

Ernest Rutherford – Radioactive Change

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ABSTRACT

At the beginning of the 20th century, Rutherford, born in New Zealand, carried out a series of remarkable experiments in Montreal, some of which in collaboration with Frederick Soddy. He showed, using thorium, that radioactivity is the transmutation from one chemical element to another by the emission of radiation. In 1903, Rutherford and Soddy drew together the conclusions of their work in the article *Radioactive Change*.

After his Nobel Prize for Chemistry in 1908, Rutherford discovered in Manchester during 1911 that the atom possessed a nucleus, and in 1919 observed the first nuclear reaction. He became the director of the Cavendish laboratory in Cambridge and could count amongst his colleagues and students many prestigious chemists and physicists.

A handwritten signature of Ernest Rutherford in black ink. The signature is written in a cursive style and is underlined with a thick black line.

Figure 1: Ernest Rutherford (1871-1937) (Nobel Foundation Prize)

FROM NEW ZEALAND TO MONTREAL VIA CAMBRIDGE

Ernest Rutherford's tomb can be found in Westminster Abbey, not far from that of Isaac Newton. A major pioneer of radioactive science and nuclear physics, he was one of the great physicists of the first half of the twentieth century. He was born into a large family (he was one of twelve children) in 1871 in Spring Grove, near Nelson, on the northern edge of the southern island of New Zealand. His parents were of Scottish origin. His father had various occupations; he was responsible for a sawmill, made the sleepers for railway lines and was a linen maker. His mother was a primary school teacher, attending to the family.

The New Zealand of Rutherford's Time

New Zealand is composed of two mountainous islands, spreading North to South in the South Pacific Ocean. The southern island is made up of the highest mountains and fjords. The territories were uninhabited when the first Maoris, coming from Polynesia, landed them in the 9th or 10th century. The first significant Maori colonisation came in the 12th century, when they settled mainly on the northern island and bringing with them their food plants and way of life.

The first European to observe this country was the Dutchman Abel Tasman in 1642. New Zealand was 'rediscovered' in 1769 by the English navigator James Cook. The first missionaries arrived around 1820 and the first settlers, chiefly Scottish, from 1828. Great Britain officially took possession of the islands in 1840 and made it a colony in 1851, awarding it a 'constitutional act' the following year. From 1858, New Zealand could count more Europeans than Maoris. The latter saw themselves dispossessed of their land and forests by the colonists, leading to wars from 1842 to 1846 and from 1860 to 1868. However, the first settlers, coming from modest backgrounds, had an egalitarian spirit, which led to New Zealand becoming the first country in the world to grant women the right to vote in 1893. The social legislation was to be very advanced for its time.

The young Rutherford was very well raised, obtaining successive grants that allowed him to continue his studies. He therefore went on to study at the University of Canterbury of Christchurch, then annexed to the University of Wellington. In 1894 he was fortunate to receive the "1851 Exhibition Science" grant, allowing him to continue his studies in England. It is said that his mother told him of the news whilst he was pulling potatoes in the family garden; he sat aside his fork and said, "This is the last potato that I'm picking". Having arrived

in London, he received a proposition from J.J. Thomson (1856-1940), director of the Cavendish laboratory at Cambridge, to go and work there. In the laboratory he firstly finished the research he had started in New Zealand on the reception of radio waves.

At this time, J.J. Thomson was studying the ionisation of gas. These experiments led him to the discovery of the electron, a corpuscle nearly 2000 times lighter than the hydrogen atom, for which he will receive the Nobel Prize in Physics in 1906. Rutherford collaborated with Thomson in his research and revealed himself to be a very adroit and intuitive experimentalist and a fine observer. In 1898 he obtained the MacDonal chair of physics at the University of Montreal, where his laboratory had disposal of exceptional means. His final piece of work in Cambridge before leaving for Canada was the study of ionic radiation spontaneously emitted by uranium, discovered in Paris by Henri Becquerel. He concluded his study thus:

These experiments show that uranium radiation is complex and made up of at least two distinct types of radiation – one which is very easily absorbed and which for the sake of convenience we shall call radiation α , and another which is more penetrating and which we will name radiation β .

These denominations were quite quickly accepted by all of the researchers and are still used today. In his new laboratory, Rutherford wanted to continue his research into radioactivity (this name just having been given to the phenomenon by Marie Curie) and so he had uranium and thorium salts sent to Montreal¹.

AN EXTRAORDINARY EXPERIMENTER

During the summer of 1899, Rutherford revealed to McGill an astonishing observation, the analysis of which turned out to be very fruitful. After having placed a radioactive medallion on the lower level of an ionisation chamber, and having measured the current of ionisation created by the radioactivity, thus measuring the degree of radioactivity of the medallion, he noted:

"The intensity of thorium radiation, when examined by means of the electrical discharge produced, is found to be very variable; and this inconstancy is due to slow currents of air produced in an open room. When the apparatus is placed in a closed vessel, to do away with air

1. A relatively abundant metal, discovered in Norwegian minerals in 1828 (from where its designation comes after the Norwegian mythological god, *Thor*). Its radioactivity had been independently evidenced by Gerhardt Schmidt in Germany and by Marie Curie in France.

currents, the intensity is found to be practically constant. The sensitiveness of thorium oxide to slight currents of air is very remarkable. The movement of the air caused by the opening or closing of a door at the end of the room opposite to where the apparatus is placed, is often sufficient to considerably diminish the rate of discharge [i.e., the intensity of the current of ionisation]. When the equipment is placed in a closed enclosure, in order to suppress the air currents, one finds that the intensity is practically constant"

The physicist concluded that:

"In addition to this ordinary radiation, I have found that thorium compounds continuously emit radioactive particles of some kind, which retain their radioactive powers for several minutes. This 'emanation', as it will be termed for shortness, has the power of ionizing the gas in its neighbourhood..."

