Ernest Rutherford
Nobel Lecture

Nobel Lecture, December 11, 1908

The Chemical Nature of the Alpha Particles from Radioactive Substances

The study of the properties of the α-rays has played a notable part in the development of radioactivity and has been instrumental in bringing to light a number of facts and relationships of the first importance. With increase of experimental knowledge there has been a growing recognition that a large part of radioactive phenomena is intimately connected with the expulsion of the α-particles. In this lecture an attempt will be made to give a brief historical account of the development of our knowledge of the α-rays and to trace the long and arduous path trodden by the experimenter in the attempts to solve the difficult question of the chemical nature of the α-particles. α-rays were first observed in 1899 as a special type of radiation and during the last six years there has been a persistent attack on this great problem, which has finally yielded to the assault when the resources of the attack seemed almost exhausted.

Shortly after his discovery of the radiating power of uranium by the photographic method, Becquerel showed that the radiation from uranium like the Röntgen-rays possessed the property of discharging an electrified body. In a detailed investigation of this property, I examined the effect on the rate of discharge by placing successive layers of thin aluminium foil over the surface of a layer of uranium oxide and was led to the conclusion that two types of radiation of very different penetrating power were present. The conclusions at that period were summed up as follows:

"These experiments show that the uranium, radiation is complex and that there are present at least two distinct types of radiation – one that is very readily absorbed, which will be termed for convenience the α-radiation, and the other of a more penetrative character, which will be termed the β-radiation."[1] When other radioactive substances were discovered, it was seen that the types of radiation present were analogous to the β– and α-rays of uranium and when a still more penetrating type of radiation from radium was discovered by Villard, the term γ-rays was applied to them. The names thus given soon came into general use as a convenient nomenclature for the three distinct types of radiation emitted from uranium, radium, thorium, and actinium. On account of their insignificant penetrating power, the α-rays were at first considered of little importance and attention was mainly directed to the more penetrating β-rays. With the advent of active preparations of radium, Giesel in 1899 showed that the β-rays from this substance were easily deflected by a magnetic field in the same direction as a stream of cathode rays and consequently appeared to be a stream of projected particles carrying a negative charge. The proof of the identity of the β-particles with the electrons constituting the cathode rays was completed in 1900 by Becquerel, who showed that the β-particles from radium had about the same small mass as the electrons and were projected at a speed comparable with the velocity of light. Time does not allow me to enter into the later work of Kaufmann and others on this subject, which has greatly extended our knowledge of the constitution and mass of electrons.

In the meantime, further investigation had disclosed that the α-particles produced most of the ionization observed in the neighbourhood of an unscreened radioactive substance, and that most of the energy radiated was in the form of α-rays. It was calculated by Rutherford and McClung in 1901 that one gram of radium radiated a large amount of energy in the form of α-rays.

The increasing recognition of the importance of the α-rays in radioactive phenomena led to attempts to determine the nature of this easily absorbed type of radiation. Strutt (Lord Rayleigh) in 1901 and Sir William Crookes in 1902 suggested that they might possibly prove to be projected particles carrying a positive charge. I independently

arrived at the same conclusion from consideration of a variety of evidence. If this were the case, the α-rays should be deflected by a magnetic field. Preliminary work showed that the deflection was very slight if it occurred at all. Experiments were continued at intervals over a period of two years and it was not until 1902, when a preparation of radium of activity 19,000 was available, that I was able to show conclusively that the particles were deflected by a magnetic field, though in a very minute degree compared with the β-rays. This showed that the α-rays consisted of projected charged particles while the direction of deflection indicated that each particle carried a positive charge. The α-particles were shown to be deflected also by an electric field and from the magnitude of the deflection, it was deduced that the velocity of the swiftest particles was about 2.5 x 10^9 cm per second, or one-twelfth the velocity of light, while the value of e/m – the ratio of the charge carried by the particle to its mass – was found to be 5,000 electromagnetic units. Now it is known from the data of the electrolysis of water that the value of e/m for the hydrogen atom is 9,650. If the α-particle carried the same positive charge as the unit fundamental charge of the hydrogen atom, it was seen that the mass of the α-particle was about twice that of the hydrogen atom. On account of the complexity of the rays it was recognized that the results were only approximate, but the experiments indicated clearly that the α-particle was atomic in mass and might prove ultimately to be either a hydrogen or a helium atom or the atom of some unknown element of light atomic weight. These experiments were repeated by Des Coudres in 1903 with similar results, while Becquerel showed the deflection of the α-rays in a magnetic field by the photographic method.

