample..."

Chadwick to Soddy

7th November 1942. Thank you very much for sending me your sample .. I will take great care of it..." (Chadwick never did return the sample.)

It is clear from this exchange that Chadwick had access to the Cavendish store and the substances were being used for a military purpose. In this case, the obvious application would be a neutron source as an initiator for a nuclear bomb.

I.4.7 The fate of the Cavendish radioactive materials

After the war, most work using radioactive substances and neutron-based reactions for military or civil projects in the UK were carried out at Government institutes, e.g. at the AERE Harwell, from 1946, and at the UKAEA, from 1954. After the invention of accelerators, there was no longer any need for radioactive substances for proton-based scattering experiments for academic nuclear physics. It would appear that much of the material in Rutherford's radium store was removed sometime after 1945 when Norman Feather had moved to Edinburgh. The radium store was investigated again in 1958 and a report was made by the UKAEA, but no record of this has survived. Some measurements of residual contamination were made in 1977 and further remediation was carried out by the Cambridge Radiological Protection Service, but it would appear that any records have also not survived.

There are surviving minutes from Cambridge University meetings to deal with contamination found in the 1970s relating to the 'Tower' and some press cuttings were preserved in the Cavendish Archive held at the New Cavendish Laboratory. All of the information regarding contamination is from the Cambridge Evening News CEN).

In the Cambridge Evening News on Tuesday December 6 1977:

"The room at the top of the tower was locked in 1937. Since then it was opened only once in 1948, cleaned and materials taken out. The room was resealed again because of possible danger of radioactivity from its walls, ceiling and floor. No one has since entered the room and exterior monitoring during the past 31 years has shown no radioactive escape".

It was also reported that the University Safety Officer and Radiation Officer carried out remediation to remove the contamination for disposal at Harwell. The then Cavendish Professor Brian Pippard commented that there was:

"a great deal of unnecessary fuss ... The room was apparently perfectly well cleaned up at the end of the war and it has stayed sealed ever since ... He [Rutherford] used the room to prepare radioactive samples - and this was before the atom-splitting work of the 1930s".

In the Cambridge Evening News Thursday December 15, 1977:

"An outside body of scientists reported in February 1977 that there was a 'considerable quantity' of radium in the room, called Rutherford's Towers. The scientists from the National Radiological Protection Board (NRPB), at Harwell, Berkshire, said woodwork outside the locked doors was also contaminated ...The scientists from Harwell visited the room a year ago. They found gamma-rays emitting from radium - contaminated dust in the void between floors and the ceiling. In one area, this was described as a 'considerable quantity'. They also said the surfaces of the door, a window ledge and part of the stairs of the rooms were above the accepted level of radiation. A spokeswoman at the NRPB said their findings showed radiation levels in the room were too high and in some spots 'quite a drastic reduction in the level was required'."

The NRPB report was accepted by the Cambridge RPS. The Radiation Officer commented that:

"In fact our figures were much worse. They have not gone as deep as us and they used a higher background on their test equipment."

Remediation was carried under the independent supervision of the Health and Safety Executive and the room was again locked. The work was commented on in the CEN by Norman Feather (1904-1978), who at that time was an emeritus professor at Edinburgh:

"It is nonsense to say any experiments were carried out in the room. No experiments took place there. The room was only used for the preparation of radiation sources.... There was a fair amount of contamination, it was almost inevitable with what was known about the subject in those days, but the room was not locked when Rutherford died. I was responsible for the room and it was still being used when I left Cambridge in 1949[1945?], but no one spent more time than they had to inside the room."

In recent communications with the Cavendish, I contacted Professor Pippard who confirmed that the above sequence of events was correct. (Shortly after this communication, sadly Brian Pippard died, see Guardian Obituary Wednesday 23rd Sept. 2008) I also contacted the UKAEA and a search through their archive did not find any surviving records. At the present time, I have been unable to examine any extant records for their radio-archaeological significance..

I.5 General Discussions of the Historical Data

It is clear from the survey of historical data regarding Rutherford's use of radioactive substances in the preceding sections, that after his first acquisition of strong sources in about 1903, contamination became a problem which he struggled with throughout the rest of his career. The contamination problem was not, however, one of health and safety as it is today, but a problem of how to maintain an environment in which experimental measurement was free from artifact. Conducting an experiment in a contaminated room or even in proximity to a contaminated room or with contaminated instruments could render the experiment non-viable, especially for measurements involving the counting of low-intensity radiations.

We can also see in the history that there is clear progression of awareness. In the earliest work contamination took place without Rutherford being aware of it. It is remarkable how quickly the Macdonald laboratory became contaminated once Rutherford had acquired the 30 mg, and then 80 mg, of Giesel radium in 1903, probably within weeks or even days. This was, of course, not unique to Rutherford's laboratory. The Ramsay Laboratory at UCL was contaminated within minutes of the radium entering the building. Undoubtedly it was a similar story at all the centres of research using radium in the early days of radioactivity, not least the Curie Laboratory in Paris and the Radium Academy in Vienna. Undoubtedly it was true also at Manchester Physical Laboratories, after Schuster acquired first 20 mg in 1903, and then a further 40-50 mg by 1906, so that there was contamination from radium at Manchester even before Rutherford arrived.

Although contamination was a universal problem, it was not discovered for quite a few months, or longer. In Rutherford's case, Eve's electroscope problem is given as 1904 but the first discussion appears in the second (1905) edition of his book Rad*ioactivity*. (The first edition came out in 1903 during his visit to the England.).

"… it is impossible to make accurate measurements … in a room which is used for the preparation of radio-active material. In the course of time the walls of the room become radio-active owing to the dissemination of dust and the action of the radio-active emanations" [Rutherford 1905]

And in a foot note to the same passage:

"It is very desirable that care should be taken not to release large quantities of the radium emanation inside a laboratory. This emanation has a slow rate of decay and is carried by air currents throughout the whole building and finally leaves behind an active deposit of very slow rate of change. Eve (Nature, March 16, 1905) has drawn attention to the difficulty of making refined radio-active measurements under such conditions." [Rutherford 1905]

By the time of his second book, *Radioactive substances and their Radiations*, published in 1913 he had already experienced two episodes of contamination, the Macdonald Laboratory (1903 – 1907) and the 1900 Schuster Laboratory (1908 – 1912). He would have had these episodes in mind when he wrote about the problem of permanent contamination caused by escape of radon:

"The disturbance of measurement due to the escape of radium emanation is for the most part temporary in character; but a continuous escape of emanation leads ultimately to all the surface of the building becoming strongly active due to the deposition of the products of slow decay derived from the emanation. If accurate work with small activities is to be done in a laboratory, the importance of handling all radio-active material with the greatest care cannot be too strongly insisted upon." [Rutherford, 1913].

Despite the McGill experience, which undoubtedly influenced his methods for handling radium at Manchester and precautions for preventing contamination when he arrived in 1907, the measures he took did not prevent the 1900 Manchester Laboratory having the same fate, although as noted above there was likely contamination prior to his arrival. At Montreal the biggest problem appeared to be radium emanation escape, so that the radon diffused freely though the building with the aid of air currents. Likely it was because this of that by 1905 Rutherford had adopted Ramsay's method for keeping the radium bromide in solution in a bulb permanently attached to a Toepler pump. In this way the radium emanation could be isolated and transferred over mercury. (This is the apparatus which can be seen in the famous 1905 photograph taken in the basement of the Macdonald as shown Appendix B1) It is also clear from Hahn's anecdotes that much contamination was done by distributing active deposits by hand or cloths. At Manchester, although efforts were made to prevent radon escaping, it is clear that there was a regular sequence of accidents involving the breaking of radon tubes, resulting in the entire laboratory becoming active from the deposits. As the Antonoff anecdote shows distribution of contamination from handling contaminated apparatus continued to be a problem. We do not have any direct historical data relating to contamination of the 1912 extension but radon escape continued through this period, and given the proximity of the chemical laboratory it would be surprising if the extension did not also succumb to the inevitable (see Section II).

By the time of his third book, *Radiations from Radioactive Substances*, published in 1930 he would have had two more episodes to add to his experience.

"In all chemical operations involving radioactive bodies, the greatest care should be taken to keep the hands free from the contamination and to prevent the dissemination of active matter. Similar precautions should be taken with radioactive sources, for it must be borne in mind that sources of the active deposit of radium after decay are always coated with the long-lived deposits of radium D and radium F (polonium). To prevent the radioactive contamination of a laboratory, no material which has been exposed in the presence of the radium emanation should be made use of in the workshop. It is surprising how easy it is to contaminate the tools in a workshop, resulting in a radioactive contamination of all apparatus under construction. This is obviously a great disadvantage in all ionisation experiments where a very low natural leak is desired." [Rutherford, Chadwick and Ellis, 1930]

At the Cavendish a more elaborate ritual had been put in place, i.e. scrubbing and changing jackets. However, apart from the tower room itself we know that some contamination did take place in other parts of the building. There is Dee's comment about Norman Feather's contaminated cloud chamber in 1932 and contamination of the Cavendish, and there is Rutherford's realization in 1924 of the problem of alpha-recoil in spreading of active deposits, although the phenomenon of alpha-recoil and "volatilisation" had been known and studied at Manchester by Makower and Russ.

One of biggest steps Rutherford took to minimise contamination due to active deposit, in common with other institutions such as the Vienna Radium Academy, was to separate the storage and the radio-chemical processing of radioactive substances from the experiments using sources derived from substances. Rutherford's set up at Cambridge, at least in the early years after his return in 1919, was in many ways a recreation of the Manchester arrangement. Special "radium rooms" were set aside at the top of the building to house the (same) radium bromide apparatus while much of the experimental work was done at the bottom of the building or in the basement. Of course, after the expansion in the number of research students and co-workers, with pressure on space research rooms were used wherever available, and eventually extensions were built to meet the demands.

Many experiments had been done on the diffusion of radium emanation in air and other gases and through porous materials, and the diffusion coefficients were known. The choice of the top of the building seems odd, however, given that the density of radon had been determined by Gray and Ramsay (1909) and it was known then to be a heavy gas. (Current values put the density of radon at 9.73 kg/m^3, compared with air at 1.2 kg/m^3.) The effect of gravity on the distribution of active deposit from emanation was known from experiments done by Curie (1907). It was thought though, that the effect of gravity was not a direct one on the atoms of radon, as it was a monatomic gas, but as a result of aggregation around particles of moisture.

"The effect indicates that nuclei of some kind must be present in the gas on which the active deposit collects by diffusion. These nuclei fall slowly under gravity, … In order to exhibit this effect, the gas must not be at too low a pressure and water vapour must be present in reasonable amount. It is produced in moist air, hydrogen, and carbonic acid. … The general results indicate that nuclei are produced in the gas by radiations from the emanation when water is present. These nuclei are invisible, but act as centres for the collection of the active deposit, and gradually fall under gravity like a fine cloud, carrying the deposit with them. Mme Curie estimated that the particles fall with a velocity of the order of 10^{-4} cms per second." [Rutherford 1913.]

A factor critical to the behaviour of radon in the building is convection and the ventilation systems within the Laboratory. As noted by Moseley, during the winter the building was extremely well-heated, to the extent that even with his jacket removed he was too hot. A good description of the heating/ventilation system is provided in the pamphlet distributed for the 1900 Opening Ceremony. In the section describing the large Elementary Laboratory on the first floor we have the following:

"Visitors may notice the complication of pipes in the north-east corner of this room. These pipes, which will be painted in different colours so as to enable them to be easily distinguished, convey the gas, the water, the steam for heating purposes, the steam for experimental purposes, and air compressed to three or four atmospheres. A large opening for ventilation purposes will be seen in the wall. The general scheme of ventilation has been to place all the rooms which are likely to be crowded or to require a rapid change of air, round a central flue through which heated gases from the boiler furnace will always pass. This flue being always warm will cause sufficient up-draught in the ventilating shafts to draw the vitiated air out of the rooms, but it will also be possible to suck this air downwards by means of fans placed in the basement, and there to throw it into one of the hot flues. Air inlets will be seen in this room in which the air passes over a surface of oil which will deprive it of its coarse dust. This arrangement, the invention of Mr Kenneth Steell, will it is hoped, keep the Laboratory free from that black dirt which at present is so difficult to exclude from our rooms." Schuster 1900

The up-draughts from the ventilation then, could to some extent counter downwards diffusion and the effect of gravity. The location of a radium room at the top of the building makes some sense from this perspective. A corner room would provide the possibility of additional through drafts from open windows. At the Macdonald Laboratory the ventilation was by flues drawn into a central turret by a by 5 HP fan. The heating by the boilers at the south end of the basement would have given rise to additional convection. These factors would undoubtedly have contributed to the spread upwards of radium emanation from the basement where Rutherford worked. At this time I do not know what ventilation systems were present in the Cavendish, but presumably upwards convection may have been a factor.

In addition to the separation of radium storage, it was general practice to have a separate room for radio-chemistry. At Montreal it would appear that the “chemist’s kitchen”, as Otto Hahn described it, although at some distance from his electroscopes, was still in the same basement floor. At Manchester the radio-chemistry was initially done in a shed outside the back to the laboratory, according to the 1908-09 Report to Council, and after 1912 a special chemical laboratory was built onto the extension. At this time I do not know what arrangements there were for radio-chemistry at the Cavendish.

II RADIO-ARCHAEOLOGICAL PERSPECTIVES OF THE SCHUSTER LABORATORY

Between 1999 and 2004, there were a number of radiological surveys of the Rutherford Building and adjacent buildings, as well as substantial remediation and post-remediation analyses, many of which are documented in Churcher *et al.* (2008). These data provide valuable data for an archaeological analysis of this site of activity from the early period of nuclear physics. The ideal from an archaeological perspective would be to use the historical evidence to ensure that the site was accurately and fully defined, and to design the measurements and analyses to test hypotheses concerning the extent and use of substances. Unfortunately, the data that do exist are rather piecemeal, and complicated by the fact that the management of the site was divided arbitrarily between the Manchester Museum and Psychology. Nevertheless, there are sufficient data available to carry out some statistical analysis. Prior to doing such analysis, in order to make any sense of radiological data from an archaeological point of view, it is necessary to consider the mechanisms of contamination.

II.1 Mechanisms of Contamination

Four principal mechanisms can be inferred from the historical review which could contribute to the radiological signature found at any of the sites. These are: (a) Radon escape and distribution of active deposit, (b) distribution by handling contaminated objects, (c) spillage of powder, salts or solutions and (d) radioactive recoil.

(a) Radon escape and distribution of active deposit

Undoubtedly, this mechanism contributed significantly to contamination at the Macdonald and Schuster Laboratories. As was made clear by Rutherford, continued emanation escape would eventually lead to the entire laboratory becoming active due to the longer half-life products of radium. These are Ra D (Pb210), Ra E (Bi210) and Ra F (Po210) with half-lives of, respectively, 22 years, 5 days and 140 days. In section I.5, I discussed the critical issue of transport of radon within a building and it is clear that the most significant factor in distribution is the flow of air within the building. In the Macdonald Building, the radium bromide apparatus was kept in the basement and, as Rutherford noted, the whole building became contaminated. Probably for this reason, the radium rooms in the Schuster and Cavendish Laboratories were located at the top of the building. In the Schuster Laboratory, however, significant use was made of radon tubes between 1908 and 1914, and documented accidents did occur, in spite of the strict regime which Rutherford had put in place. After 1914, Rutherford practically abandoned the use of radon tubes as a source . Thus, the contamination of the Cavendish due to active deposit of radon from the radium bromide apparatus and procedures for preparing sources may have been more localized to the radium room and immediate area.

A surface contaminated with Pb/Bi/Po210 will produce a mix of beta radiation from Pb210 (at least two distinct groups of maximum energy 0.06 MeV, range 4.0 cm), Bi210 (with a continuous spectrum) and alpha radiation from Po210 (5.3 MeV, range 3.8 cm in

air). In addition, there is a significant gamma emission from Pb210 with a 46 keV energy. The short range of the Pb210 beta and Po210 alpha would mean that these might be more difficult to detect. However, the beta radiation which forms the continuous spectrum of Bi210 has a range of velocity of about 0.5 - 0.9 times the speed of light, with a mode of about 0.8 (Gray 1910). This translates into an energy range of 0.076 – 0.649 MeV and range in air of about 0.1 – 1.95 m. Thus, Bi210 could potentially contribute significantly to the beta count in any radiological analysis.

The gamma emission of Pb210 could also contribute, but the measuring-instrument would need to be set up to detect energies as low as about 40 keV. The gamma emission of Bi210 is generally considered to be of low intensity, but in principle it could still make a contribution to the total count, with energies of 305 and 266 keV given in the Chart of Nuclides.

(b) Distribution by handling contaminated objects

Another major source of contamination, as exemplified by the Antonoff incident (see p. ?), is the spread of active matter by handling radioactive materials or contaminated apparatus. This problem was clearly recognised by Makower and Geiger (1912):

"The danger of the experimenter accidentally contaminating his hands and cloths cannot be too strongly emphasized. [p74]

It is advisable not to work with electroscopes immediately after transferring the emanation, for it is difficult to prevent the hands and cloths becoming slightly active in the process." [p132]

It is obvious that radioactive material could have been widely distributed to any surfaces with which workers came into contact on a daily basis, along the common routes taken within the laboratory, such as doors, walls, banisters, etc, as well as on utensils, apparatus, and other common objects handled in every day life, not least coins, as in Antonoff's case. It is certain that material was transported around the laboratories at Montreal and Manchester by this mechanism and contributed significantly to contamination. At the Cavendish, more elaborate procedures, including scrubbing and change of cloths, were put in place to reduce the spread of contamination from preparation of sources, but it is unlikely that these procedures were 100% effective – the contamination of Norman Feather's 1932 cloud chamber being one example where the procedures failed.

(c) Spillage of powder, salts, liquids and solutions.