During his experiments, Rutherford discovered another astonishing property of "emanation":

"The positive ion produced in a gas by the emanation possesses the power of producing radioactivity in all substances on which it falls... The emanation from thorium compounds thus has properties which the thorium itself does not possess."

This emanation, was it a gas? A vapour? An aerosol? In November he added, in a second article on the subject in *Philosophical Magazine* (which would appear in February of 1900), that the particularly penetrating radiation of this "excited radioactivity", which was present on all bodies touched by emanation, saw its intensity drop by half in roughly eleven hours when the body on which it appeared was no longer in contact with the emanation. He succeeded in completely eliminating it by rubbing the surface vigorously with emery paper – thereafter called the "active deposit". He noted in the advance sheets of his article that Pierre and Marie Curie had just, at the beginning of November, observed on bodies placed close to sources of radium, a radioactivity that they called "potential", analogous to the stimulated radiation that he had documented. He believed that Pierre Curie had arrived at the same conclusions as he had, but the French physicist opted for another interpretation for quite some time, as we will later see. We can see that Rutherford had the double disadvantage of having less intense sources at his disposal than those of Paris, and of seeing his articles take a certain amount of time to reach the editor at the other side of the Atlantic, in London. However, in June of 1900, following the same experimental method

as the researcher in Montreal, a German physicist, Ernst Dorn (1848-1916), observed that radium also emitted an “emanation” – this would be named a “radon” in 1923.

Having now, in McGill, stable employment, Rutherford returned to New Zealand during the summer of 1900 to marry his fiancé, Mary Newton, and to take her with him to Canada. At the beginning of 1901, he wrote to his mother in their faraway land:

I have to keep going, as there are always people on my track. I have to publish my present work as rapidly as possible in order to keep in the race. The best sprinters in this road of investigation are Becquerel and the Curies who have done a lot of very important work on the subject of radioactive bodies during these last years.

ENCOUNTERING SODDY

The 28th of March 1901 was the date of a passionate debate between physicists and chemists at the local Society of Physics in Montreal. The subject was ‘*The Existence of Bodies Smaller than an Atom*’. There, Rutherford exposed the discovery by his master, J.J. Thomson, of the electron, the mass of which was 1000 times weaker than that of the hydrogen atom. However, he found a young and talented chemist facing him, Frederick Soddy, who had a keen spirit and had not long arrived from Oxford. Formidable in an open debate, he defended the indivisible atom as the basis of modern chemistry.

Frederick Soddy (1877-1956, 1921 Nobel Prize) and the Notion of Isotopes



Six years younger than Rutherford, Frederick Soddy was born in 1877 in Eastbourne, Sussex. After his studies at Oxford, followed by two years of research, he left for Canada and became an assistant at the

chemistry department of the McGill University. For 18 months he worked with Rutherford, checking the chemistry of their experiments. Together they discovered the law of radioactive transformations.

In the spring of 1904, Soddy returned to Great Britain, and, after a spell at the William Ramsay laboratory in London, became, from 1904 to 1914, master of conferences at the University of Glasgow. From 1905 to 1921 he wrote for the Chemistry Society of London an annual report on new results in radioactivity achieved in the previous year. In his 1910 report, published in 1911, he remarked that the number of radioelements that made up the last part of the Mendeleev table was too big. Many of them, such as thorium, radiothorium and ionium, or radium D and lead, were chemically identical.

It was therefore found that atoms of the same chemical element had different atomic weights (masses). This must also have to have been the case for non-radioactive elements. In 1913, he named isotopes as different atoms of the same element. He wrote:

"Chemical homogeneity is no longer a guarantee that a given element is not a mixture of several atomic masses, or that an atomic mass is not simply an average number."

This evidencing of isotopes and his earlier work would lead Soddy, then a professor at Oxford, to the 1921 Nobel Prize in Chemistry.

In the weeks that followed, Rutherford proposed to Soddy to come working with him. He was indeed convinced that only cooperation with a chemist would allow him to elucidate the true nature of thorium *emanation*. It would be a particularly fruitful collaboration, lasting a year and an half, with Soddy undertaking the chemical separations and Rutherford dealing with the physics measurements. Soddy used all chemical reagents possible in the attempt to breakdown the emanation or to carry out chemical reactions with it, but without success. Emanation must therefore be an inert gas, a new element, analogous to argon, as discovered by William Ramsay and John Strutt (Lord Rayleigh) several years previously, a heavy member of the rare gas family and the homologue to xenon. The two young scientists had a key realisation; thorium, a metal, constantly produced a gas – *the* so-called emanation! It is told that Soddy said, "It's a transmutation!", with Rutherford responding, "Be quiet, they'll think us alchemists!".

They went back to their research. Thorium, was it the real source of emanation? Soddy isolated some extremely pure thorium, and, to their great astonishment, it was the precipitate from which the thorium had been separated which was producing the emanation and which contained a large part of the original

radioactivity hitherto attributed to thorium. A new radioelement therefore accompanied thorium, which Rutherford and Soddy would name 'thorium X'.