Whenever there are any manipulations or procedures involving substances, the possibility of spillage is always present. As discussed in section 1.3.2.2, there were many procedures for making sources which involved the use of solutions for the separation of products of decay. Even a small drop of strong solution could lead to a significant contamination. For this reason, radiochemical procedures at Manchester after Rutherford's arrival were routinely carried out in a room external to the main laboratory. However, it is likely that some manipulations were carried out in the main laboratory. In

contrast to emanation escape, spillage would result in localized concentration of contamination around a site of activity.

In addition to radioactive substances and solutions, mercury was widely used in the apparatus to keep, purify and manipulate radium and its products. At Manchester, much of the glass apparatus in and around the radium room made use of mercury and mercury was also used to transfer burettes of radium emanation to other locations. A good example of such apparatus was the Toepler pump, which can be seen in the 1905 photograph of Rutherford in the Macdonald cellar and is described in part I. It is easy to see how it would be possible to produce a spillage, for example when lowering the reservoir of a Toepler or other mercury pump. Such spills would again be expected to be localized around the site of activity.

(d) Radio-active recoil

The phenomenon of radioactive recoil was known since the earliest days of work at Manchester, with notable work by Sydney Russ and Walter Makower. When a particle of mass m is expelled with velocity v during the decay of a nucleus, the conservation of momentum requires that the residual atom mass M - m recoils with a velocity $V = mv/(M - m)$, where M is the mass of the parent atom. In fact, atomic recoil occurs for both alpha and beta decay, but the velocity of recoil is two orders of magnitude less for beta decay, given the relatively small mass of the electron.

A phenomenon associated with recoil was referred to as “volatilisation” whereby an active deposit would appear to “volatilise” from a surface when recoil atoms were shot out of the surface. The distance traveled by the recoiling atom in air, a fraction of a millimeter, is considerably less than that of the alpha or beta particle, but it could nevertheless be exploited for the separation of sources (Makower and Geiger 1912). When the surface was held in a vacuum, however, the distance traveled by a recoiling atom could be considerable. It is this phenomenon of “volatilization” which could give rise to the contamination of apparatus referred to by Rutherford in which an active deposit source was not confined.

An additional phenomenon associated with recoil is a mechanism of active transport resulting from the momentum of recoil atoms not shot out from the surface being transferred to neighboring atoms. According to Makower and Geiger’s (1912) analysis, it would be expected that half of the recoil atoms would be expelled from the surface, contributing to “volatalisation”, and the other half would recoil into the surface. Some poorly understood process could result in the transport of aggregates of active deposit. In the case of the long half-life active deposits of radium emanation (Pb/Bi/Po210), this could contribute to its dispersion within a building.

II.2 The extent of radioactive contamination of the Rutherford Building

An issue of critical importance is the extent to which the Rutherford Building and 1912 extension became contaminated. The historical evidence clearly indicates that the original

Schuster Laboratory became contaminated quite early. It was Rutherford's intention to keep the 1912 extension free from contamination in order to carry out fine measurements of beta and gamma radiation. It is of interest to determine the extent to which this goal was achieved.

In order to obtain a statistical test of this, it is necessary to have comparative measurements of rooms within the Rutherford and adjacent buildings. The most complete survey which provides such a comparison is the NNC Survey of Coupland I, Annexe and Old Dental Hospital carried out by S M Adams in September 2000. The survey was carried out using three instruments: a Bicron gamma detector set to detect gamma energies > 60 keV, a Berthold LB122 beta/gamma detector and a Mini Instruments 900/AP2 alpha monitor. The Bicron gamma measurements were taken at waist height, on the floor and wall of each room. The data were made public in Appendix C14 of Churcher et al (2008).

From the above survey of mechanisms of contamination, we might expect there to be some localized hotspots due to radium and other long half-life substances. From the radium series, the main gamma emitters are radium (Ra226, 186 keV, 3.5%), radium A (Pb214, 351 keV, 36%), radium B (Bi214, 609 keV, 45%) and radium D (Pb210, 46 keV, 54%). In addition, we might expect a general elevation of the radiation count due to the wide distribution of the active deposits of Rn222. After 100 years, any Rn222 active deposits would consist of radium D+E+F, i.e. Pb210/Bi210/Po210. As the main spectral peak of Pb210 is 46 keV, gamma rays from this source would not be detected by the Bicron instrument. Although the gamma radiation from Bi210 is known to be of low intensity, with sufficient concentration it could contribute to a background, with energies of 305 and 266 keV.

In order to test the hypothesis that the Rutherford building is significantly more contaminated than the surrounding buildings, a univariate ANOVA was carried out for each of the four dependent variables: β - the beta/gamma count (cps), $\gamma 1$ - the gamma count at waist height (counts in 1 min), $\gamma 2$ - the gamma count measured at floor level (cpm) and $\gamma 3$ - the gamma count measured at the walls (cpm). The independent factor used was "building": 1900 Building, 1912 extension, 1920s extension, Annexe and Old Hospital. The results of the ANOVA are as shown in Table II.1. The values displayed represent the marginal means of count values across rooms within the category of building.

TABLE II.1: ANOVA of NNC 2000 data.
N is the number of rooms in each category of building.

	1900	1912	1920s	Annex	Hospital	F	df	p
β	82	33	23	21	21	.69	4,96	.601
$\gamma 1$	17513	17799	13129	10191	11255	24.6	4,100	<.001
$\gamma 2$	23553	21166	18000	12500	13866	17.7	4,98	<.001
$\gamma 3$	21118	23833	21000	12833	13851	32.1	4,81	<.001
N	34-50	6	1-2	18	25-30			

The analysis shows that, there is a highly significant main effect of building for the gamma count, although not for the beta count. A problem with this analysis, though, is that the numbers are small for some cases and it is not possible, without further analysis, to identify the source of the effect. If the physics and non-physics buildings are pooled together, however, i.e. so that there are only two levels of the independent variable, then the analysis reduces effectively to an independent t-test, as shown in Table II.2.

TABLE II.2: ANOVA of NNC 2000 data.
(N is the number of rooms in each category of building, which may vary for the different counts.)

	1900+1912+1920s	Annexe+Hospital	F	df	p
β	75	21	2.25	1,99	.136
γ1	17391	10847	93	1,103	<.001
γ2	23090	13354	68	1,101	<.001
γ3	21512	13444	122	1,84	<.001
N	58	41-47			

We may be confident from this analysis (Table II.2) that the buildings historically occupied by the Department of Physics have a statistically significant higher mean gamma count than the adjacent buildings. The mean beta count was also higher, but did not reach statistically significance.

II.3 Room Use and Localization of Contamination

Having provided some statistical evidence that the mean pooled gamma counts for the 1900 Building and the 1912 and 1920s extensions were higher than those for the adjacent buildings (the Annexe and Hospital), it is of interest to consider the localization of contamination within the Schuster Building. The historical survey points to a number of locations which might be expected to be more contaminated than others. In particular, we would predict that the principal radium room (2.62), Rutherford's ground floor laboratory (G55/54), the basement laboratories (CB10, CB09, CB04/5/6/7, CB02), which include Geiger's room, and the chemical laboratory attached to the 1912 extension, would be hotspots. In order to investigate this hypothesis, we may make use of the NNC 2000 survey as above, in addition to which there are some more recent data by IRAS Ltd obtained by AJ Frith in 2004, although of a more limited scope.

In addition to the data on radioactive contamination, there are also data regarding levels of mercury contamination from a survey carried by Casella Winton in 2004. As discussed in II.1, we would expect there to be localized mercury contamination at positions in the laboratory where any glass apparatus was present which employed a mercury pump.

Ranking Analysis based on the NNC 2000 data

Using the NNC 2000 data, each room was ranked according to the magnitudes of the four count measures separately. Although this does not provide a test of whether observed

differences are statistically significant, it does provide some useful qualitative data about which rooms were the most contaminated. The results of this analysis are shown in Table II.3. Only the top 10 ranking rooms in case of each of the four measures are given.

TABLE II.3: Top 10 Rankings of Rooms in the Schuster Building According to each of the Four Measures of Radioactivity (NNC 2000 data.)

rank	room	β	room	γ1	room	γ2	room	γ3
1	C 1.10	1338	G54A	33563	G.54A	50000	CB.10	29000
2	G.55	1321	G55	33441	G.55	50000	H24	29000
3	2.53	45	CB10	25996	CB.10	50000	H22	28000
4	2.52	41	1.54	22589	2.53	40000	Switch	26000
5	CB10	37	H24	21925	2.52	40000	2.58	26000
6	CG 03	36	2.53	21437	H24	25000	G.56	25000
7	H23	36	G.52	20394	2.64	25000	2.59	25000
8	H24	36	H23	20195	2.54	25000	C 1.10	25000
9	2.54	35	switch	20009	CB.09	25000	G.51	24000
10	2.58	35	G51	19332	CB.05	25000	Cohen	24000

It is unfortunate that some key rooms were not included in the survey (2.63, the chemical lab, the 1st floor of the extension) and some rooms do not have all four measurements. Nevertheless, this analysis indicates the G54/55 (Rutherford Ground Floor Lab) and CB10 (Basement Lab) as consistently in the top three, and Basement Labs CB05 and CB 09 in the top 10. In addition to these rooms, the following are also implicated: C1.10 (Balance Room), 2.52/2.53 (Preparation Room), H22/23/24 (1912 extension), 2.54 (Apparatus Room), 2.58/2.59 (Museum), Large Lecture Theatre, 1.54 (General Physics), CG03 (Electro-Chemistry) and G51/52. (Library)

Ranking Analysis based on the IRAS 2004 data

It should be noted that the IRAS 2004 data were collected after some remediation had taken place in 2001 (See Appendices C17/C18/C19/C20/C21 of Churcher et al 2008). The decommissioned rooms were 2.62/63, 2.52/53, C1.10, CB05/09/10. In principle, had the 2001 decommissioning been complete, we should expect there to be no significant contamination in the targeted rooms. As is apparent, this was not the case.

Using the IRAS 2004 data, three measures were derived: maximum alpha count (cps, Mullard Alpha Probe Type L313), maximum beta count (cps, Mini Instruments 900 Type EP15) and maximum gamma (cpm, Mini Instruments 42A NaI scintillation detector). Before examination of the rankings, it is of interest to compare the IRAS 2004 and NNC 2000 measurements for consistency. The correlation coefficient between the Berthold and Mini Instruments 900 beta measurements is $r=0.71$, $p<0.01$, $n=17$. Interestingly, the correlation coefficient between the gamma measurements is significant for only the Bicron floor count, $r=0.61$, $p<0.05$, $n=16$, which reflects the fact that most spots of maximum contamination found in the 2004 survey were obtained from the floor. Nevertheless, the correlations obtained do indicate some consistency between the 2000 and 2004 measurements.

As for the IRAS 2004 data, each room was ranked according to the magnitudes of the three count measures separately and the results of this are shown in Table II.4.

TABLE II.4: Top 10 Ranking of Rooms in the Schuster Building According to each of the three Measures of Radioactivity (IRAS 2004 data.)

rank	room	α	room	β	room	γ
1	2.53	300	2.53	2000.00	Bees	36000
2	2.52	300	2.52	2000.00	2.53	15000
3	2.62	50	Bees	2000.00	2.52	15000
4	Mezz	40	1.52	700.00	1.52	12000
5	Bees	1.0	2.63	400.00	2.63	9000
6	1.54	.50	1.54	250.00	1.56	6000
7	2.63	.50	1.55	250.00	1.54	4800
8	1.56	.50	2.60	200.00	1.55	4800
9	Tank	.50	2.61	250.00	2.60	4200
10	1.55	.50	2.54	200.00	2.61	4200

There are several features of interest in these rankings. First, 2.52/53 (the Preparation Room) and 2.62/2.63 (Radium and Research Rooms) both feature prominently despite that fact that they were subject to "decommissioning" in 2001, although G55/54 does not, indicating that for this room at least the 2001 decommissioning was successful. Second, there are several rooms which appear for the first time, including 2.60/2.61 (the Grating Room), 1.52 (Electricity Room), 1.54/1.55 (General Physics and Chemistry), 1.56 (the Laboratory Director's Room), Mezzanine (the Chart Room) and Beekeepers (Observatory).

Ranking Analysis based on the CASELLA 2004 Mercury Contamination data

The data for the mercury survey were obtained using a Mercury Instruments Tracker 3000 which sampled air for vapour above and below the floor boards. Concentrations are given in $\mu g/m^3$ and rankings are given in Table II.5.

TABLE II.5: Top 10 Ranking of the Rooms in the Schuster Building According to Two Measures of Mercury Contamination (CASELLA 2004 Data).

Rank	Room	Mg Floor	category	Room	Mg Sub	category
1	2.52	157.00	A	2.63	370.00	A
2	G.53	111.40	A	G.53	232.60	A
3	2.63	109.20	A	2.52	230.00	A
4	2.62	46.00	A	2.62	80.00	A
5	1.52	23.30	B	1.52	43.90	B
6	G.55	20.50	B	G.55	41.20	B
7	2.53	18.30	B	2.53	35.30	B
8	1.51	15.70	B	1.51	33.40	B
9	2.60	10.40	B	1.53	20.00	B
10	2.58	6.60	C	2.60	19.70	B
11	2.54	6.40	C	2.61	18.80	B

Among the most mercury -contaminated rooms (category A) are 2.62/2.63 (the Radium and Research) and 2.52/2.53 (the Preparation Room) which are also among the most radioactively contaminated. Also in category A is G53, which was designated as "Alternating Currents" in the 1906 plan and would have been used by the Electro-technical Department prior to 1912. Among the category B rooms are 2.60/2.61 (Grating Room), 1.51 (Electricity), 1.52 (Electricity), 1.53 (Optics) and G55 (Rutherford Laboratory).

II.4 Radionuclide analysis of remediated radioactive substances

We know from the historical data that radioactive substances from all three natural decay series were used by Rutherford and co-workers. We might expect, therefore, that contamination from the long half-life products from the three series would be present. Summarized below are the results of radionuclide analysis of the material removed in the 2001 and 2004 remediations.

Radionuclide analysis from NIRAS Analytical Report 2001

Table II.6: Radionuclide Analysis of Sample Material Taken from Three of the Contaminated Rooms Prior to Remediation.

Radionuclide	**CB. 05 Bq/g**	**G55 Bq/g**	**C.1.10 Bq/g**	**C. 1.10 MBq**
RADIUM				
Ra226	53.7	70.1	<5.5	2.99
Rn222				1.39
Po218				1.39
Pb214	12.2	0.44	<0.39	1.35
Bi214	14.4	0.9	1.0	1.15
Po214				1.39
Pb210			4103	28.1
Bi210				1.39
Po210				1.39
THORIUM				
Ra228				0.016
Ac228	0.81	0.57	0.243	0.019
Pb212	<0.4	<4.3	<0.38	0.013
Bi212	<2.4	<3.7	<2.6	

Prior to the 2001 remediation, gamma ray spectroscopy was reported for three samples [See Appendix C11, NIRAS Analytical Report, Churcher et al 2008] and the detailed analysis of material remediated from Room C. 1.10 was reported [Appendix C19 of Churcher et al 2008]. A summary of these data is given in Table II.6. For rooms CB.05 and G55, the spectroscopy indicated that contamination was primarily due to Ra226, while for C.1.10 a strong Pb210 source was indicated. The strong Pb210 signature was confirmed from analysis of the remediated material.

NNC Analysis of the material from the 2001 remediation.

Table II.7: Estimated Activity of Ra226 and Pb210 in Material Removed in the 2001 Remediation

Room	Ra 226 (Bq/g)	Pb210/Pb210 (No of spots @ 20 kBq)	Mass (kg)	Activity (MBq)
2.52/2.53 (Preparation)	0.37-0.72	2	2.3	0.051
2.62/2.63 (Radium)	1.27	20	64	0.48-1.0
C 1.09 (Elementary Lab)	-	-	-	-
C 1.10 (Balance Room)	<5.5	-		
	24-4000 (Pb210)		3-751	14.93-55.54
G 54/55 (Rutherford Lab)	9.6-70.1	6	712-902	8.83-9.3
CB 05 (Geiger Lab)	43-53.7	-	38.8	1.67
CB 09 (Research)	0.5-0.66	-	19.4	0.0097
CB 10 (Research)	4.9	-	3.3	0.016
		28	**1668**	**68**

Table II.7 summarises the quantity, activity and estimated radionuclide content of the material removed in the 2001 remediation [See Appendix C21, Wastestream Characterisation for LLW Disposal to BNFL, Churcher et al 2008]. The analyses concluded that apart from C.1.10, which showed a strong Pb210 profile, the contamination was due primarily to Ra226. The largest amount of material was taken from G55/54 (the Rutherford Lab) followed by C.1.10, which together accounted for the vast bulk of the total mass removed and of the total activity. Three rooms were identified as having significant Pb210/Po210 under the floor boards: 2.62/63 (Radium and Research), 2.52/53 (Preparation Room) and G55/54 (Rutherford Laboratory). It was estimated that a significant amount of undetected Pb210/Po210 would have been present in other rooms.

IRAS 2004 Analysis of Contamination

Table II.8. Summary of Gamma Ray Spectrometry from the IRAS 2004 Survey of Rooms in the Schuster Building

Room	Radionuclide	Areas identified	Beta (cps)	Gamma (cps)
Mezzanine (Chart Room)	Ra226	2	100	20-30
Beekeepers (Observatory)	Ra226	1	2000	600
Tank	Ra226	1	40	10
2.62 (Radium Room)	Ra226	1	100	20
2.63 (Research)	Pb210/Po210	1	400	150
2.60/2.61 (Grating Room)	Ra226	1	200	70
2.52/2.53 (Preparation)	Ra226	3	50-2000	40-250
2.54/55/56 (Apparatus)	Ra226	2	3-150	8-15
1.52 (Electricity)	Ra226	1	700	200
1.53 (Optics)	Ra226	1	60	40
1.54/55 (General and Chemistry)	Ra226	3	20-250	9-80
1.56 (Director's Office)	Ra226	3	30-120	20-100
1.57 (Ante Room)	Ra226	2	30-70	30-40

During the 2004 survey by IRAS Ltd, radionuclide identification was made of 21 of the 50 areas of contamination using mobile low-resolution gamma ray spectrometry. 20 of the identified spots were contaminated by Ra226 and one by Pb210/Po210 (2.63). These results are summarised in Table II.8. There were 30 spots, however, for which the contaminating substance was not identified.

II.5 Discussion of the Manchester Data

There are several important issues which arise from this review of the radiological data and which will be discussed in the rest of the section. The main issues are: the extent of the contamination in the Schuster Laboratory, the distribution of contamination within the Schuster Laboratory and the nature of the substances which formed the contamination.

II.5.1 Building Use and Extent of Contamination

The radiological data that are available are consistent with the historical evidence in showing beyond doubt that the entire original 1900 Schuster Laboratory had become contaminated. Areas of contamination were found to be widely distributed on all floors from the basement up to the Mezzanine and to this day, 80 years after Rutherford left for Cambridge, the afterglow in the form of gamma radiation is significantly higher than that from adjacent buildings. It is also clear from section II.2 that Rutherford's intention of keeping the 1912 extension free from contamination was not met. At the time of writing, we do not have data from the six physics rooms on the 1st floor or from the external radiochemical laboratory, but the mean gamma counts from the ground floor of the 1912 extension are very similar those in the 1900 building. Indeed, some of the highest values in the gamma counts were found in the extension.

II.5.2 Room Use and Distribution of Contamination

In reviewing the variation in the distribution of contamination, I have confirmed that those rooms which had been previously identified on historic grounds as being used by Rutherford were highly contaminated. These were: the Radium Room (2.62) where Rutherford kept his radium bromide apparatus and where Royds carried out his experiments; the adjacent Research Room (2.63), probably where Boltwood worked in 1909-1910; the Research Laboratory (G.55/54) on the ground floor, probably where Rutherford did his 1919 work, and the Geiger Laboratory (CB05) in the basement. In addition, the other basement rooms designated for research in 1906, probably occupied variously by Makower, Russ and Moseley, were also highly contaminated (CB09/10).

Of significance is the observation that rooms 2.62/2.63 were also contaminated with mercury, which is entirely consistent with the regular use of mercury pumps which were an important feature of the radium bromide apparatus, the Rutherford and Royds apparatus and the Boltwood apparatus.

However, it is clear that several other rooms, not previously identified as being contaminated, were also highly contaminated. Undoubted the most significant of these

was the Preparation Room (2.52/2.53). As well as being contaminated with Ra226 and Pb210/Po210, to the extent that it required two rounds of remediation, it was one of the most contaminated with mercury. This suggests that it was the location for a piece of glass apparatus which was evacuated by a mercury pump. In section I.3, I reviewed some historical evidence for a secondary radium bromide apparatus containing the original Schuster radium, and the Preparation Room is a good candidate for its location. This room had features in common with the principal Radium Room, *i.e.* it was at the top of the building in a corner with a good flow through of air. It was also a room with a fume closet and ventilation connecting with the Large Lecture Theatre. It could have provided smaller sources for experiments as well as support teaching. Thus, it could have supplied the Chart Room (Mezzanine) above, which was found to be contaminated in the 2004 survey.

Another room which was highly contaminated was the Balance Room (C1.10). We know from the pamphlet produced for the March 1st opening of the 1912 extension that it is likely to have been used as "Room 2" for an exhibit of:

"Radioactive minerals and Radioactive Preparations. New radioactive Minerals lent by Professor MARKWALD, of Berlin." [Schuster 1912]

Among the minerals which Markwald had dealt with was Rutherfordine (Uranyl Carbonate) and he was considered to be the co-discoverer of ionium, the parent of radium. It is entirely possible that one of the preparations on display in the Balance Room in 1912 could have resulted in the contamination by Pb210 found there. It is also likely that the room was used to weigh out quantities of radioactive substances, and this could easily have given rise to contamination.

Among the other rooms on the first floor in which radioactive contamination was found were 1.52 (Electricity), 1.53 (Optics) and 1.54/55 (General and Chemistry). Two of these three rooms were also used for the 1912 opening in which many radioactive exhibits were on display. The most likely order of progression of the exhibits, as discussed in section I.3, would suggest that room 1.52 (Electricity) was "Room 4", in which there were experiments illustrating "methods of measurement employed in radioactivity, and the properties of the radiations". Many of these were those described in Makower and Geiger's book, and indeed it is entirely possible that this room was the location of the training laboratory, or the room adjacent to it (the reception room, "Room 1", normally doubling up as the training lab). All of the methods described as being used in "Room 4" were electrical in nature (e.g. the magnetic deflection of beta rays, electrical effect of radium), thus being consistent with the 1906 designated function of the room.

In contrast, all of the experiments in "Room 5" were optical in nature (e.g. phosphorescent effects, spectroscopic analysis of helium) and this would be consistent with the location of "Room 5" being 1.53 (Optics). Both 1.52 and 1.53 were designated, in the 2004 survey of mercury contamination by Casella Winton, as being in category B on the mercury contamination scale, consistent with the presence of glass apparatus in these rooms for handling radium emanation. Undoubtedly, these rooms would have been used for experiments with radioactive substances both prior to and after the completion of

the 1912 extension. The presence of contamination in other rooms on the 1st floor is indicative of radioactive research having been carried out in 1.54/1.55 (General) and in 1.56/157 (Private and Ante Room), which was used by the Laboratory Director, suggests that either Schuster, between 1903 – 1907, or Rutherford, between 1907 and 1919, had handled radium in this room.

Table II.9: Summary of Inferred Room use in the Schuster Laboratory.

Room	**1906 (1912) Designation**	**Inferred use by Rutherford and co-workers**
Cohen	L Lecture Theatre (Room 7)	Teaching/Radioactivity Demonstration
2.52/53	Preparation room	**Secondary Radium Room**
2.54/55/56	Apparatus Room (Room 10)	Apparatus, some research
2.57/58/59	Museum (Room 9)	Research?
2.60/61	Grating Room (Room 8)	Spectroscopy, including work by Royds
2.62	Transit room	**Primary Radium Room/ Royds Experiment**
2.63	Research	**Boltwood Experiments**
2.64	S Lecture Theatre	Teaching
C 1.09	Elementary Lab (Room 3)	Teaching,/Some radioactivity training
C 1.10	Balance Room (Room 2)	Display of radioactive Minerals
1.51	Electricity (Room 1, Reception)	Radioactivity training/Tea Room
1.52	Electricity (Room 4)	Radioactive Exhibits/Research
1.53	Optics (Room 5)	Radioactive Exhibits/Research
1.54/55	Sound & General (Room 6)	Radioactivity Research
1.56	Private Room	Rutherford's Private Office
1.57	Ante Room	Ante Room
G 51/52	Reading Room	Research?
G 53/54	AC Currents (Room 13)	Research after 1912
G 54/55	Private Lab	Rutherford's Private Laboratory
G 56/57	Workshop	Workshop
CG 01	Electricity (Room 11)	Research after 1912
CG 02	Switchboard (Room 12)	Research after 1912
CG 03	Electrochemistry	Electrochemistry (Antonoff's work)
H22	1912 expansion	Electrotechnics
H23	1912 expansion	Electrotechnics
H24	1912 expansion	Electrotechnics
H26	1912 expansion	Electrotechnics
CB 01	Photographic Room	Research?
CB 02	Spectroscopic Research (Room 15)	Radioactivity Research (noted by Geiger 1937)
CB 03	Boiler Room	Boiler Room
CB 04/…/07	Liquid Air & Research (Room 14)	Geiger' Laboratory (Liquid air moved 1908)
CB 09	Research	Radioactivity Research
CB 10	Research	Radioactivity Research
CB 11/12	Supplementary Workshop	Workshop
CB 13	1920s expansion	-
CB 14	1920s expansion	-

It is clear, then, that work using radioactive substances was widespread throughout the entire laboratory. In the earliest days from 1903 before Rutherford's arrival, work would have been confined to those rooms designated as for "research" (mainly in the basement), but with the rapid expansion in the number of workers from 1908 to 1912, there would have been a general encroachment into all available rooms, including those originally designated for teaching on the 1st floor. After the 1912 expansion, up to the start of the

world war in 1914, it is likely that some work using radioactive substances also took place in rooms on the ground floor originally designated as part of the Electrotechnics Department. A summary of inferred room use for the Schuster Laboratory is given in Table II.9 above.

II.5.3 Substance Use and Distribution of Contamination

Radionuclide analysis from the NIRAS 2001 Analytical Report, the Wastestream Characterisation from the 2001 remediation and the IRAS 2004 LRGS are consistent in indicating that the contamination is predominantly from Ra226, with smaller amounts of Pb210/Po210. Although isotopes from the thorium series are shown in the NIRAS 2001 Analytical Report, these are not commented upon and there is no indication of isotopes from the actinium series. There are two major issues which arise from these indications. First, given the wide use of substances from all three series, it seems curious that contamination from other long half-life substances was not indicated. Second, given the strong indication of Ra226, a question is raised as to the absence of an equivalent amount of Pb210, which would be in equilibrium after 100 years. There would appear to be a large amount of missing Pb210.

Absence of long half-life isotopes other than Ra226

In all three radionuclide analyses, Ra226 was strongly indicated, and areas throughout the building were identified as being contaminated with Ra226. We know, however, that long half-life substances from all three series were widely used historically. From within the uranium series, uranium oxide, probably in the form of powder or paste, was used by Geiger in counting experiments in the basement, for example, and von Hevesey studied its diffusion properties in the chemical laboratory. We know that the “actinium residues” contained some residual radium and also ionium. Any extracted ionium (Th230, 77,000 yrs), being an isotope of thorium, would have also contained uranium X (Th234) which is the parent of uranium 2(U234, 240,000 yrs) and thorium (Th232, 14 billion years). Other than the thorium contained in the “actinium residues”, thorium oxide was also widely used for counting and other experiments. We should not be surprised, then, that Th232 series isotopes (Ac228, Pb212m Bi212) were found in the NIRAS analyses. However, given that Th228, the immediate daughter of Ac228, and Tl208, the immediate daughter of Bi212, are significant gamma emitters, it seems curious these were was not indicated.

The 21 kg of “actinium residues” contained a significant amount of actinium (Ac227), which has a half-life of 22 years, about the same as Pb210, and we know that Boltwood separated 10g of actinium preparation. This was subsequently used widely by a number of workers, not least by the poor fellow who flushed some of the precious stuff away in 1913. Given that the immediate daughters of actinium, i.e. Th227, Ra223, Rn219, Pb211 and Bi211, are significant gamma emitters, it is again curious that these were not indicated. Pb211 in particular, being chemically inseparable from the Pb210, would have been present from the pitchblende residues.

There are probably two good reasons why these other long half-life isotopes were not detected. (It is difficult to believe that there was no contamination from these other isotopes.) One reason might be that the persons carrying out the analyses of the material removed during remediation were not looking for isotopes other than radium and its daughters. Identification of isotopes by gamma-ray spectrometry can be a complex business, especially if there is a mix of isotopes. If identification is done by a library-directed search by matching a template spectrum against the spectrum produced by the source, then it is quite possible that unexpected isotopes could be missed (Gilmore 2008). The observations above suggest that the printed analyses were selective and that the analysts who undertook the spectrometry were guided by the assumption that the contamination was primarily due to Ra226. A second possible reason is the complexity of the gamma-ray spectra themselves. Gamma spectrometry of naturally-occurring radioactive substances in particular is notoriously complicated by interference between difference isotopes, a good example being that between U238 (49.55 keV) and Pb210 (46.54 keV). This problem would be compounded by the use of a low-resolution system. Also there is very considerable variation between? in emission probability which could result in the masking of one isotope by another. Thus, some isotopes may be inherently difficult to detect, Pb210 being one such example.

Missing Pb210

This brings us to the issue of missing Pb210. Clearly, the sampling process would disturb the equilibrium, but we may infer from the low values for Pb214/Bi214 in the radionuclide analysis (Table II.6) and the absence of Pb210, which is a gamma emitter, that the sampling in the 2000 survey will have significantly underestimated the Rn222 and accumulated active deposits of Pb210. The Wastestream Characterisation document [Appendix C21 in Churcher *et al*. 2008] estimated the summary of the radionuclide fingerprint to be 74% Ra226, 13% Pb210 and 13% Po210 activity concentration. Given that the radium has been present for nearly 100 years, in a closed system the Pb210/Po210 would be in secular equilibrium with the Ra226 (see Appendix A3) so that we should expect a ratio of 33%, 33%, 33% for these three isotopes. The observed ratio is indicative that the Rn222 had widely dispersed over the century to form active deposits throughout the building so that the remediation which focused on the vicinity of the hot spots has clearly missed a possibly considerable amount of Pb210/Po210. Excluding the activity from room C 1.10, the total activity of remediated material in 2000 is about 10 MBq of which 7.4 MBq is due to Ra226. In equilibrium, this would produce 7.4 MBq each of Pb210 and Po210, or 14.8 MBq. Subtracting the 2.6 MBq of Pb/Po210 which was present in the remediated material would leave about 12.2 MBq of Pb/Po210 in the building, which is not an inconsiderable amount. We now know that the 2000 remediation was incomplete because further material was removed in 2004. At the time of writing (December 2008), we still await any analysis of the 2004 material.

Levels of Rn222 and origin of Pb210 in the Radium Room

An issue of critical importance for estimating historic levels of Rn222 is the origin of the Pb210/Po210 found under the floor boards. The location underneath the gaps in the

floorboards is possibly indicative that it was a result of the radon seeping through the gaps. In rooms 2.62/2.63, we may be sure that some of the Pb210 is an historic remnant from escaped emanation during the period 1908 – 1919, but given that some Ra226 contamination was found in this room and other rooms, then some of the Pb210/Po210 would have been generated between 1919 and 1999 when the contamination was discovered.

After the 2000 remediation, further amounts of Ra226 were found in 2.62/2.63, but nevertheless, assuming that the values for contamination found in rooms 2.62 and 2.63 were accurate, then at 1.27 Bq/g the 64 kg of remediated material from these rooms would contain 0.082 MBq of Ra226 and the 20 spots of Pb210/Po210 would total to 0.40 MBq. If secular equilibrium had been achieved between Ra226 and newly generated Pb210, then at most there would be 0.082 MBq of Pb210, so that 0.32 MBq of activity would be due to historic emanation escape. The activity in 1919 can be calculated as follows. The number of atoms of any radioactive substance S is given by $S = S_0 \exp(-\lambda t)$ where S_0 is the initial number and λ is the decay-constant, which for Pb210 is 3.15×10^{-2} y^{-1} (Rutherford 1913). The activity *A* at any time is λS so that if 80 years had passed since Rutherford took his radium off to Cambridge, then the activity in 1919 would be $A / \exp(-\lambda \times 80) = 3.2 \times 10^5 / 8 \times 10^{-2} = 4 \times 10^6$ or about 4 MBq. The radium having been present in 2.62/63 for between 1 to 10 years between 1908 and 1919, the activity ratio would have been about 1:10 (see Appendix A3). Thus it would have required the equivalent of about 40 MBq or about 1 mg of radium to be continuously exposed to produce this activity level of Pb210 in 1919.

An alternative, and more realistic, contamination scenario was that Rutherford's equivalent of 250 mg of radium, which was kept in 2.62/63 (the radium room), was exposed, *i.e.* unsealed, during a series of short accidents. This poses the following question : how long would 250 mg of radium need to be exposed to produce 4 MBq of Pb210 activity in 1919? The answer can be found in article 161 of Rutherford (1913) which tells us that the activity level A_T of a daughter isotope after exposure of the parent for time *T* is $A_T = A_0(1 - \exp(-\lambda T))$, where A_0 is the parent activity. Thus, the exposure time *T* is given by $T = -\ln(1 - A_T / A_0) / \lambda$. In this case, the parent activity is 9.25 GBq and for these values *T* computes to about 5 days. Over a period of 10 years of occupation, this seems reasonable.

Since the 2000 remediation, a further amount of Ra 226 was found in the radium room in 2004, although at this time we do not know how much. The above estimates would have to be adjusted to take this into account, but it would have the effect of reducing the amount of Pb210 due to historic escape of radon.