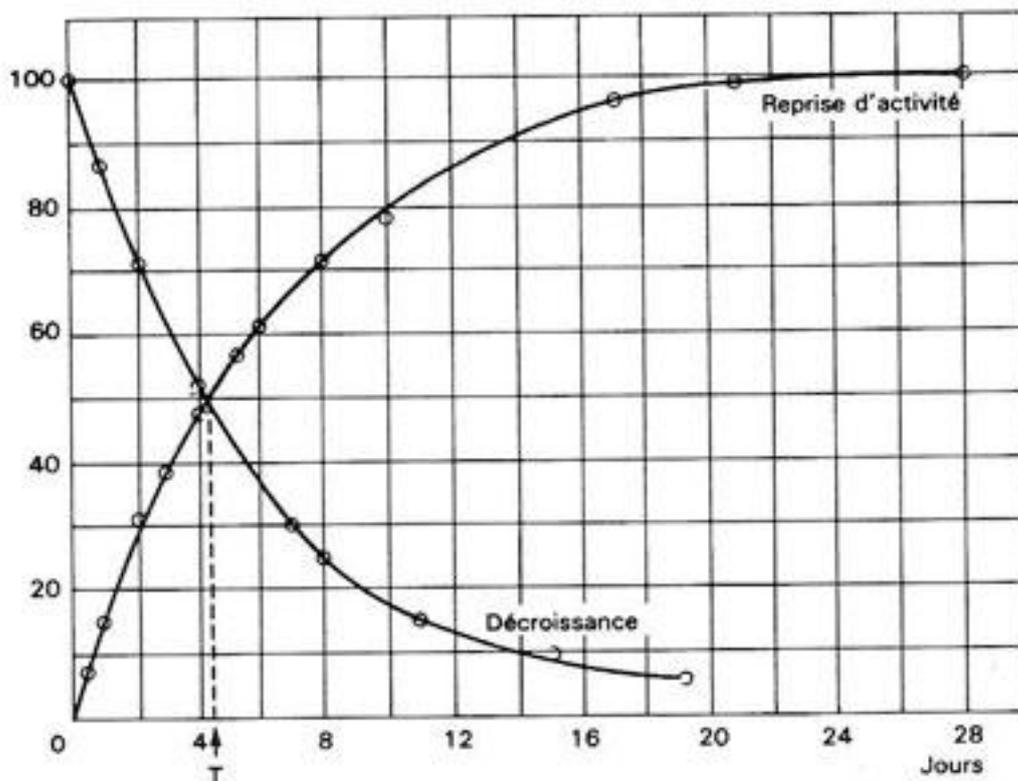


Figure 2: Decrease of radioactivity of thorium X separated and increase in radioactivity of the sample of purified thorium in the experiments of Rutherford and Soddy. (image extracted from 'History of Atoms', P. Radvanyi, M. Bordry, Belin 1988, after Rutherford and Soddy, Phil. Magazine, series 6, vol. 4, September 1902, p.370). *T* is the period of thorium X (Radium 224), the recent measurements give 3,63 j for this period.²

They ordered new quantities of very pure thorium salts. The chemist and the physicist worked in tight collaboration. Just before Christmas, Soddy separated thorium X as completely as possible. Rutherford was stunned when he returned to his radiation measurements at the beginning of January 1902 – the radioactivity of thorium X had considerably decreased, while the thorium had regained a little of its original radioactivity and its power to produce emanation since it continued to produce thorium X through radioactive transformation (see figure 2). They had, therefore, the proof that thorium, of an extremely long period of life, spontaneously transmuted into thorium X, and that the latter

2. After the period *T*, the two curves cross each other due to the activity of the thorium X having decreased by half, while the thorium X being continually formed in the sample of purified thorium has returned to half of its **poised value**. The sum of the two appears constant, as thorium has an extremely long duration (the decrease of its activity does not appear on a scale of 28 days).

decreased by half in a little less than 4 days through emanation³; the latter, for its part, within a period of around 1 minute, produced the active deposit⁴. **They showed, in this way, that radioactivity was the spontaneous transformation of a chemical element into another through the emission of radiation.** Each of the elements of the chain (later called the “*radioactive family*”) had its own particular radiation, that is to say that it possessed its own radioactive characteristics: it decreased exponentially with its own period, by emitting a specific radiation, giving the following radioelement. Eventually there would be a balance between the number of atoms formed and the number of the same atoms that survived the radioactive disintegration.

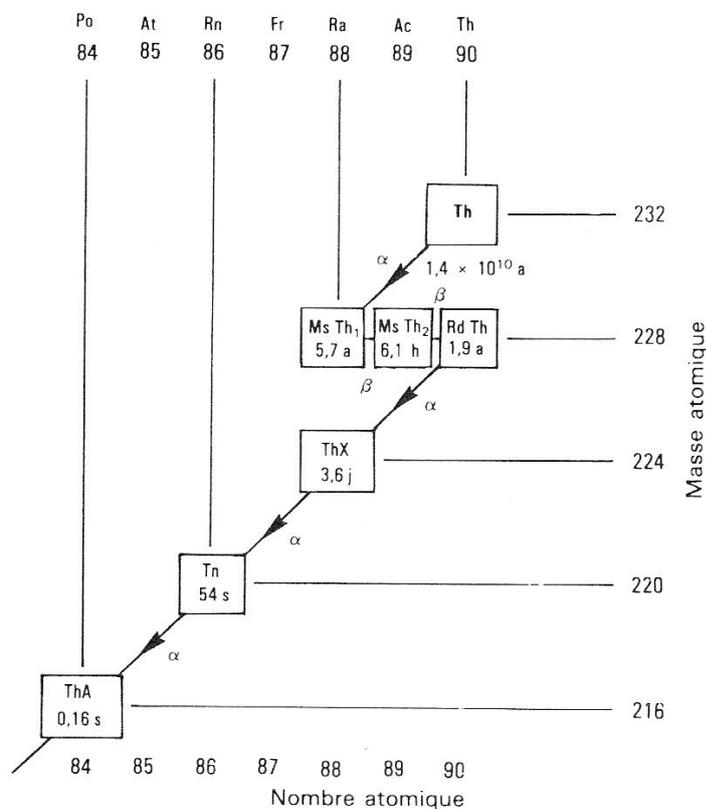


Figure 3: the thorium family until the first radioelement of the active deposit (thorium A)⁵.

3. The interval of time at the end of which the quantity of a given radioelement and its radiation have diminished by half will be called “*period*”. At the end of a period, there survives only half of the initial radioactivity, at the end of two periods there exists only a quarter, etc.

4 The active deposit was in fact a succession of radioelements, of which the first, from the emanation of thorium, was called thorium A (polonium 216).

5 During the writing of their article, Rutherford and Soddy could not ‘see’ the emanation that they called ‘thorium X’. The emanation would turn out to be radon 220, thorium proving itself to be Radium 224. The three intermediary elements, Radium 228 emitter β, Actinium 228 emitter β and Thorium 228 emitter α, have yet to be evidenced. The aforementioned are the radioactive isotopes of Thorium with a mass number (atomic number) of 232, of Radium with a mass number of 226, discovered by the Curies in 1898 from uranium minerals, and of Actinium with a mass number of 227, discovered by Debierne in 1899,

Each radioelement receives a particular name with an abbreviation (which appears in the little squares). The intermediary radioelements, Rd Th, Ms Th1 and Ms Th2 were discovered by Otto Hahn in 1905 and 1907. The beginning of the family was therefore complete and was recorded thus: Thorium → Mesothorium 1 → Mesothorium 2 → Radiothorium → Thorium X → Thoron (isotope of radon) → Thorium A → ... After the discovery of isotopy and the understanding of the physical meaning of the atomic number and mass number, we write this succession like so: Thorium 232 → Radium 228 → Actinium 228 → Thorium 228 → Radium 224 → Radon 220 → Polonium 216 → ...: the last part of this family, called the active deposit, begins at Polonium 216 and finishes up at Lead 208, stable – it is not represented here.

However, Pierre Curie, carrying out his own experiments, remained fixed to his preferred interpretation, a hypothesis according to which (January 1902), "the radioactive atom is a mechanism which draws at every instant outside of itself the energy which it generates." In January 1903 he wrote, "M. Rutherford seems to believe in the material nature of emanation". The accusation was far reaching. Rutherford then became annoyed and wrote to the *Philosophical Magazine*, "M. Curie has apparently not noticed one of our latest articles... in which we show that if we slowly move the emanations of thorium or radium in a spiral tube, emerged in liquid air, the emanations condense and the gas which leaves it is no longer radioactive." Emanation liquefied at a certain temperature. It was therefore indeed a gas – the proof was irrefutable. P. Curie repeated the experiment and was convinced – he then followed Rutherford and Soddy's way of thinking and adopted their conclusions.

RADIOACTIVE CHANGE

In May 1903, Rutherford and Soddy published a large report in *Philosophical Magazine* in which they summarized their results and conclusions.⁶

They wrote:

In previous papers it has been shown that the radioactivity of the elements radium, thorium, and uranium is maintained by the continuous production of new kinds of matter which possess temporary activity.

[...]

As an example that this is no argument against their specific material existence, it may be mentioned that the same is true of radium itself as it occurs in nature. [...] and the results go to show that that radium is in reality one of the best defined and most characteristic of the chemical elements.

6. It is the text presented on *Bibnum*.

They now had to examine the nature of the changes that produced these new bodies:

*When several changes occur together these are not simultaneous but successive. Thus thorium produces thorium X, the thorium X produces the thorium emanation, and the latter produces the excited activity. Now the radioactivity of each of these substances can be shown to be connected, not with the change in which it was itself produced, but with the change in which it in turn produces the next new type. Thus after thorium X has been separated from the thorium producing it, the radiations of the thorium X are proportional to the amount of emanation that it produces, and both the radioactivity and the emanating power of thorium X decay according to the same law **and at the same rate.***

Their conclusion at this stage was clear:

*Hence it is not possible to regard radioactivity as a **consequence** of changes that have already taken place. The rays emitted must be an **accompaniment** of the change of radiation system into the one next produced.*

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The two scientists then examine the material nature of radiation, of beta rays, negatively charged electrons and of alpha rays, positively charged, the mass of which was one thousand times higher than that of electrons (supposing that the value of their charge was the same):

There are thus strong reasons for the belief that the α rays are projections [...] The value of e/m , the ration of the charge of the carrier to its mass, is $6 \cdot 10^3$ [...] Now $e/m = 10^4$ for a hydrogen atom in the electrolysis of water. The particle that constitutes the α ray thus behaves as if its mass were the same as that of the hydrogen atom.⁷

Rutherford and Soddy, at the foot of the page, note the existence of another type of ray, beyond α and β , when they remark that the three known natural radioactive bodies (radium, thorium and uranium) emitted this other type of ray. These rays, a strong electromagnetic form of radiation (therefore with no charge), had been discovered in 1900 by the French physicist Paul Villard (1860-1934); they would be dubbed by those that followed ' γ rays'; they did not correspond to a change of a chemical element.

One conclusion from this analysis seemed evident to them:

7. Rutherford and Soddy obtained around 0.6 for the e/m ratio of the α particle, divided by the e/m ratio of the hydrogen ion. This was a good class of magnitude for this size, which was approximately 0.5.

In light of this evidence, there is every reason to suppose not only that the expulsion of a particular charged particle accompanies the change, but that this expulsion is the change itself.

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They then expound the law of radioactive change that they had established. The radioactive decrease was exponential. If N_0 was the number of radioactive atoms initially present, and N_t was the number of atoms which remained unaltered during time t , then it could be said that $N_t / N_0 = e^{-\lambda t}$. It follows that:

[...] the rate of change of the system at any time is always proportional to the amount remaining unchanged.

This proportionality is given by $dN_t/dt = -\lambda N_t$. The law could therefore be formulated:

the proportion of the whole which changes in unit time is represented by the constant λ , which possesses for each type of active matter a fixed and characteristic value. λ may therefore be suitably called the "radioactive constant."

The period⁸ T was linked to this constant by the ratio $T = 0.693/\lambda$. They give one of the experimental results of this law:

The complexity of the phenomena of radioactivity is due to the existence as a general rule of several different types of matter changing at the same time into one another, each type possessing a different radioactive constant.