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APPENDIX A1.1: The Uranium Series

Name	Nuclide	Half life	Decay (MeV)	Range in air (cm)	Gamma-ray energy (keV)
Uranium 1	U238	4.5 billion years	α (4.2)	2.5	49.6 <1%
Uranium X	Th234	24 days	β (0.2)	35	**63 4.8%** 92 3% 93 3%
Uranium Z	Pa234	1.2 minutes	β (2.3)	921	**1001 1%** 766 0.4% 258 <1%
Uranium 2	U234	240,000 years	α (4.8)	2.9	53 28%
Ionium	Th230	77, 000 years	α (4.7)	3.0	68 <1% 144 <1%
Radium	Ra226	1,600 years	α (5.5)	3.3	**186 3.5%**
Emanation	Rn222	3.8 days	α (5.5)	4.2	510 <1%
Ra A	Po218	3.1 minutes	α (6.0)	4.8	
Ra B	Pb214	27 minutes	β (1.03)	350	**351 36%** 295 18% 242 7%
Ra C	Bi214	20 minutes	β (1.5, 3.3)	564 1300	609 45% **1764 15%** 1120 15% 1238 6% 2204 5%
Ra C'	Po214	160 μs	α (7.7)	7.0 9.0	800 <1% 298 <1%
Ra D	Pb210	22 years	β (0.06)	4.0	46.5 4%
Ra E	Bi210	5 days	β (1.2) 0.07-0.65	 10 – 195	305 <1% 266 <1%
Ra F	Po210	140 days	α (5.3)	3.8	803 <1%
lead	Pb206	stable			

APPENDIX A1.2: The Thorium Series

Name	Nuclide	Half life	Decay (MeV)	Range in air (cm)	Gamma-ray energy (keV)
Thorium	Th232	14 billion yrs	α (4.0)	2.7	63.8
Mesothorium1	Ra228	5.8 years	β (0.05)	3.3	
Mesothorium2	Ac228	6.1 hours	β (2.1)	833	**911 26%** **969 16%** 338 11%
Radiothorium	Th228	1.9 years	α (5.4)	3.9	84 28%
Thorium X	Ra224	3.7 days	α (5.6)	5.7	240 5.5%
Emanation	Rn220	56 seconds	α (6.3)	5.5	550 <1%
Th A	Po216	0.15 seconds	α (6.8)	5.9	805 <1%
Th B	Pb212	11 hours	β (0.6)	176	238 44% 300 3%
Th C	Bi212	25 minutes 61 minutes	α (6.1) β (2.3)	5.0 921	 723 6.7% **1621 1.5%**
Th C'	Po212	310 ns 45.1 seconds	α (8.8) α (11.7)	8.6 9.8 11.7	 2615 583
Th D	Tl208	3.1 minutes	β (1.8)	699	2614 99% **583 85%** 511 23% **860 12.5%**
lead	Pb208	stable			

APPENDIX A1.3: The Actinium Series

Name	Nuclide	Half life	Decay (Energy)	Range in air (cm)	Gamma-ray energy (keV)
Actino-Uranium	U235	704 million years	α (4.4) 45% α (4.6) 8%		**185 57%** **143 11%** **163 5%** 205 5%
Uranium Y	Th231	26 hours	β (0.3)	65	26 84
Proactinium	Pa231	32,760 years	α (5.0)		27 300 302
Actinium	Ac227	21.8 years	β (0.04) 99% α (5.0) 1%	3.1	100 <1%
Radioactinium	Th227	18.7 days	α (6.0)	4.8	**235 13%** 50 **256 7%**
Actinium X	Ra223	11.4 days	α (5.7)	4.4	154 **269 14%**
Emanation	Rn219	4 seconds	α (6.8)	5.7	**271 11%** **401 6%**
Ac A	Po215	1.8 ms	α (7.4)	6.5	439 <1%
Ac B	Pb211	36 minutes	β (1.4)	519	405 832
Ac C	Bi211	2.1 minutes	α (6.6)	5.4	351
Ac D	Tl207	4.8 minutes	β (1.4)	519	898 <1%
lead	Pb207	stable			

APPENDIX A2

Rutherford's Inventory of Radioactive Substances

	Uranium Series	Thorium Series	Actinium Series
Cambridge 1895-1898	U metal (1897 - 1898) U Nitrate (1897 - 1898) U Oxide (1897 - 1898) U Potassium Sulphate (1897 - 1898)	Th Nitrate (1898) Th Sulphate (1898)	
Montreal 1898-1907	U Ox 1 (Schuchrart 1898) U Ox 2 (Eimer & Amend NY, 1898-1902) Ra Cl_2 (Estler & Geitel 1900) Ra Cl_2 (P de Haen, Hannover, 1901) Ra salt (Paris, 1902) 130 mg Ra Br_2 (Giesel 1903) Radiolead (Boltwood 1904) Polonium (1902)	Th Ox 1 (Schuchrart 1898) Th Ox 2 (Eimer & Amend NY) Th Nitrate (Knofler 1901) Radiothorium (Ramsey 1905)	Actinium (Giesel 1905)
Manchester 1907-1919	U_3O_8 (Boltwood, 1908) Uraninite 1 (Joachimsthal, Boltwood, 1908) Uraninite 2 (Joachimsthal, Boltwood, 1908) Ionium (Boltwood 1909-10) 20 mg $RaBr_2$ 1 (Schuster 1903) 40-50 mg $RaBr_2$ 2 (Schuster 1903?) 500 mg $RaBr_2$ 3 (Vienna 1908) 7 mg $RaBr_2$ 4 (Vienna 1912) Polonium residues (Royal Society, 1907)	Th O_2 1(Boltwood, 1908) Th O_2 2 (Boltwood, 1908) Th salt (Hahn) Mesothorium (Hahn)	40 kg actinium residues (Royal Society, 1907) Actinium (Boltwood, 1909)
Cambridge 1919-1937	10 mg $RaBr_2$ 1 (Vienna 1921) 500 mg Ra salt 2 (MRC 1921)	Radiothorium (McCoy, 1921)	Proactinium (1929)

```
%
% Set up the constants for 1 mg radium and products
%
NA=6.02252*10^23; A_Ra226=226.025; P0=0.001*NA/A_Ra226;
C=365*24*60*60;
t=0:0.0001:100;
T_Ra226=1622;
T_Rn222=3.82/365;
T_Po218=3.1/(365*24*60);
T_Pb214=26.8/(365*24*60);
T_Bi214=20/(365*24*60);
T_Po214=0.16/(365*24*60*60*1000);
T_Pb210=22.7;
T_Bi210=5/365;
T_Po210=140/365;
lamda1=0.693/T_Ra226;
lamda2=0.693/T_Rn222;
lamda3=0.693/T_Po218;
lamda4=0.693/T_Pb214;
lamda5=0.693/T_Bi214;
lamda6=0.693/T_Po214;
lamda7=0.693/T_Pb210;
lamda8=0.693/T_Bi210;
lamda9=0.693/T_Po210;
%
% Compute the parameters for successive transformation of radium and products
%
a1=lamda1/(lamda2-lamda1);
b1=lamda1/(lamda1-lamda2);
a2=a1*lamda2/(lamda3-lamda1);
b2=b1*lamda2/(lamda3-lamda2);
cc2=lamda1*lamda2;
c2=cc2/((lamda1-lamda3)*(lamda2-lamda3));
a3=a2*lamda3/(lamda4-lamda1);
b3=b2*lamda3/(lamda4-lamda2);
c3=c2*lamda3/(lamda4-lamda3);
dd3=lamda1*lamda2*lamda3;
d3=dd3/((lamda1-lamda4)*(lamda2-lamda4)*(lamda3-lamda4));
a4=a3*lamda4/(lamda5-lamda1);
b4=b3*lamda4/(lamda5-lamda2);
c4=c3*lamda4/(lamda5-lamda3);
d4=d3*lamda4/(lamda5-lamda4);
ee4=lamda1*lamda2*lamda3*lamda4;
e4=ee4/((lamda1-lamda5)*(lamda2-lamda5)*(lamda3-lamda5)*(lamda4-lamda5));
a5=a4*lamda5/(lamda6-lamda1);
b5=b4*lamda5/(lamda6-lamda2);
c5=c4*lamda5/(lamda6-lamda3);
d5=d4*lamda5/(lamda6-lamda4);
e5=e4*lamda5/(lamda6-lamda5);
ff5=lamda1*lamda2*lamda3*lamda4*lamda5;
f5=ff5/((lamda1-lamda6)*(lamda2-lamda6)*(lamda3-lamda6)*(lamda4-lamda6)*(lamda5-
lamda6));
a6=a5*lamda6/(lamda7-lamda1);
b6=b5*lamda6/(lamda7-lamda2);
c6=c5*lamda6/(lamda7-lamda3);
d6=d5*lamda6/(lamda7-lamda4);
e6=e5*lamda6/(lamda7-lamda5);
```

```
f6=f5*lamda6/(lamda7-lamda6);
gg6=lamda1*lamda2*lamda3*lamda4*lamda5*lamda6;
g6=gg6/((lamda1-lamda7)*(lamda2-lamda7)*(lamda3-lamda7)*(lamda4-lamda7)*(lamda5-
lamda7)*(lamda6-lamda7));
a7=a6*lamda7/(lamda8-lamda1);
b7=b6*lamda7/(lamda8-lamda2);
c7=c6*lamda7/(lamda8-lamda3);
d7=d6*lamda7/(lamda8-lamda4);
e7=e6*lamda7/(lamda8-lamda5);
f7=f6*lamda7/(lamda8-lamda6);
g7=g6*lamda7/(lamda8-lamda7);
hh7=lamda1*lamda2*lamda3*lamda4*lamda5*lamda6*lamda7;
h7=hh7/((lamda1-lamda8)*(lamda2-lamda8)*(lamda3-lamda8)*(lamda4-lamda8)*(lamda5-
lamda8)*(lamda6-lamda8)*(lamda7-lamda8));
a8=a7*lamda8/(lamda9-lamda1);
b8=b7*lamda8/(lamda9-lamda2);
c8=c7*lamda8/(lamda9-lamda3);
d8=d7*lamda8/(lamda9-lamda4);
e8=e7*lamda8/(lamda9-lamda5);
f8=f7*lamda8/(lamda9-lamda6);
g8=g7*lamda8/(lamda9-lamda7);
h8=h7*lamda8/(lamda9-lamda8);
ii8=lamda1*lamda2*lamda3*lamda4*lamda5*lamda6*lamda7*lamda8;
i8=ii8/((lamda1-lamda9)*(lamda2-lamda9)*(lamda3-lamda9)*(lamda4-lamda9)*(lamda5-
lamda9)*(lamda6-lamda9)*(lamda7-lamda9)*(lamda8-lamda9));
%
% compute number of atoms of each successive product
%
P=P0*exp(-lamda1*t);
Q=P0*(a1*exp(-lamda1*t)+ b1*exp(-lamda2*t));
R=P0*(a2*exp(-lamda1*t)+ b2*exp(-lamda2*t)+c2*exp(-lamda3*t));
S=P0*(a3*exp(-lamda1*t)+ b3*exp(-lamda2*t)+c3*exp(-lamda3*t)+d3*exp(-lamda4*t));
T=P0*(a4*exp(-lamda1*t)+ b4*exp(-lamda2*t)+c4*exp(-lamda3*t)+d4*exp(-
lamda4*t)+e4*exp(-lamda5*t));
U=P0*(a5*exp(-lamda1*t)+ b5*exp(-lamda2*t)+c5*exp(-lamda3*t)+d5*exp(-
lamda4*t)+e5*exp(-lamda5*t)+f5*exp(-lamda6*t));
V=P0*(a6*exp(-lamda1*t)+ b6*exp(-lamda2*t)+c6*exp(-lamda3*t)+d6*exp(-
lamda4*t)+e6*exp(-lamda5*t)+f6*exp(-lamda6*t)+g6*exp(-lamda7*t));
W=P0*(a7*exp(-lamda1*t)+ b7*exp(-lamda2*t)+c7*exp(-lamda3*t)+d7*exp(-
lamda4*t)+e7*exp(-lamda5*t)+f7*exp(-lamda6*t)+g7*exp(-lamda7*t)+h7*exp(-
lamda8*t));
X=P0*(a8*exp(-lamda1*t)+ b8*exp(-lamda2*t)+c8*exp(-lamda3*t)+d8*exp(-
lamda4*t)+e8*exp(-lamda5*t)+f8*exp(-lamda6*t)+g8*exp(-lamda7*t)+h8*exp(-
lamda8*t)+i8*exp(-lamda9*t));
%
% plot the activity values (rate of decay dN/dt = lamda*N)
%
figure (1);
plot (t, lamda1*P/C, t, lamda2*Q/C, t, lamda3*R/C, t, lamda4*S/C, t, lamda5*T/C,
t, lamda6*U/C, t, lamda7*V/C, t,lamda8*W/C, t,lamda9*X/C);
figure (2);
TOT=lamda1*P+lamda2*Q+lamda3*R+lamda4*S+lamda5*T+lamda6*U+lamda7*V+lamda8*W+lamd
a9*X;
plot (t, 100*lamda1*P./TOT, t, 100*lamda2*Q./TOT, t, 100*lamda3*R./TOT, t,
100*lamda4*S./TOT, t, 100*lamda5*T./TOT, t, 100*lamda6*U./TOT, t,
100*lamda7*V./TOT, t, 100*lamda8*W./TOT, t, 100*lamda9*X./TOT);
```

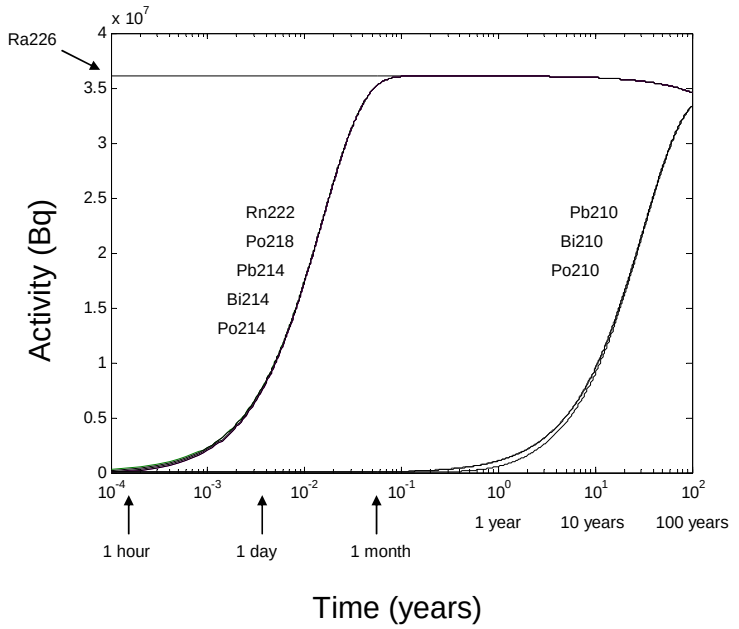


Figure A3.1. Activity from 1 mg of radium and daughters calculated from equations provided in Chapter XI "Theory of Successive Transformations" in Rutherford (1913) *Radioactive Substances and Their Radiations.* CUP. The time axis is logarithmic. 1 mg of radium has an activity of 37 MBq. The Pb210 would have an activity between 1 – 5 MBq after an exposure of 1 – 10 years and reaches secular equilibrium with radium after about 100 years. Rn222 and daughters reach equilibrium after about one month.

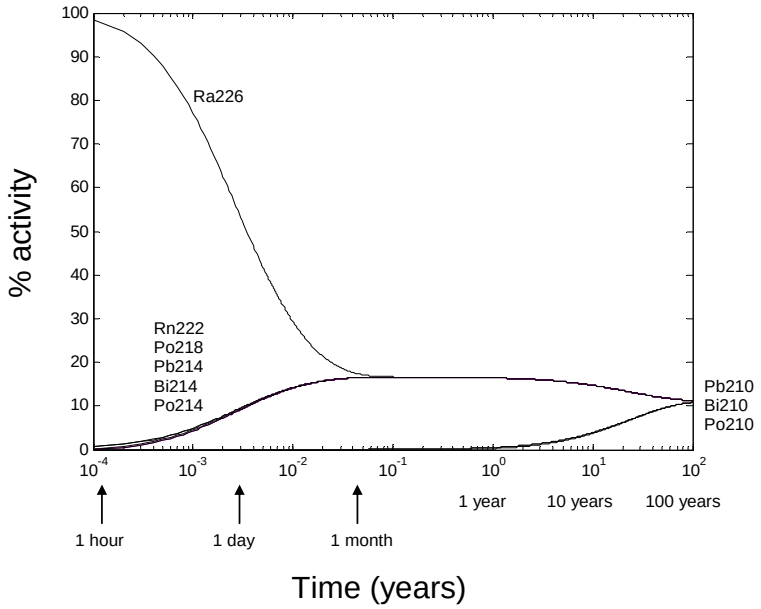
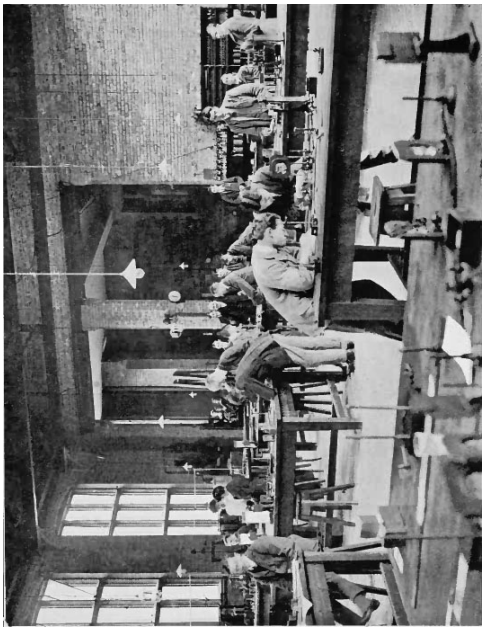


Figure A3.2. Activity of radium and daughters expressed as a percentage of total activity, calculated from equations provided in Chapter XI "Theory of Successive Transformations" in Rutherford (1913) *Radioactive Substances and Their Radiations.* CUP. Rn222 and daughters reach equilibrium after about one month and Pb210 and daughters reaches secular equilibrium with radium after about 100 years.