They then explain and stress that

Radioactivity, according to present knowledge, must be regarded as the result of a process which lies wholly outside the sphere of known controllable forces, and cannot be created, altered, or destroyed.

[...]

Mme. Curie's original position, that radioactivity is a specific property of the element, must be considered to be beyond question.

[...]

It will be shown later that radioactive change can only be of the nature of an atomic disintegration...

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The authors continued their analysis of radioactive changes:

If elements heavier than uranium exist it is probable that they will be radioactive. The extreme delicacy of radioactivity as a means of chemical

8. We recall here the radioactive "half-life" : in a period of T , the number of radioactive **atoms** is divided by two. Therefore we have $e^{-\lambda T} = 1/2$, or $T = 0,693/\lambda$.

analysis would enable such elements to be recognized even if present in infinitesimal quantity.

[...]

Radioactive change, therefore, must be of such a kind as to involve one system only, for if it were anything of the nature of a combination, where the mutual action of two systems was involved, the rate of change would be dependent on the concentration [...] This is not the case.

From that they logically deduce that:

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

The radioelements possess of all elements the heaviest atomic weight. This is indeed their sole common chemical characteristic. The disintegration of the atom and the expulsion of heavy charged particles of the same order of mass as the hydrogen atom leaves behind a new system lighter than before, and possessing chemical and physical properties quite different from those of the original element.

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Rutherford and Soddy then establish for the first time the existence of *radioactive families*, each made up of a group of radioelements that are disintegrating from one into another⁹. This was a giant step forward for the science of radioactivity. They believe that they had recognized three families, sketching them out as those of uranium, of thorium and of radium; the question marks in the table (see figure 4 below) represent the final products of the families, then unknown. The rates of disintegration of thorium and of uranium are markedly slower in comparison to the geological scale that is used nowadays with important quantities. This rate seemed to be around a million times faster for radium; its period could not then be greater than several thousand years; radium therefore seemed to be derived from the successive disintegration of another element with a very long life present in the mineral:

[...] the radium present in a mineral has not been inexistence as long as the mineral itself, but is being continually produced by radioactive change.

9. In this article, they call the radioelements with a short life which they have documented 'metabolons'. Those who followed would later abandon this denomination.

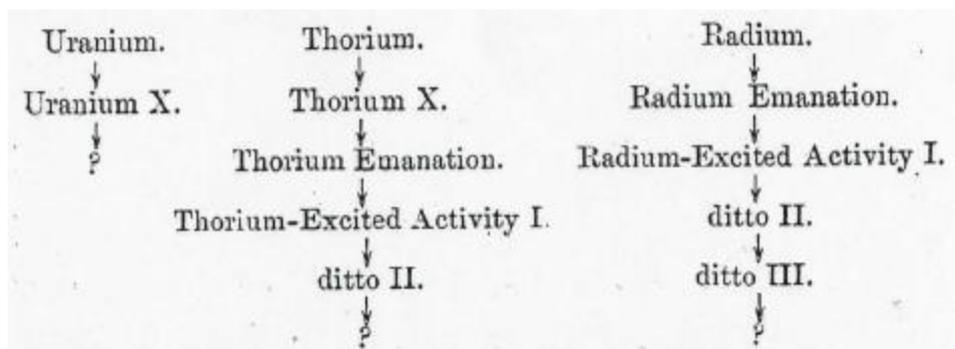


Figure 4: The first sketch of the radioactive disintegration process – later called “radioactive families” – is found in Rutherford and Soddy’s 1903 article. We find in nature three families of heavy radioactive elements, derived from radioelements with very long lives, all three of which end up as stable isotopes of lead. These families are Uranium 238/Radium, Thorium and Uranium 235/Actinium¹⁰. A fourth family, that of Neptunium 237, is reserved uniquely for artificial radioelements and ends up at bismuth. There can only exist four families of this type.

In fact, it was later shown that the family of radium, as is shown in the above sketch by Rutherford and Soddy, came from that of uranium (we say today ‘of uranium 238/radium’). The family of thorium was to be completed. The family of actinium, descending from uranium 235 (another element with a very long half-life), would also be documented, and, in the forties, that of neptunium 237 too (neptunium would be the first man-made “artificial” transuranic element¹¹). “Natural radioelements” are those with a very long life and have existed since the creation of the earth. They are accompanied by radioelements with a shorter life that are created through their disintegration (certain natural elements, such as potassium 40, don’t always derive from the four families which take up the last part of Mendeleev’s table, those of heavy metals).

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The authors then calculated, on the basis of their experiments, the energy released by the disintegration of one gram of radium, and compared it to that released by a high energy yielding chemical reaction, such as the union of hydrogen and oxygen to give a gram of water. Considering that each disintegration of a gram of radium produced at least one α particle (and more if the successive filiations were considered), and having measured the kinetic energy of one such particle and estimating the number of atoms per gram of

10. In figure 4, only two of contemporary families appear: the family in the centre corresponds to that of thorium; the family to the right would later come from the continuation of the family on the right, which corresponds to the family of uranium 235/radium.

11. The entire of the radioactive family of neptunium is made up of artificial radioelements. The three other radioactive families (uranium 235, uranium 238/radium, and thorium) come from natural radioelements.

radium, Rutherford and Soddy reached a minimum value of the energy released by the radioactive change of all atoms in a gram of radium. The energy released by the synthesis of a gram of water was known. They therefore concluded that:

The energy of radioactive change must therefore be at least twenty thousand times, and may be a million times, as great as the energy of any molecular change.

From the other part:

[...] the total energy of radioactive change [...] can only be a portion of the internal energy of the atom, for the internal energy of the resulting products remains unknown. All these considerations point to the conclusion that the energy latent in the atom must be enormous compared with that rendered free in ordinary chemical change. Now the radio-elements differ in no way from the other elements in their chemical and physical behaviour [...] there is no reason to assume that this enormous store of energy is possessed by the radio-elements alone.

Rutherford and Soddy conclude:

The existence of this energy accounts for the stability of the chemical elements as well as for the conservation of radioactivity under the influence of the most varied conditions. It must be taken into account in cosmic physics. The maintenance of solar energy, for example, no longer presents any fundamental difficulty if the internal energy of the component elements is considered to be available, i.e. if processes of sub-atomic change are going on.

These discoveries were remarkable. The law of radioactive transformations brought clarity and order into the field of radioactivity. Rutherford continued his research in Canada until 1907, when he became a professor at the University of Manchester. The young radio-chemist, Otto Hahn (1879-1968), a future Nobel Prize winner who had just found a new radioelement, radiothorium (thorium 228), spent a year next to him in Montreal.

THE REST OF THE PROGRAM

The question regarding the nature of the ultimate product of radioactive families had now been raised. Already in 1902, Rutherford and Soddy had written: "*The speculation naturally arises whether the presence of helium in minerals and its invariable association with uranium and thorium, may not be connected with their radioactivity*". If Helium was an ultimate product of disintegration, it could

be possible that the alpha particle was itself a helium atom. From 1903, using a very intense source of radium bromide, Soddy and Ramsay, in the laboratory of the latter in London, effectively evidenced the presence of helium in radium and in emanation (radon) thanks to its optical spectrum.

The geological dating by Boltwood, based on Rutherford's idea

At a conference in Saint-Louis in the United States, in September of 1904, Rutherford suggested using the helium content of uranium minerals to determine their minimum age, the minimum age because helium trapped within can escape.¹² The American physicist, Bertram B. Boltwood (1870-1927), was a professor at the University of Yale and a great admirer of Rutherford's, with whom he exchanged a rich correspondence and became friends. Boltwood was for several years the co-director of a private mine engineering laboratory. He corroborated the suggestion of Rutherford by carrying out measurements on rocks of different ages. He showed that radium was a product of the disintegration of uranium, as radium and its emanation were always present in the same proportion in relation to the uranium in uranium minerals. He discovered, in 1907, the missing intermediary radioelement, which then was called "ionium" (thorium 230), the immediate successor of a very long period of radium. Finding lead in all the minerals that contained uranium, Boltwood was the first to think that lead was the final product of the succession of radioactive disintegration. What is more, the proportion of lead was significantly more important than the mineral from a geological point of view. He also established, between 1905 and 1907 a new method of dating rocks, the oldest of which totalled billions of years old.

It was one of the first rigorous geological dating methods, preceding the carbon 14 method of William Libby, established in the 1940s; the latter also making use of radioactive residue, but used for more recent dating (several millions of years).

Rutherford had already attempted to more closely examine the nature of the most energetic of rays emitted by radioelements – alpha particles. This quest led him to new discoveries. One of his first ingenious experiments allowed him to show that they were positively charged particles, the mass of which being similar to that of a hydrogen atom. More precise measurements gave him the ratio of

12. This idea had already been suggested in the 1903 article, analyzed here, in which one can read: "*In the naturally occurring minerals containing the radio-elements these changes must have been proceeding steadily over very long periods, and, unless they succeed in escaping, the ultimate products should have accumulated in sufficient quantity to be detected, and therefore should appear in nature as the invariable companions of the radio-elements.*"

charge to mass of alpha particles. He also suspected that these articles were helium atoms with a double charge, but he had to prove it.

In his new Manchester laboratory, Rutherford welcomed young researchers, among them the German physicist, Hans Geiger (1882-1945), who had arrived in Manchester in 1906 after having received his thesis in Erlangen on electrical discharge in gas. Rutherford and Geiger developed a device – the ancestor of Geiger’s famous counter – which allowed them to detect individual alpha particles and thus to measure the number emitted per second from a given quantity of radium. They checked their result with the help of the scintillation method, carried out independently. The determination of the total positive charge carried by the collection of alpha particles allowed them to conclude, in 1908, that these particles were indeed helium atoms, emitted at very high speed and which were carrying two units of electric charge.

In December 1908, Rutherford received the Nobel Prize in Chemistry “*for his research into element disintegration of radioactive substances*”. Concluding his presentation speech, the president of the Swedish Royal Academy of Sciences underlined the following:

"The above-mentioned disintegration theory and the experimental results upon which it is based, are synonymous with a new departure in chemistry, involving a fresh and decidedly extended comprehension of the very basis of that science. To the chemists of the 19th century the atom and the element represented each in its sphere the uttermost limit of chemical subdivision or disintegration, and at the same time the point beyond which it was impossible for experimental investigation to proceed. If it were queried what there was beyond, nothing but more or less vague and fruitless speculations were forthcoming. This line of demarcation, for so long regarded as insurmountable, has now been swept away.

THE ATOM HAS A NUCLEUS AND A RAYS ALLOWED THEM TO DISCOVER IT!

Rutherford was now sure of the nature of alpha particles. He then wanted to understand the nature of these high velocity particles when they passed through matter. And so, in 1909, he asked his colleague, Hans Geiger, and an English student, Ernest Marsden (1889-1970), who had recently arrived at his laboratory, to study the diffusion of alpha particles through thin metal sheets, particularly gold ones; the young physicists used a strong source of radon and the scintillation method to count the alpha particles. Geiger and Marsden then

showed him a surprising result, which they were unable to explain. The majority of the particles went through the sheets, deviating only slightly from their original course; but with a gold sheet, several deviated from their course by more than 90° , therefore coming back on themselves. Rutherford described his astonishment thus: *"It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."* It would then take him a year and a half, during which he even took a statistics course, to understand it.