APPENDIX B1: FLOOR PLAN OF THE 1874 CAVENDISH LABORATORY

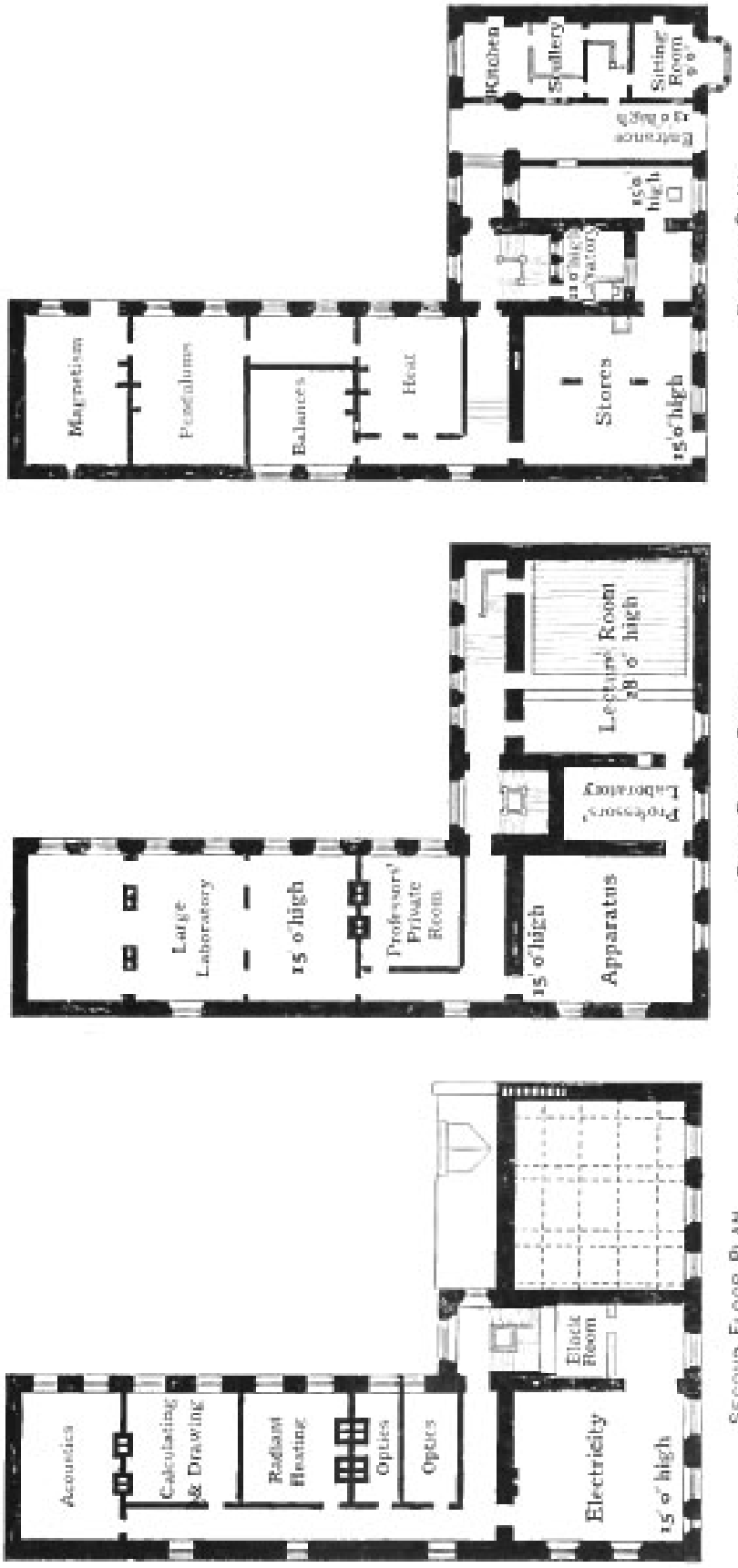
The plans shown here were originally published in *Nature* on June 25th 1874. A modified version of these plans appeared in "A History of the Cavendish Laboratory 1871 - 1910" published by Longmans, Green and Co in 1910. This was published to celebrate JJ Thomson's 25th year as Cavendish Professor in 1909.

A photograph of an Elementary Class is reproduced from "A History of the Cavendish Laboratory". This class would have been located in the "Large Laboratory" on the 1st floor.



Elementary Laboratory

PLAN OF ORIGINAL LABORATORY



APPENDIX B2: FLOOR PLAN OF THE 1893 MACDONALD LABORATORY

The plans shown here were reconstructed from the floor plan of the Macdonald Library in conjunction with a description of the Laboratory given in “Formal Opening of the Engineering and Physics Buildings” published by McGill University in 1893.

Several photographs are reproduced from “Formal Opening of the Engineering and Physics Buildings” including the following.

On the First Floor (Basement):
- Research Laboratory
- Boiler Room

On the Second Floor:
- Electrical Laboratory

On the Third Floor:
- Large Lecture Theatre

On the Fourth Floor:
- Large Lecture Theatre
- Library

On the Fifth Floor:
- Elementary Laboratory

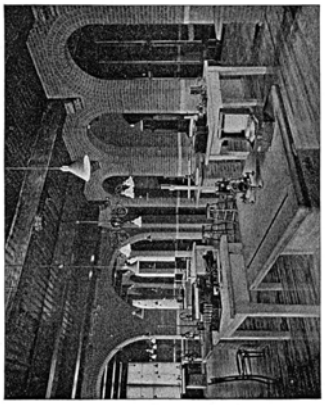
In addition to above a photograph of Rutherford (1905) is reproduced. This illustrates his laboratory and was probably located in the basement as indicated. The photograph was taken during Otto Hahn’s visit in 1905 and appeared in *Nature* in 1906. Note that the reproduction is laterally (mirror) inverted from the familiar image.

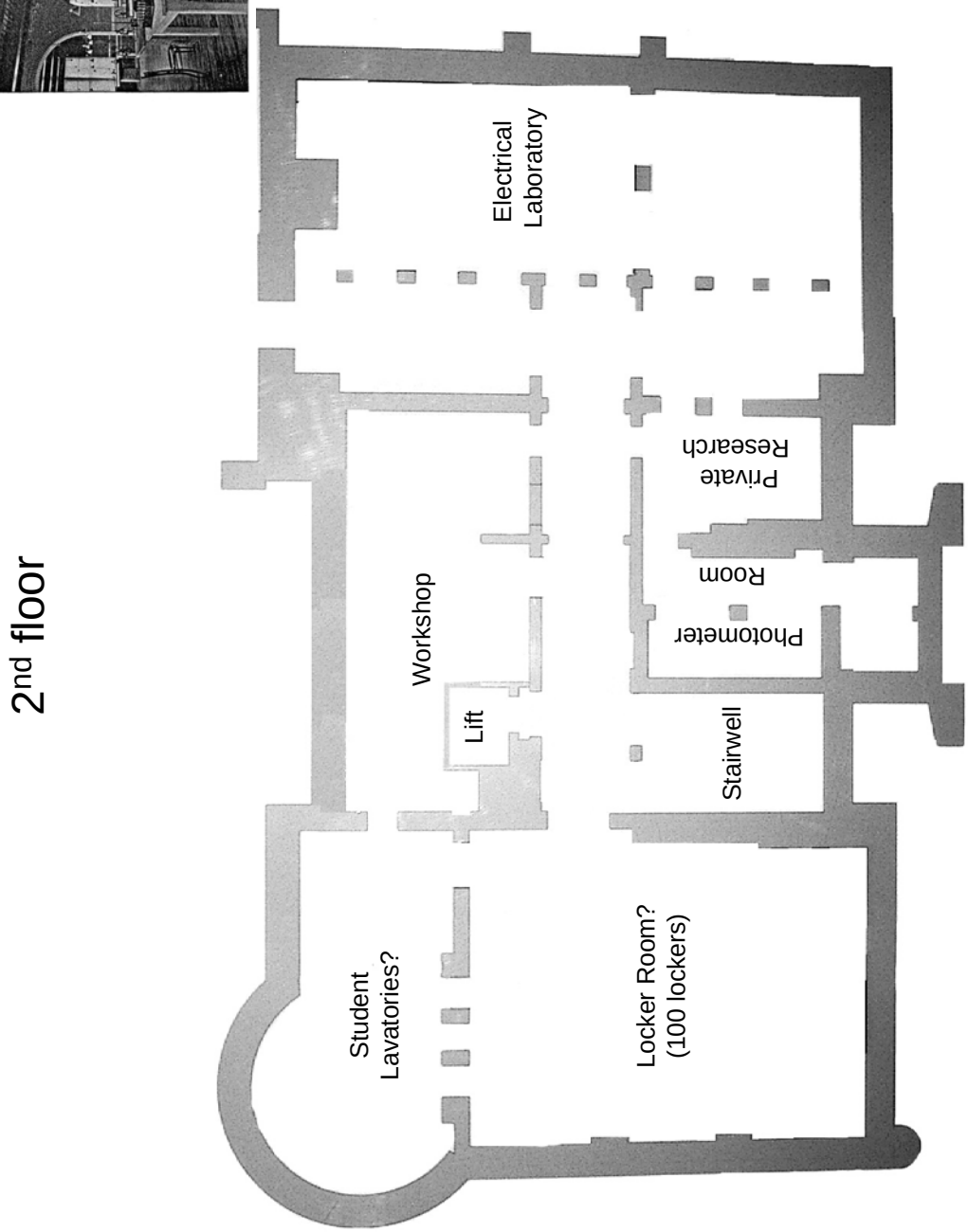
Macdonald Laboratory 1893

Research Laboratory

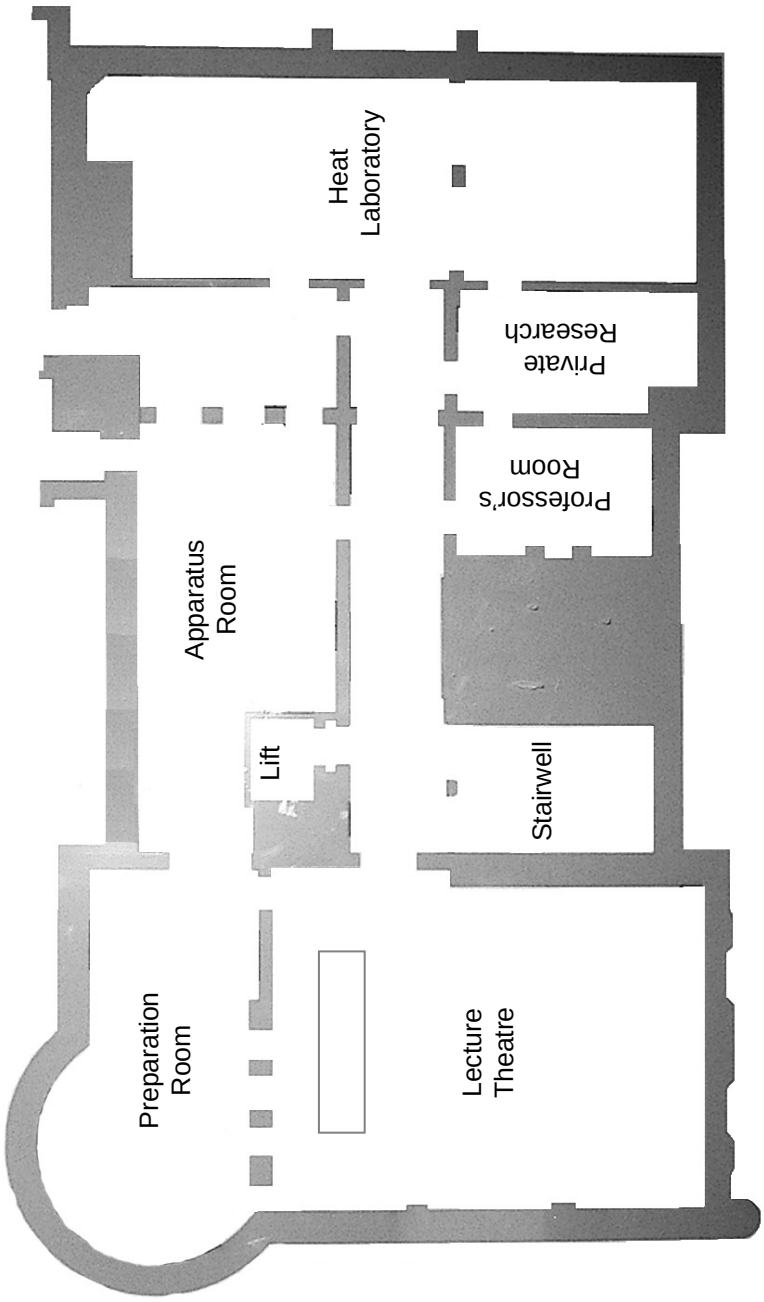
Rutherford's Laboratory 1905

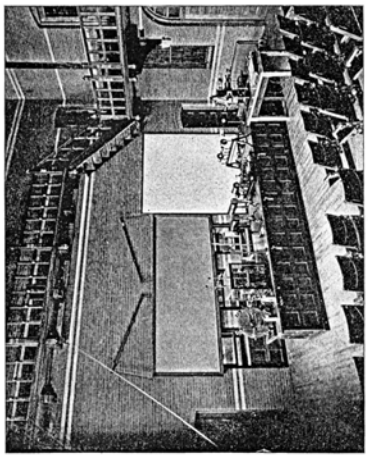
1st floor (basement)



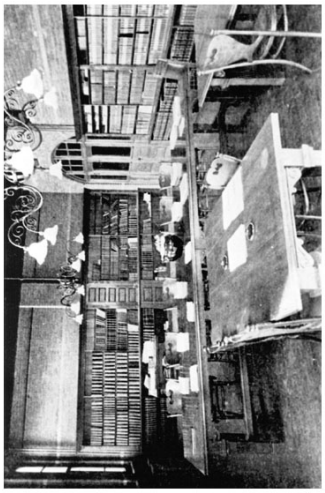

2nd floor
Electrical Laboratory
Electrical Laboratory
Private Research Room
Photometer
Stairwell
Workshop
Lift
Student Lavatories?
Locker Room? (100 lockers)

3rd floor



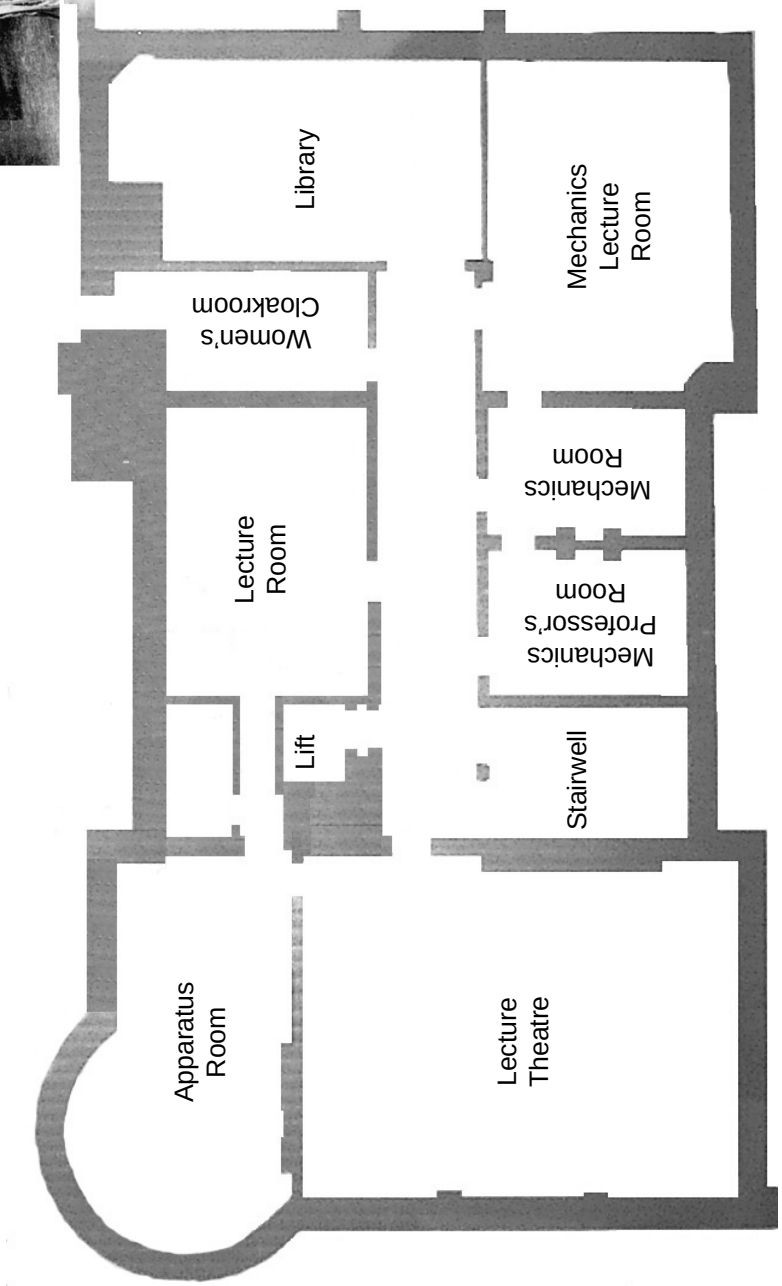


Lecture Theatre

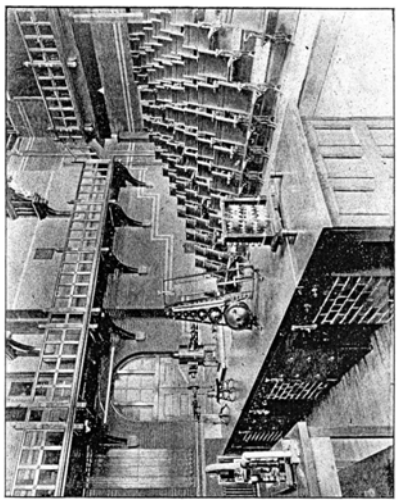


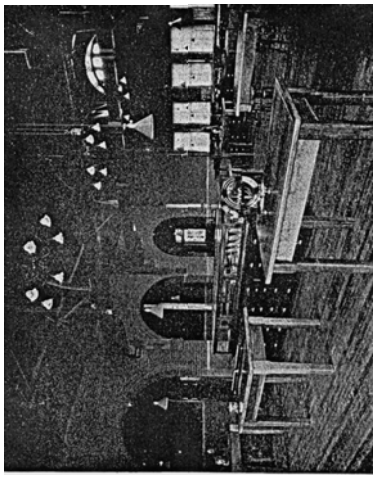
Library

4th floor



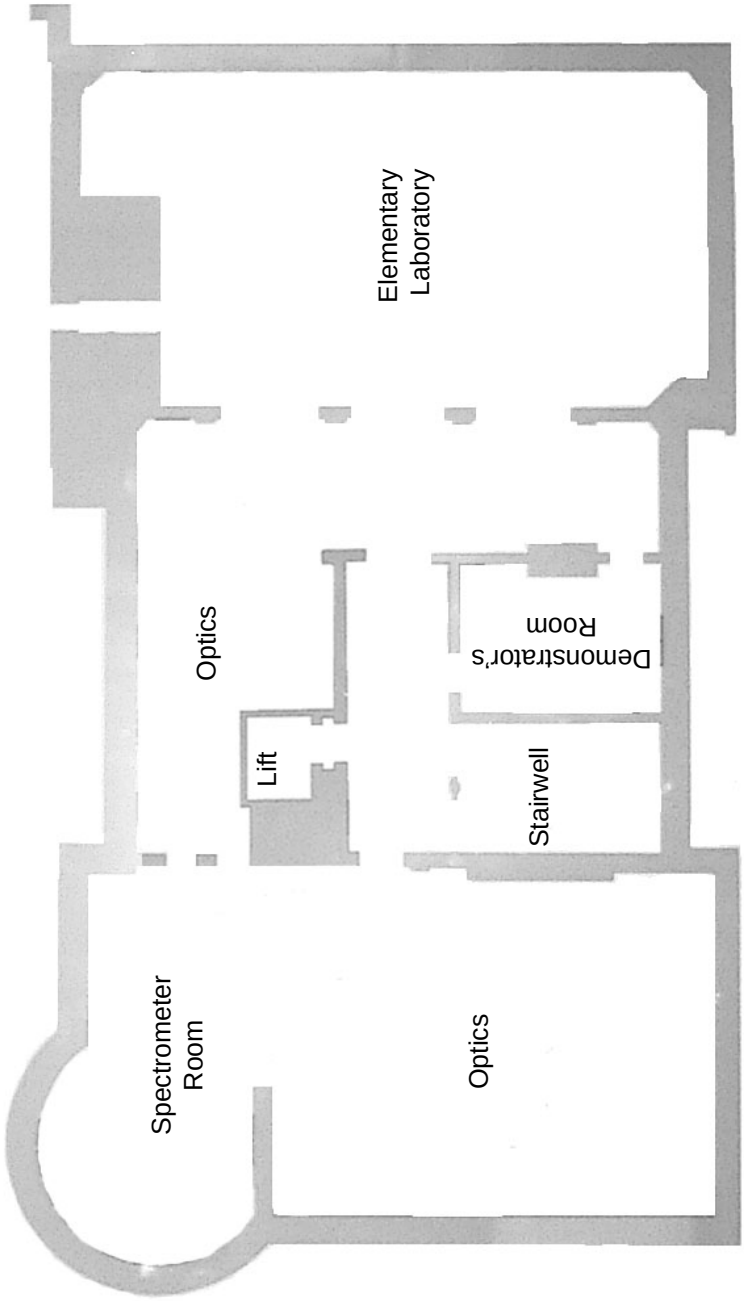
Lecture Theatre





Elementary Laboratory

5th floor



APPENDIX B3: FLOOR PLANS OF THE 1900 SCHUSTER LABORATORY

These plans are based on Shuster and Hutton (1906) “The Physical Laboratories of the University of Manchester” which were published by the University of Manchester in commemoration of the 25th anniversary of Arthur Schuster’s Professorship.

Several photographs are reproduced from “The Physical Laboratories of the University of Manchester” including the following.

On the Ground Floor:
- The Dynamo House
- The Electrochemical Laboratory
- The Switchboard Room

On the First Floor:
- The Elementary Laboratory

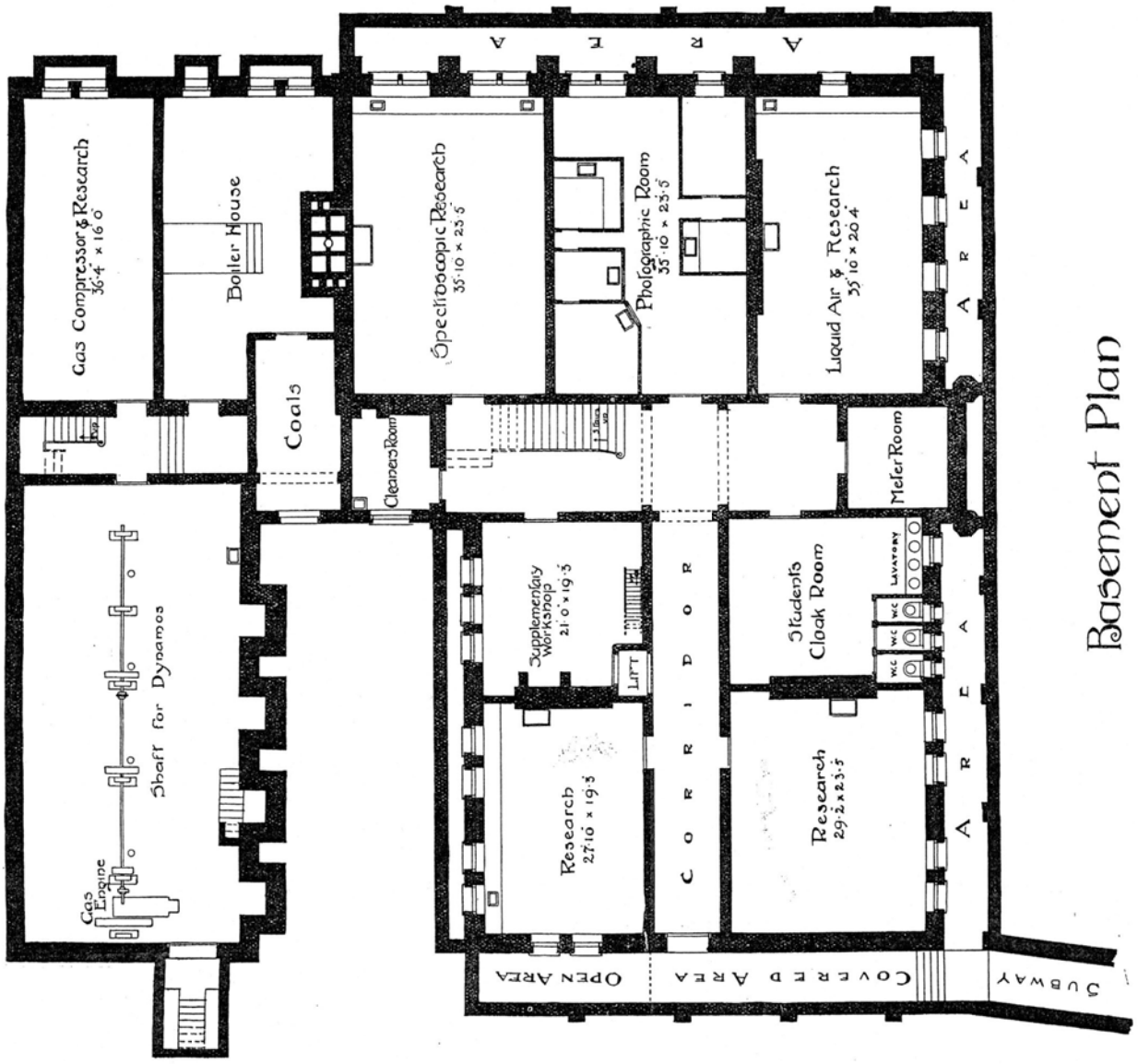
On the Second Floor:
- The Large Lecture Theatre

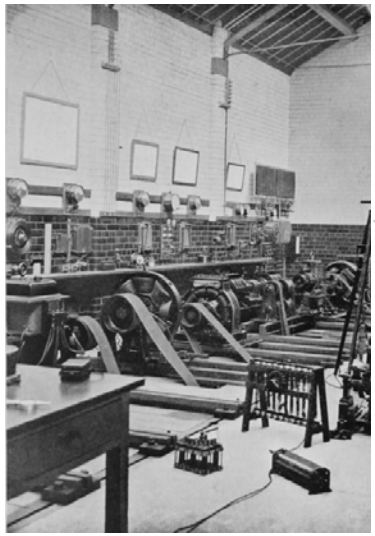
In addition to above the following photographs are shown illustrating their location:
- Rutherford and Geiger (1912), located in the basement
- Arthur Schuster (1907), located in the Large Lecture Theatre

The location of the Radium Room and the apparatus which was probably contained within it are also illustrated.

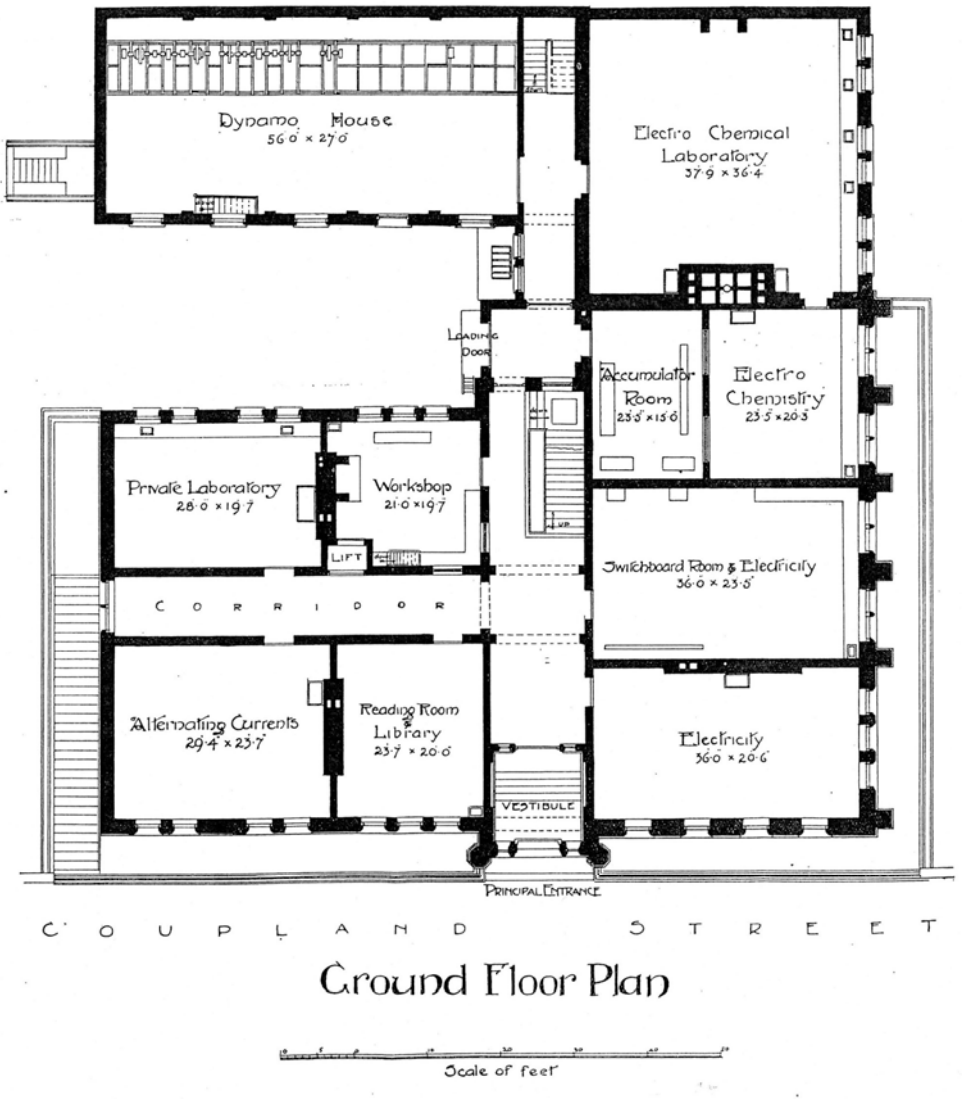
Rutherford (on right) and Geiger with their apparatus for counting α particles; this appears to be the later apparatus of 1912

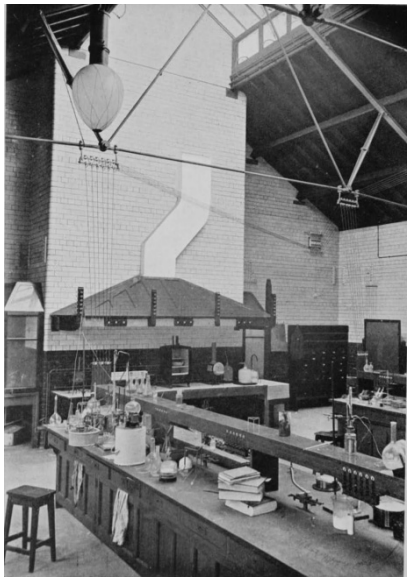
Geiger & Rutherford 1912, taken in "Liquid Air Room"