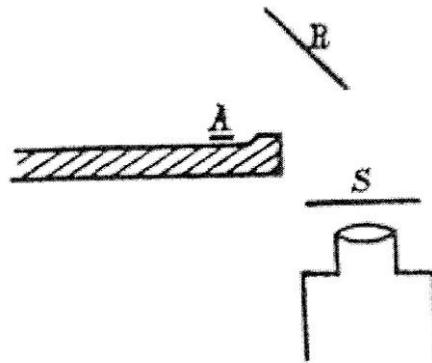
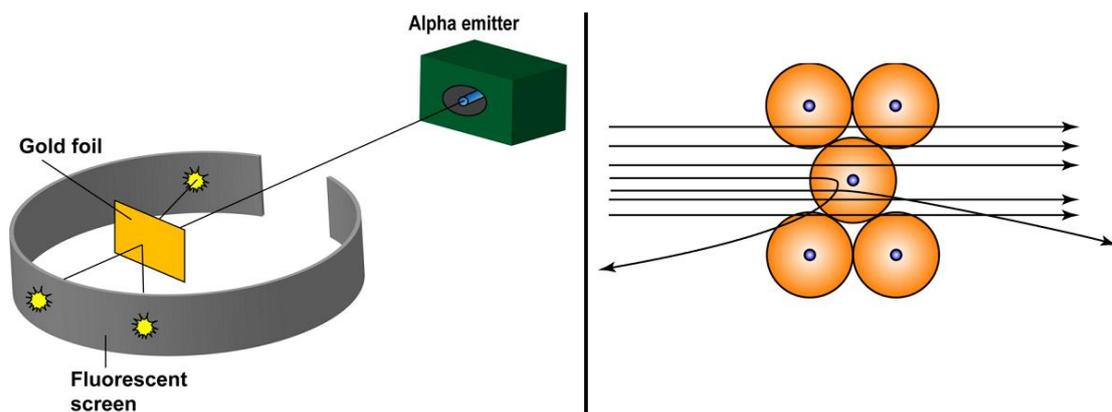


Figure 5: Sketch of one of Geiger and Marsden's experiments (1909). The radioactive source of the α particles is at A, a sheet of platinum is at R, S is the screen for the scintillations seen through the microscope: the physicists observed that certain α particles went back on themselves (H. Geiger and E. Marsden, Proc. Royal Soc. 1909 A, vol. 82, p. 495)

Figure 5Bis: (below) simplification of the modern Geiger and Marsden experiment. On the left, the device used: we can see certain particles being deflected backwards. On the right is the explication; the presence of atoms in the centre of the atoms.



In December of 1910, Rutherford eventually said to Geiger, *"I now know what an atom looks like!"*. His fundamental article appeared in *Philosophical Magazine* in May 1911. He concluded that if the alpha particle passed close to the centre of an atom, its trajectory, due to a repellent force that varied inversely from the square of the distance, would be an hyperbole, and that the atom

contained a central charge distributed in a very small amount; the large deflections were due to the total of the central charge. The following year he named this central area of the atom where its positive charge and majority of its mass were concentrated the *nucleus*. Geiger and Marsden confirmed with new experiments the quantitative predictions of Rutherford's theoretical analysis.

Contemporaries immediately seized upon the importance and consequence of this discovery. A dutch property lawyer and remarkable amateur physicist, Antonius J. van den Broek (1870-1926), proposed in 1911 and 1913, in two letters to the *Nature* review, that: *"The number of possible chemical elements is equal to the number of possible permanent charges per different atom, or, put differently, each possible permanent charge (of one or another type) per atom corresponds to a potential element"* He added: *"If we list all the elements by increasing atomic weight, the number of each element in the classification should be equal to its intra-atomic charge."* A young assistant of Rutherford, Henry G. J. Moseley (1887-1915), immediately began to attempt to verify experimentally van den Broek's suggestion. Using Bragg's new spectroscopic method of X-rays by crystal reflection, he made a 'count' of elements (he found 92 of them up to Uranium), and confirmed in 1913-1914, the suggestions of the amateur Dutch physicist. The classification number of Mendeleev's periodic table now had physical meaning.

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At the beginning of 1912, a young Danish theoretical physicist, Niels Bohr (1883-1962), after having handed in his thesis in Copenhagen, decided to make a scientific trip to Great Britain. He went firstly to the home of J.J. Thomson in Cambridge, however, having learned of Rutherford's discovery of the nucleus, he went to work with him at the University of Manchester. There, he began to expand upon his first model of the atom, using the new description of Rutherford and the quantification of the microscopic scale introduced by the German physicist, Max Planck. This would be Bohr's atom (Nobel Prize in Physics, 1922).

A Hungarian chemist, Georg de Hevesy (1885-1966), having finished his studies in Germany and an assistantship post in Zurich, joined up with the laboratory of Rutherford in 1910. He suggested that he separate radium D from lead. Succeeding in this (radium D later being recognized as an isotope of lead), Hevesy had the idea whilst on the train between Vienna and Budapest, to use this property of radium D as the first radioactive indicator (1913); he carried out

the first experiment of this type shortly after with the Austrian physicist and chemist, Friedrich Paneth. The great success of radioactive indicators was achieved by Hevesy with artificial radioelements, for which he was awarded the 1943 Nobel Prize in Chemistry.

Another young physicist, who arrived at Rutherford's laboratory in 1911 to fulfil his studies, was James Chadwick (1891-197), who in 1913 received a bursary to continue his research abroad. He chose to go and work in the laboratory in Berlin where Hans Geiger had just been named director. There he studied the β rays emitted by radioactive bodies, at that point considered to be, like alpha particles, single energy electrons. However, Chadwick observed, using the counter method, that the majority of electrons were forming continuous spectres (beta spectres). During the entire of the 1914-1918 war, Chadwick, a British citizen, was held at the Ruhleben internment camp. There he met another prisoner, Charles D. Ellis, who had dreamed of becoming an artillery officer after the war. Chadwick convinced him to become a physicist and to go, like him, to work with Rutherford after the end of the conflict. Ellis was the first to evidence the existence of levels of excitation of the nucleus.

THE BEGINNINGS OF "NUCLEAR PHYSICS"

In 1909, still in Manchester, Rutherford carried out a simple experiment that opened a new path for the science of radioactivity. In a small room (a parallelepiped box), enclosed by a scintillation screen, he placed a powerful, alpha ray emitting source of radiation. He filled the room with nitrogen. When the source was sufficiently far from the screen, the alpha particles couldn't reach it, and yet Rutherford continued to observe impacts that were causing scintillations. This phenomenon could not be produced when the room was filled with oxygen or a carbonic gas. He noted that it must have been due to protons (hydrogen nuclei) and concluded that some alpha particles had been disintegrated by the nitrogen atoms.

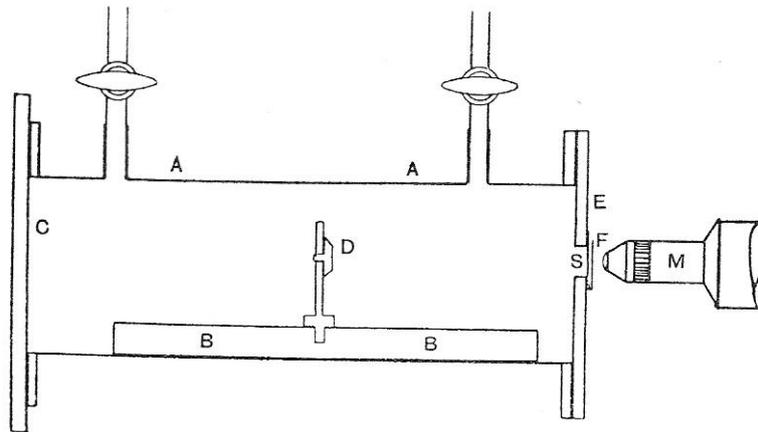


Fig. 81.

Figure 6: Observation of the first nuclear reaction. A source of radium is placed at *D*, a zinc sulphate scintillator screen is at *F*, the chamber is closed by a slim sheet of silver at *S* (Rutherford, *Phil. Mag.* 1919, vol. 37, p. 581 and Rutherford, Chadwick & Ellis, *Radiations from Radioactive substances*, Cambridge University Press, 1930).

It was the first provoked transmutation, the first *nuclear reaction*, the beginning of **nuclear physics**. In 1924, his colleague, Patrick M. S. Blackett (1897-1974), 1948 Physics Nobel Prize winner, showed on images from a cloud chamber, that the reaction of nitrogen produced oxygen:



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At the end of 1919, Rutherford received directorship of the Cavendish laboratory in Cambridge, taking over from the man who had been his master, J.J. Thomson. In Cambridge he notably welcomed the young soviet physicist, Piotr L. Kapitsa (1894-1984), another future Nobel Prize winner (1978), who helped him to obtain his own super cooled physics laboratory. Two other young physicists, Edward V. Appleton and Cecil F. Powell, who also received the Nobel Prize for their later discoveries, carried out their first research in the laboratory of Rutherford.

Rutherford was interested very early on in the realisation of particle accelerators: it would therefore be necessary to have access to beams of particles that were more intense than those of radioactive sources, well defined in direction and doubtlessly with a higher level of energy. He asked a young Irish physicist, Ernest T.S. Walton (1903-1995), to pursue plans to this end. In January 1929, the Russian-born physicist, George Gamow (1904-1968), arrived in Cambridge to put forward his theory of alpha radioactivity that he had worked on in Gottingen using the new theory of quantum mechanics. According to this

theory, alpha particles had a certain probability to leave the nucleus by crossing the “barrier of potential” which, due to the *tunnel effect*¹³, surrounded it. The physicist John D. Cockcroft (1897-1967) assisted Gamow’s conference and immediately realised that the theory could be applied differently, and thus predicted that a particle coming from outside could penetrate the nucleus more easily than had been previously thought. He immediately went to see Rutherford, who had charged him with constructing, alongside Walton, the necessary high-tension small accelerator. They had envisioned producing 700 kilovolt protons, with a vertical beam that would fall on a very thin lithium target. Once at 400 kilovolts, Walton would be able to see – through a small microscope – the scintillator placed under the installation. He observed the first scintillations, and then with Cockcroft called Rutherford for him to see. The latter exclaimed: *“Those scintillations look mighty like alpha-particle ones. I should recognize an alpha-particle scintillation when I see one. I was in at the birth of alpha particles and have been observing them ever since.”* The two young physicists then observed two alpha particles coincidentally emitted back-to-back during the reaction: $\text{proton} + \text{lithium } 7 \rightarrow \text{alpha} + \text{alpha}$. It was the first nuclear reaction caused by artificially accelerated particles. For this, Cockcroft and Walton would win the Nobel Prize in Physics in 1951.

At the beginning of 1932, following on from observations made a month earlier at the Paris Institute of Radium by Frederic and Irene Joliot-Curie, and drawing on a suggestion made twelve years earlier by Rutherford, James Chadwick, whom we have mentioned above, discovered the *neutron*, which, with the proton, was one of the constituents of the nucleus of the atom (as it would be shown a little after by the German physicist, Werner Heisenberg). Chadwick received the 1935 Nobel Prize in Physics.

Rutherford was made a Lord in 1931. He died following a surgical intervention in October 1937. This great scientist left his mark on a large number of scientists throughout the world, constantly taking new ideas to his colleagues; his observation and intuition were incomparable.



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(translated in English by Luke Mackle, published September 2013)

13. This was the first result where quantum mechanics had been effectively used in nuclear physics: it is considered that this was the moment where these two disciplines created a “junction”.