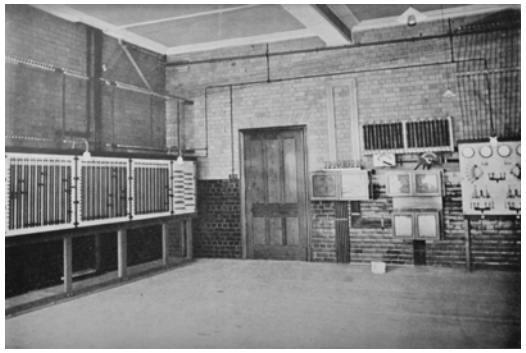


Dynamo House

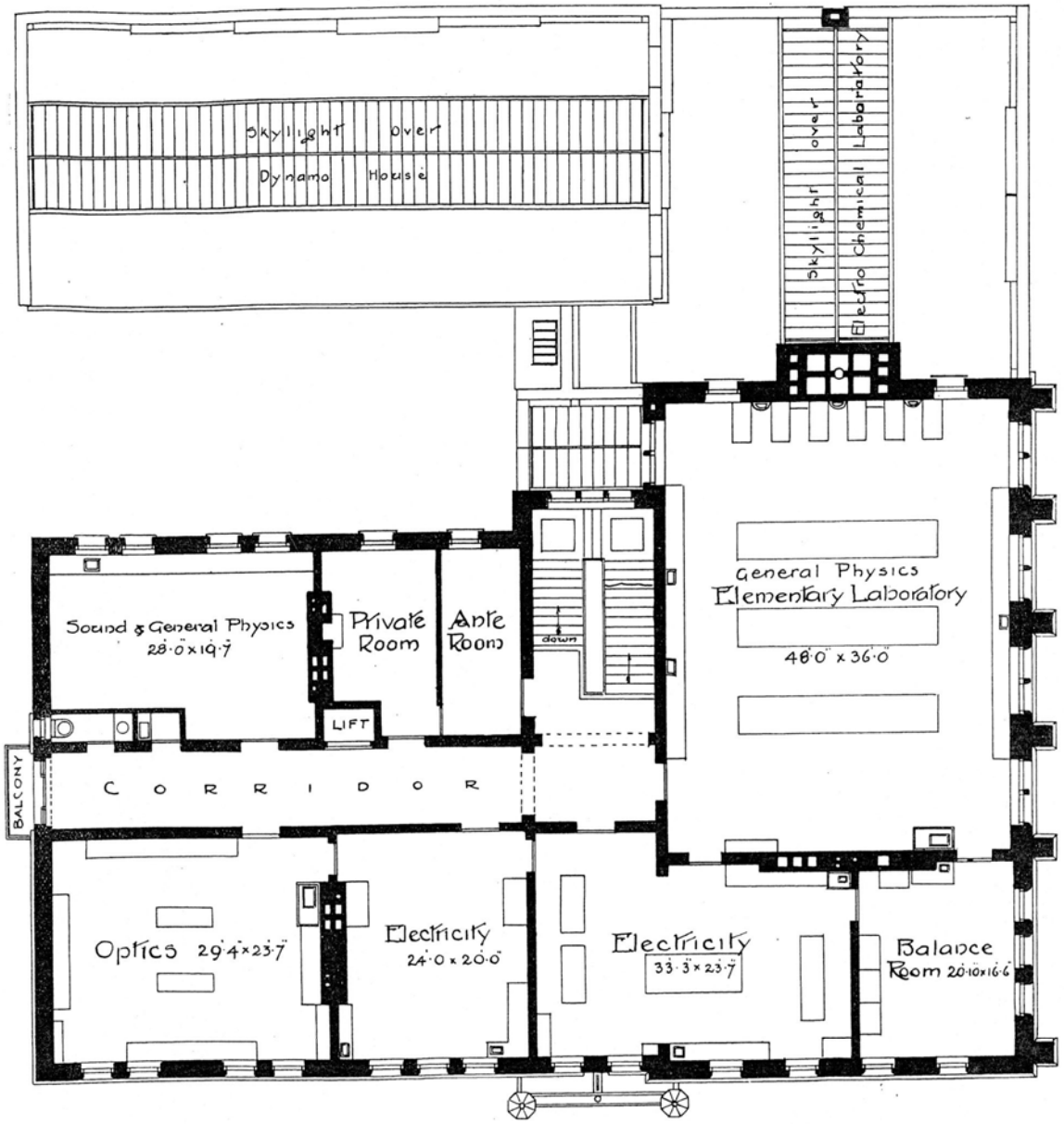




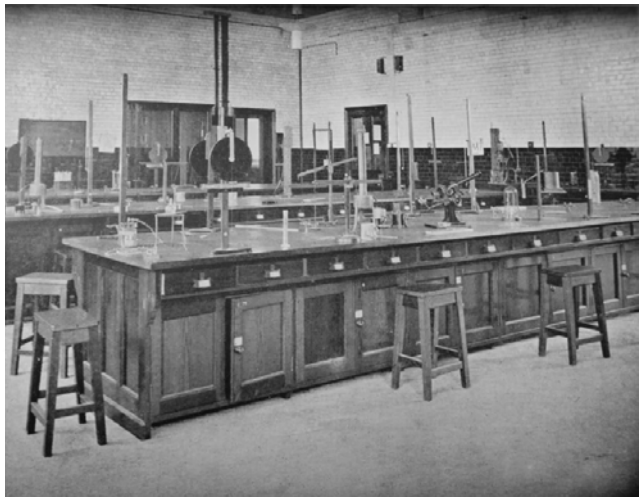
Electro Chemical Laboratory



Switchboard Room

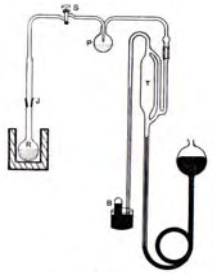


First Floor Plan

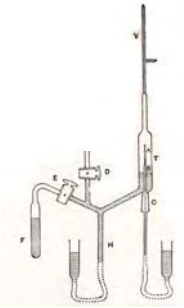


Elementary Laboratory

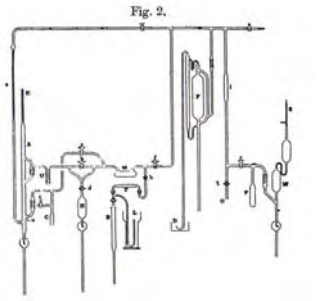
Rutherford's $RaRr_2$ Apparatus



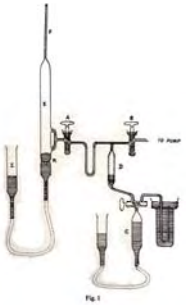
Rutherford&Royds Apparatus



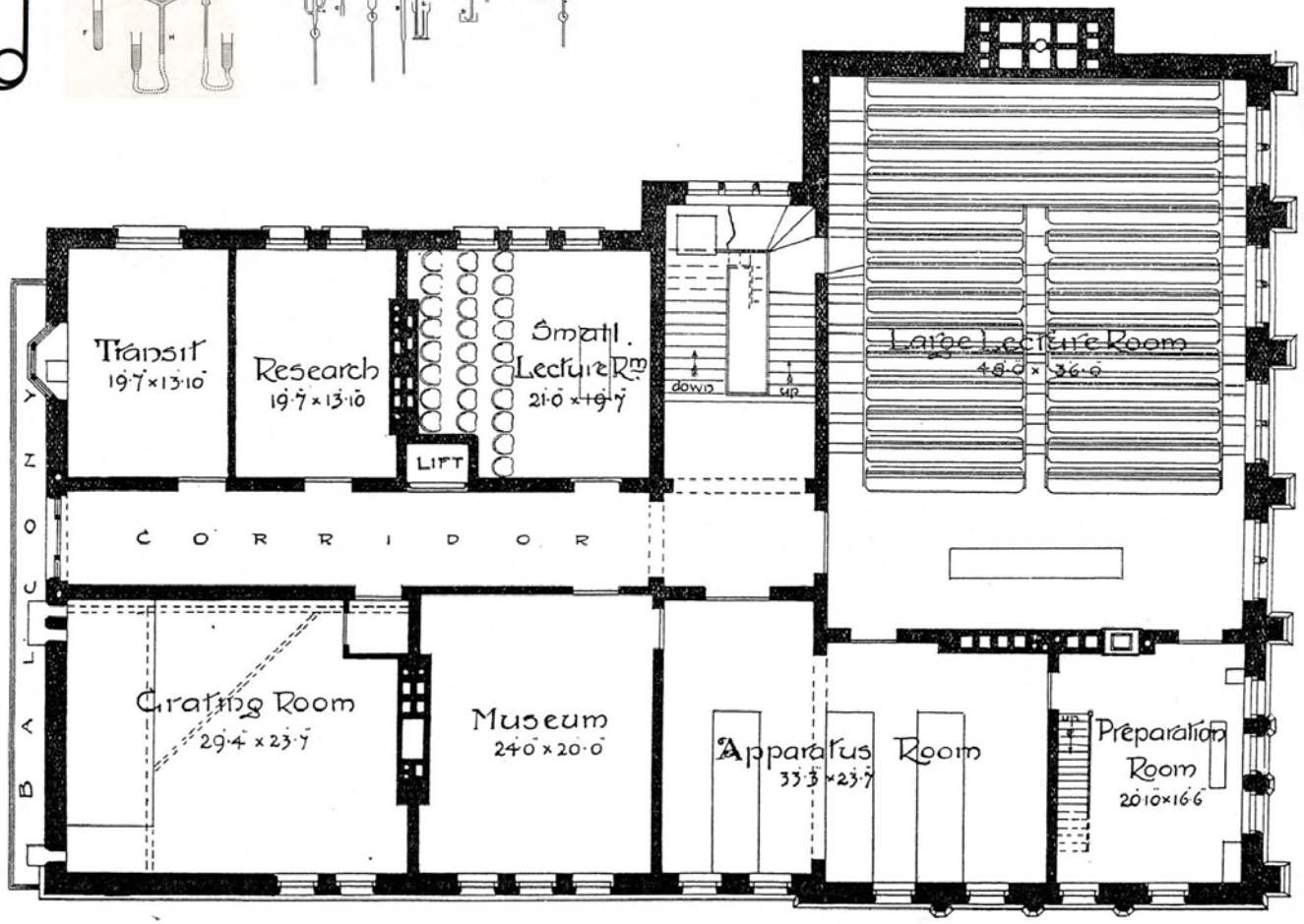
Rutherford&Boltwood Apparatus

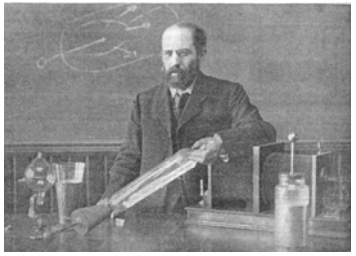


The Large Lecture Room



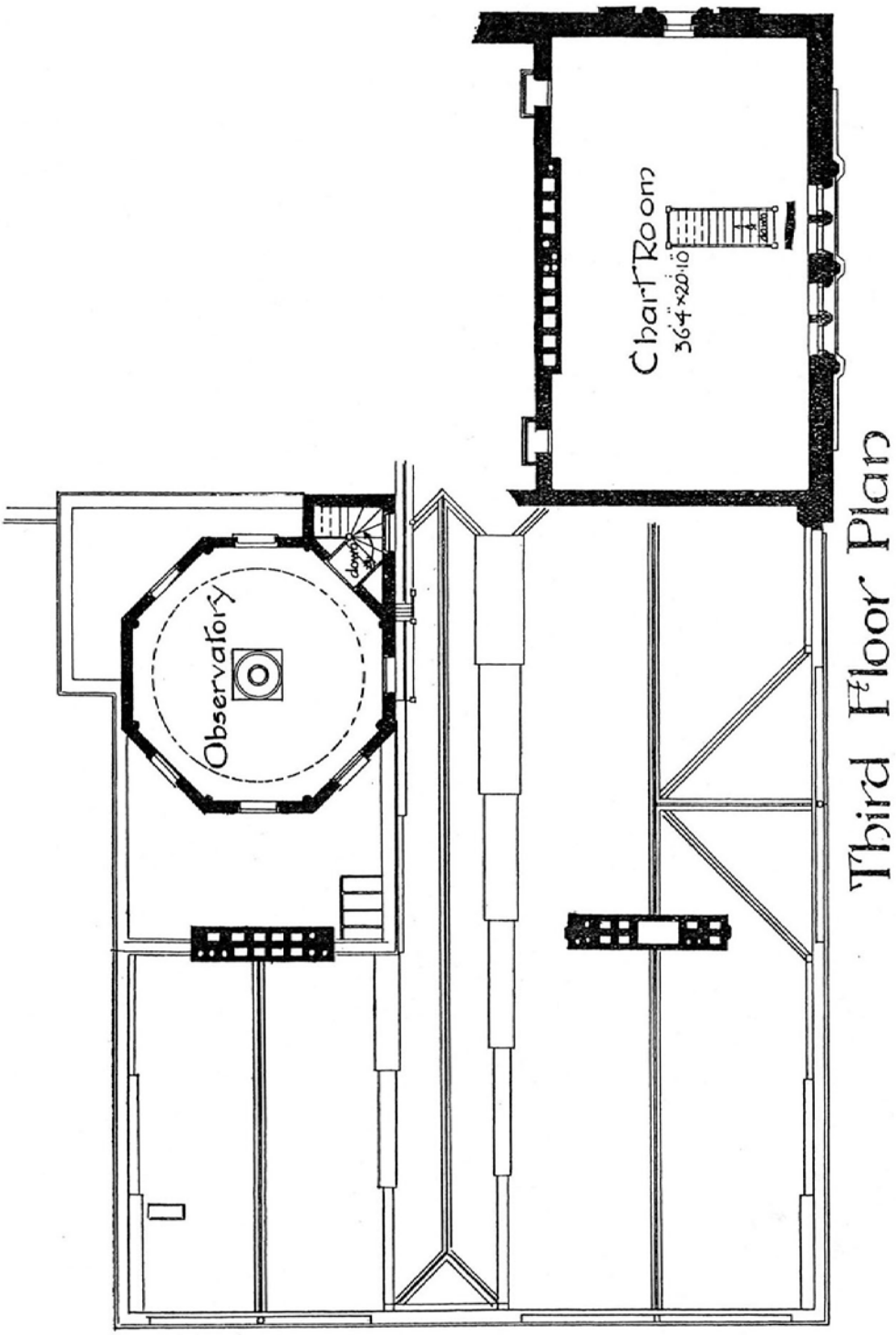
Purification Apparatus





Arthur Schuster in Lecture Room

Schuster Laboratory 1900



Third Floor Plan

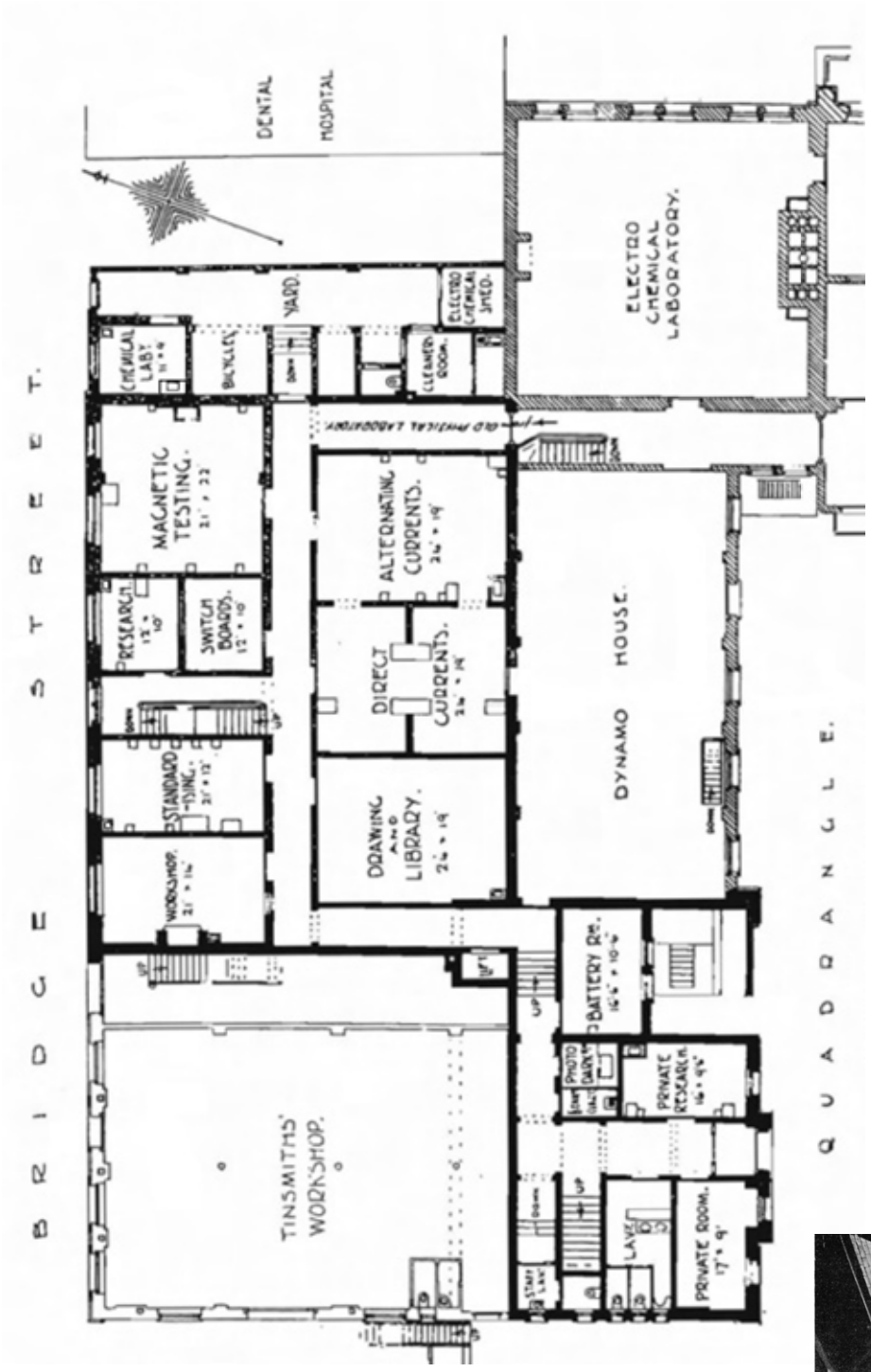
APPENDIX B4: FLOOR PLANS OF THE 1912 EXTENSION

These plans are based on Shuster and Hutton (1912) “The Physical and Electrotechnical Laboratories of the University of Manchester” published in 1912 by The University of Manchester for the opening of the 1912 Extension.

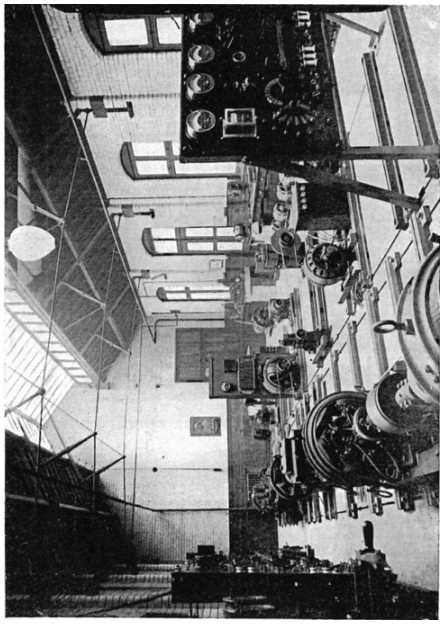
Three photographs are reproduced from “The Physical and Electrotechnical Laboratories of the University of Manchester” including the following.

The Dynamo House in 1912
A southern view of the 1912 extension
A northern view of the 1912 extension

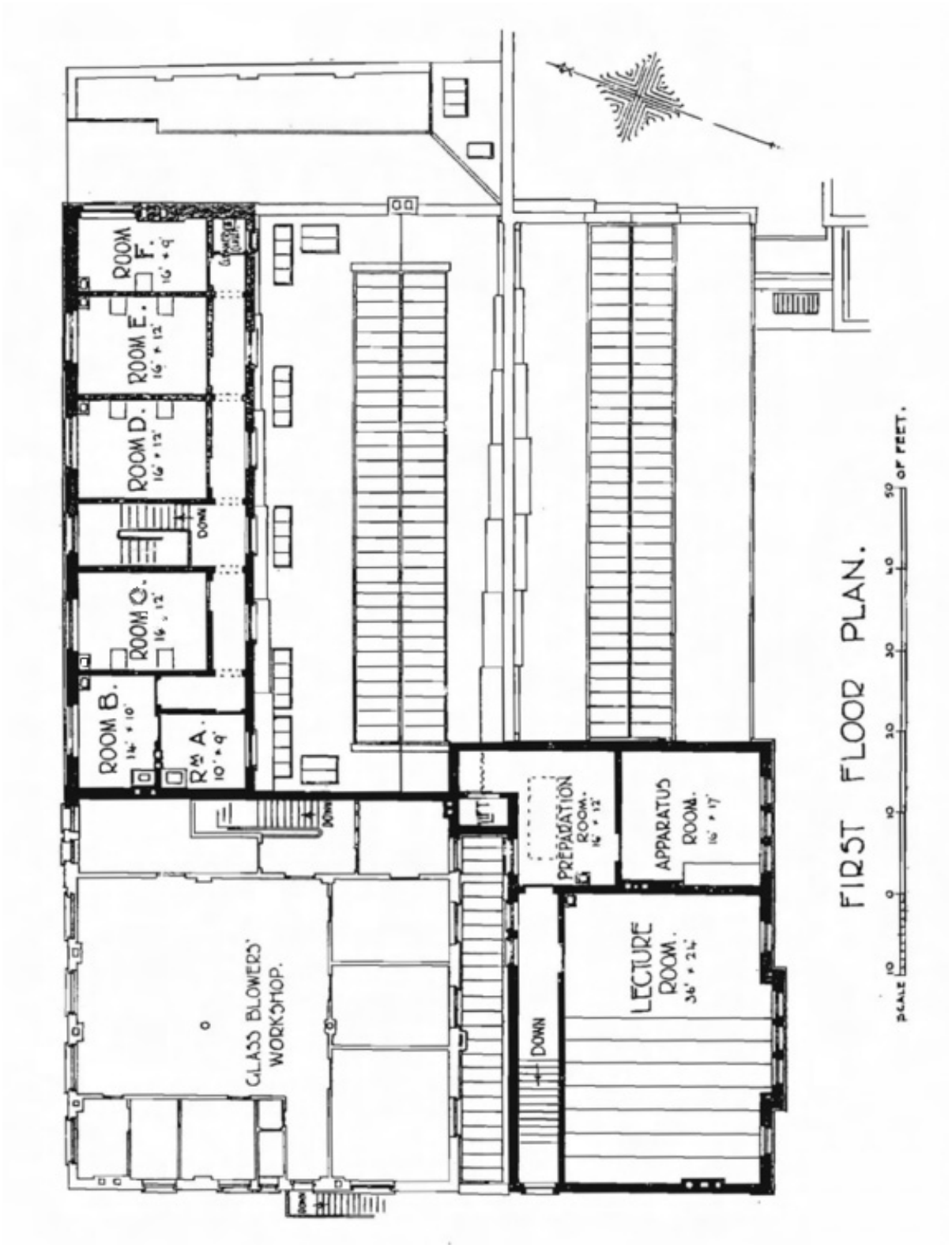
An external view of the chemical laboratory attached to the extensions can be seen at the east end of the northern view.



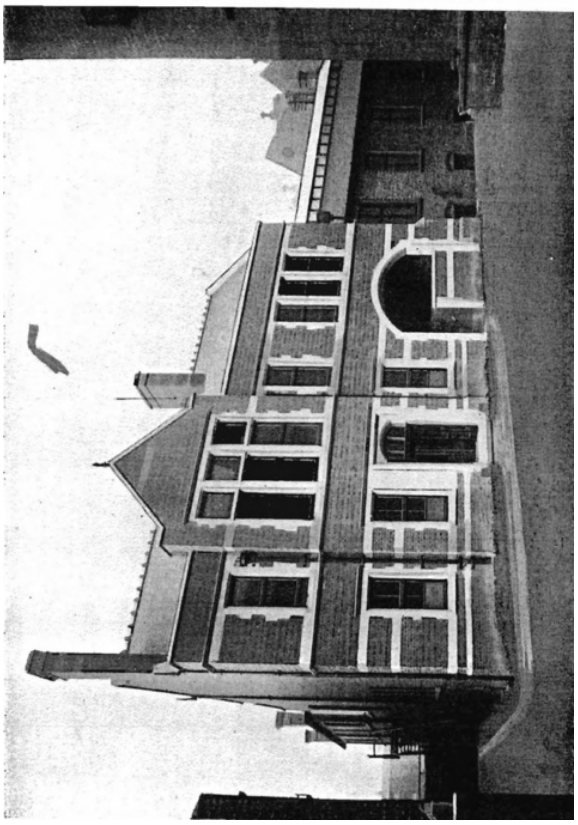
GROUND FLOOR PLAN.



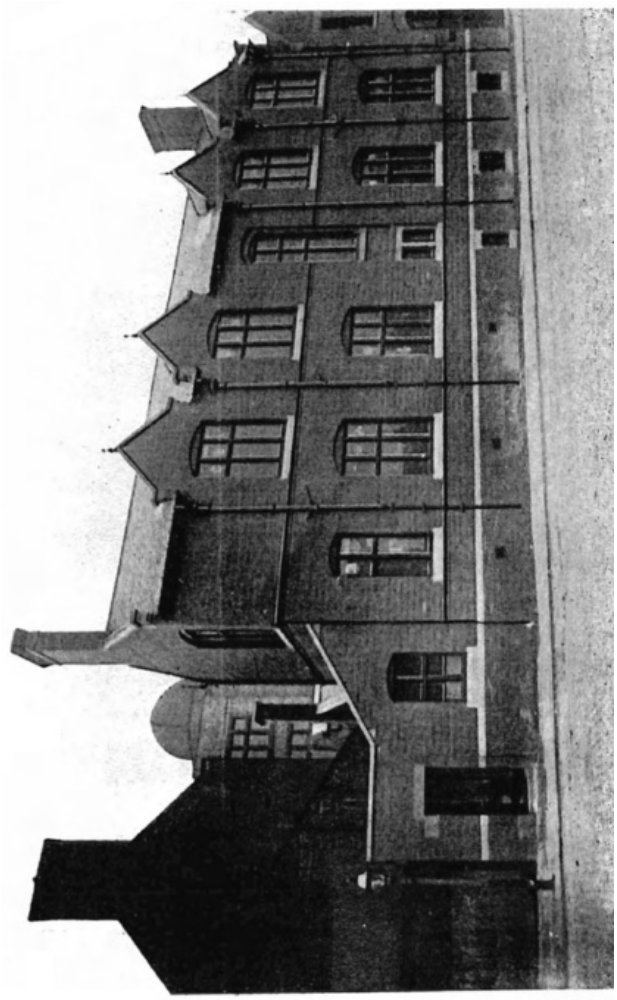
Dynamo House 1912


ROOM F.
ROOM E.
ROOM D.
ROOM C.
ROOM B.
RM A.
DOWN
GLASS BLOWERS' WORKSHOP.
PREPARATION ROOM.
APPARATUS ROOM.
LECTURE ROOM.
DOWN
FIRST FLOOR PLAN.
SCALE
FEET.

Southern view of the 1912 extension



Northern view of the 1912 extension



APPENDIX B5: LOCATION OF RUTHERFORD'S LABORATORIES IN THE CAVENDISH 1919 -1937

In the absence of more detailed plans of the Cavendish Laboratory, for the purpose of this interim account, the probable location of Rutherford's laboratory room and those of his co-workers are indicated on the 1874 plan of the Maxwell wing.

The photograph of Rutherford's Research Room from the early 1920's is reproduced from "The Collected Papers of Lord Rutherford of Nelson, Volume Three", George Allen and Unwin Ltd. The room was probably located at the east end of the Maxwell wing on the ground floor. Much of the apparatus contained within this room was transported down from Manchester in 1919.

The photograph of Rutherford in conference with Kempton and Westcott in about 1936 is reproduced from "The Collected Papers of Lord Rutherford of Nelson, Volume Three", George Allen and Unwin Ltd. The room was probably located in the Maxwell wing on the ground floor.

The photograph of the Rutherford and Oliphant apparatus was reproduced from Figure 10 in Cockroft (1946) "Rutherford: Life and Work after the Year 1919". The room was probably located in the basement of the Maxwell wing and was adjacent to the basement room used by Chadwick and Rutherford in the early 20s.

The probable location of the Radium Room was in the attic above the Maxwell Lecture Theatre with access from the top of the "Tower". Also illustrated is the radium bromide apparatus which was probably housed in this room.

The probable location of key rooms in the Cavendish is also illustrated on the 1960 New Museums Site Map.

Rutherford's Research Room (Ground)

Rutherford with Kempton (Ground)

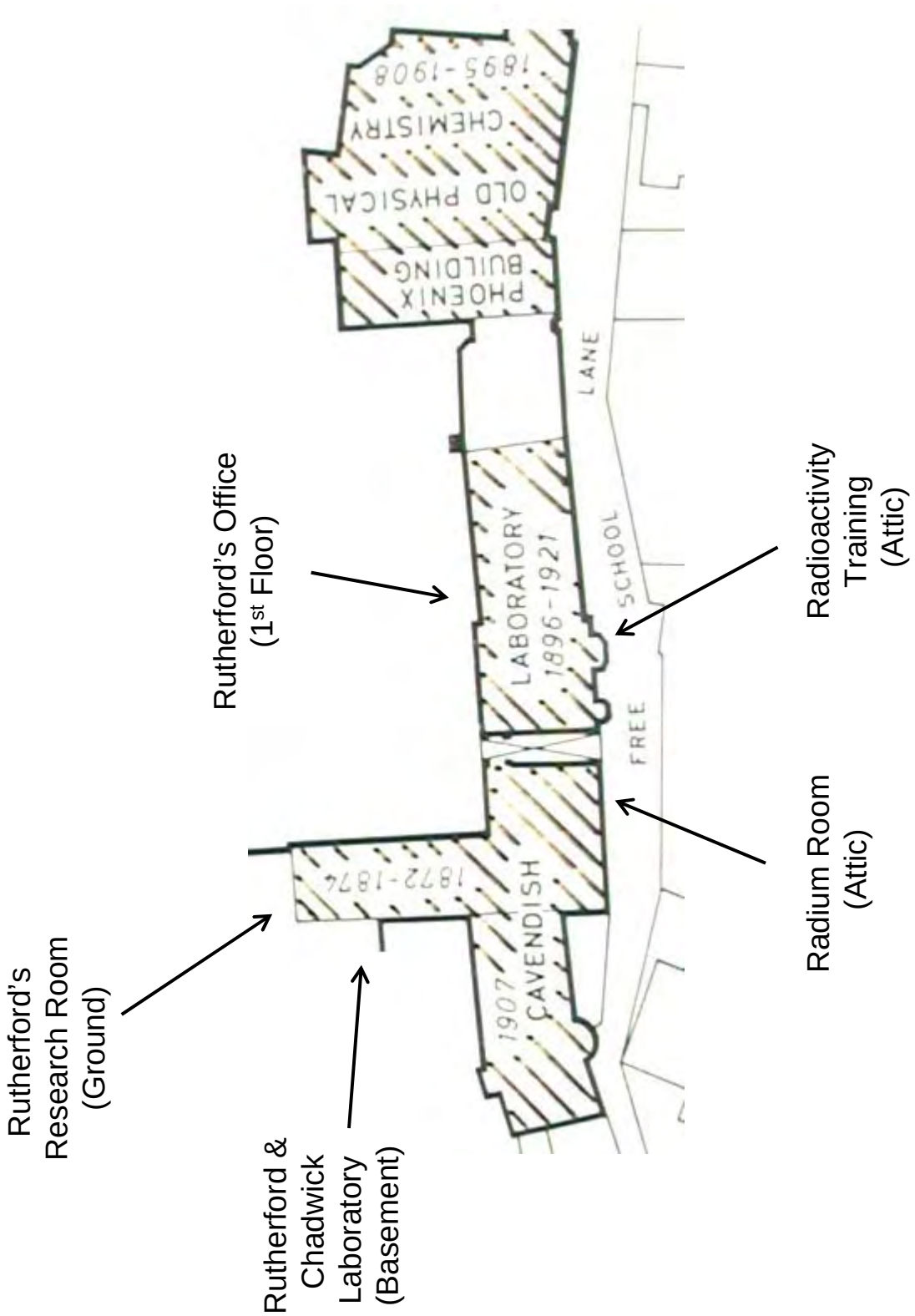
Rutherford & Oliphant Laboratory (Basement)

GROUND PLAN.

Radium Bromide Apparatus

Fig. 107.

SECOND FLOOR PLAN


Rutherford's Research Room (Ground)
Rutherford & Chadwick Laboratory (Basement)
Rutherford's Office (1st Floor)
Radioactivity Training (Attic)
Radium Room (Attic)
1872-1874
CAVENDISH
1907
LABORATORY
1896-1921
FREE SCHOOL LANE
PHOENIX BUILDING
OLD PHYSICAL CHEMISTRY
1895-1908

APPENDIX C: MANCHESTER DEPARTMENTAL PHOTOGRAPHS 1903-1913

The photographs in this appendix have been reproduced from various sources.

1903: A print of this photograph is held in the Schuster Collection and was taken about September 1903 during the Meeting of the British Association in Southport when Frederick Soddy paid a visit to the Manchester Physical Laboratories. The photograph was taken in the Dynamo House.

1906: A print of this photograph is held in the Schuster Collection and was taken in 1906 During the commemoration of Arthur Schuster's 25th anniversary as Langworthy Professor.

1909: This photograph was reproduced from "The Collected Papers of Lord Rutherford of Nelson, Part II". The location is the quadrangle in front of the John Owens Building.

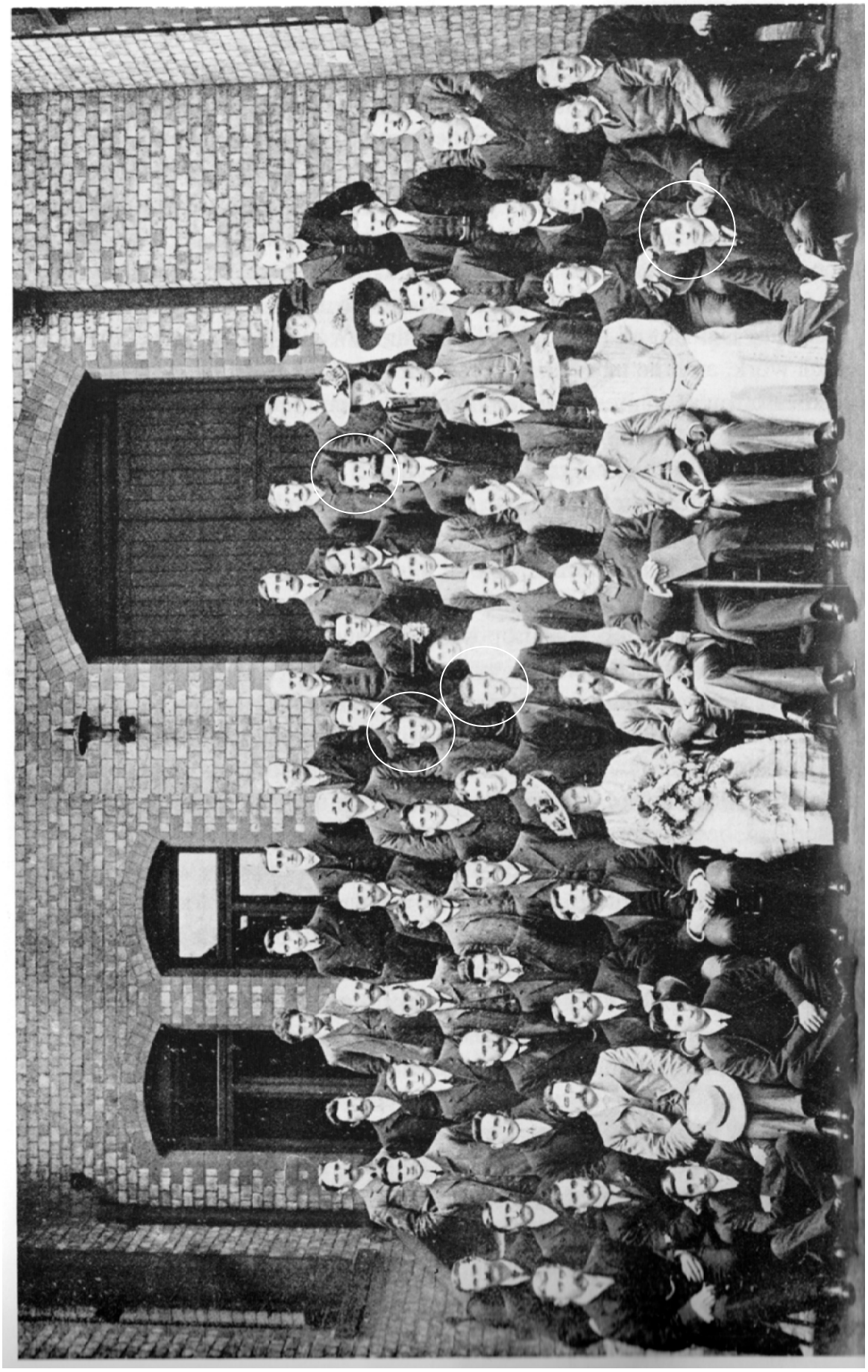
1910: This photograph was reproduced from "Rutherford and Boltwood: Letters in Radioactivity" edited by Lawrence Badash (1969). The location is the sheds at the back of the Schuster Laboratory and was taken during Boltwood's sabbatical year in Manchester.

1912: This photograph was reproduced from "The Collected Papers of Lord Rutherford of Nelson, Part II". The location is the quadrangle in front of the 1912 Extension.

1913: This photograph was reproduced from "The Collected Papers of Lord Rutherford of Nelson, Part II". The location is the main entrance to the 1900 Building.

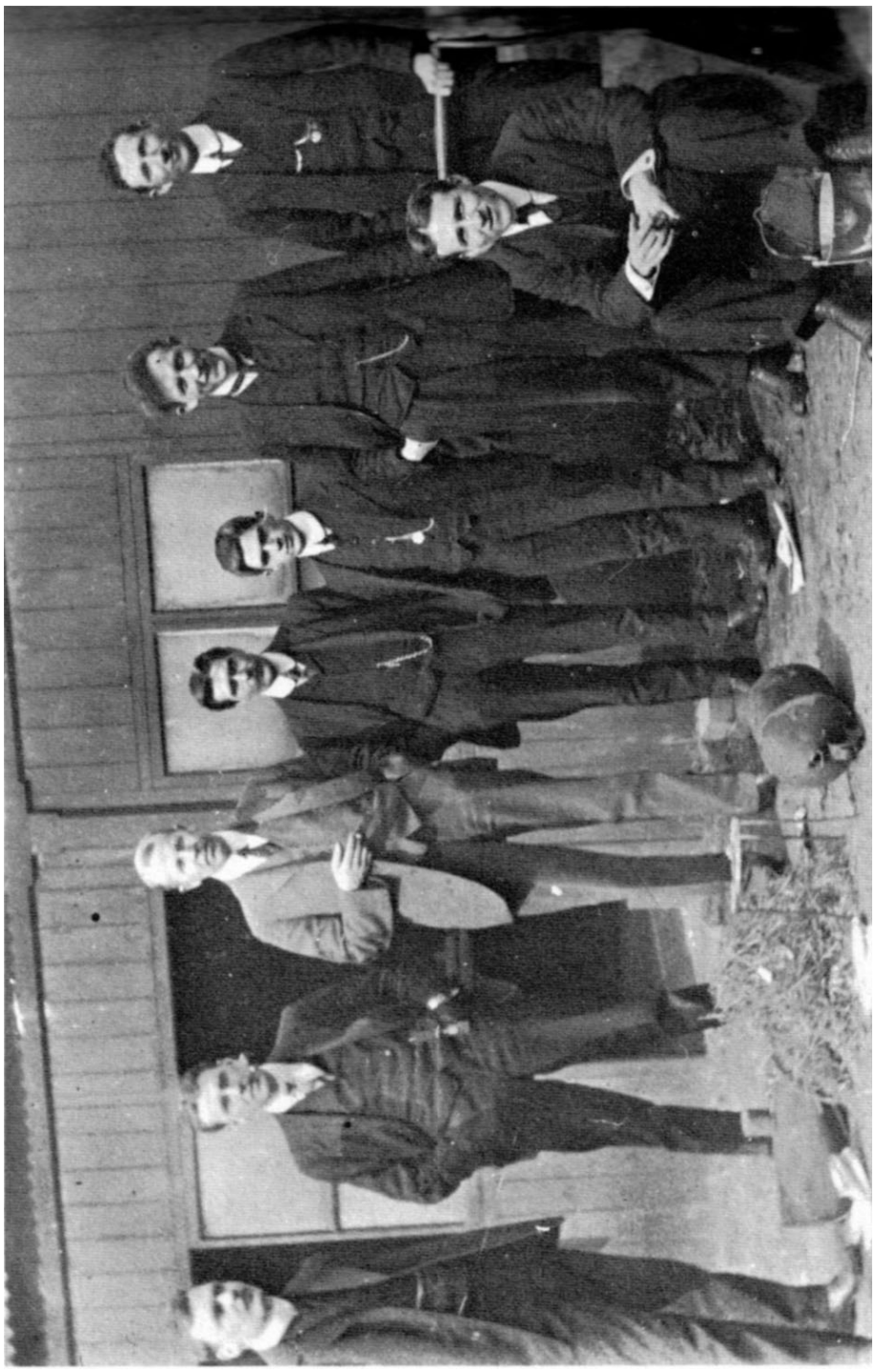
Schuster with Soddy 1903
In the Dynamo Hall

Engineering and Physics 1906
In the Quadrangle



Physics Group 1909
In Front of the Owens Building

Boltwood with Geiger, Kay and others
Outside the Chemical Shed 1910



Physics Group 1912
At Entrance to 1912 Extension

Physics Group 1913
At Entrance to 1900 Building