This proof that the α-particles consisted of actual charged atoms of matter projected with an enormous velocity at once threw a flood of light on radioactive processes, in particular upon another important series of investigations which were being contemporaneously carried on in the Laboratory at Montreal in conjunction with Mr. F. Soddy. Had time permitted, it would have been of interest to consider in some detail the nature of these researches which placed on a firm foundation the now generally accepted “transformation theory” of radioactivity. From a close examination of the substances thorium, radium, and uranium, Rutherford and Soddy had reached the conclusion that radioactive bodies were in a state of transformation, as a result of which a number of new substances were produced entirely distinct in chemical and physical character from the parent element. From the independence of the rate of transformation of chemical and physical agencies, it was recognized that the transformation was atomic and not molecular in character. Each of these new bodies was shown to lose its radioactive properties according to a definite law. Even before the discovery of the material nature of the α-rays, it had been considered probable that the radiation from any particular substance accompanied the breaking up of its atoms. The proof that the α-particle was an ejected atom of matter at once strengthened this conclusion and at the

same time gave a more concrete and definite representation of the processes occurring in radioactive matter. The point of view reached by us at that time is clearly seen from the following quotation, which with little alteration holds good today. “The results obtained so far point to the conclusion that the beginning of the succession of chemical changes taking place in radioactive bodies is due to the emission of the α-rays, i.e. the projection of a heavy charged mass from the atom. The portion left behind is unstable, undergoing further chemical changes which are again accompanied by the emission of α-rays, and in some cases also of β-rays.

The power possessed by the radioactive bodies of apparently spontaneously projecting large masses with enormous velocities supports the view that the atoms of these substances are made up, in part at least, of rapidly rotating or oscillating systems of heavy charged bodies, large compared with the electron. The sudden escape of these masses from their orbit may be due either to the action of internal forces or external forces of which we have at present no knowledge.”[2]

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

I can only refer in passing here to the large amount of work done by various experimenters in analysing the long series of transformations of radium and thorium and actinium; the linking up of radium with uranium and the discovery by Boltwood of the long looked-for and elusive parent of radium, viz. ionium. This phase of the subject is of unusual interest and importance but has only an indirect bearing on the subject of my lecture. It has been shown that the great majority of the transition elements produced by the transformation of uranium and thorium break up with the expulsion of α-particles. A few, however, throw off only β-particles, while some are “rayless”, i.e. undergo transformation without the expulsion of high-speed α– and β-particles. It is necessary to suppose that in these latter cases the atoms break up with the expulsion of α-particles at a speed too low to be detected, or, as is more probable, undergo a process of atomic rearrangement without the expulsion of material particles of atomic dimensions.

Another striking property of radium was soon seen to be connected with the expulsion of α-particles. In 1903 P. Curie and Laborde showed that radium was a self-heating substance and was always above the temperature of the surrounding air. It seemed probable from the beginning that the effect must be the result of the heating effect due to the impact of the α-particles on the radium. Consider for a moment a pellet of radium enclosed in a tube. The α-particles are shot out in great numbers equally from all parts of the radium and in consequence of their slight penetrating power are all stopped in the radium itself or by the walls of the tube. The energy of motion of the α-particles is converted into heat. On this view the radium is subject to a fierce and unceasing bombardment by its own particles and is heated by its own radiation. This was confirmed by the work of Rutherford and Barnes in 1903, who showed that three quarters of the heating effect of radium was not directly due to the radium but to its product, the emanation, and that each of the different substances produced in radium gave out heat in proportion to the energy of the α-particles expelled from it. These experiments brought clearly to light the enormous energy, compared with the weight of matter involved, which was emitted during the transformation of the emanation. It can readily be calculated that one kilogram of the radium-emanation and its products would initially emit energy at the rate of 14,000 horse-power, and during its life would give off energy corresponding to about 80,000 horse-power for one day.

It was thus clear that the heating effect of radium was mainly a secondary phenomenon resulting from the bombardment by its own α-particles. It was evident also that all the radioactive substances must emit heat in proportion to the number and energy of the α-particles expelled per second.

We must now consider another discovery of the first importance. In discussing the consequences of the disintegration theory, Rutherford and Soddy drew attention to the fact that any stable substances produced during the transformation of the radio-elements should be present in quantity in the radioactive minerals, where the processes of transformation have been taking place for ages. This suggestion was first put forward in 1902.[3] “In the light of these results and the view that has already been put forward of the nature of radioactivity, 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, and again[4]. “It is therefore to be expected that if any of the unknown ultimate products of the changes of a radioactive element are gaseous, they would be found occluded, possibly in considerable quantities, in the natural minerals containing that element. This lends support to the suggestion already put forwards, that possibly helium is an ultimate product of the disintegration of one of the radioactive elements, since it is only found in radioactive minerals.”

It was at the same time recognized that it was quite possible that the α-particle itself might prove to be a helium atom. As only weak preparations were then available, it did not seem feasible at that time to test whether helium was produced from radium. About a year later, thanks to Dr. Giesel of Braunschweig, preparations of pure radium bromide were made available to experimenters. Using 30 milligrams of Giesel's preparation, Sir William Ramsay and Soddy in 1903 were able to show conclusively that helium was present in radium some months old and that the emanation produced helium. This discovery was of the greatest interest and importance, for it brought to light that in addition to a series of transition elements, radium also gave rise in its transformation to a stable form of matter.

A fundamental question immediately arose as to the position of helium in the scheme of transformations of radium. Was the helium the end or final product of transformation of radium or did it arise at some other stage or stages? In a letter to *Nature*[5] I pointed out that probably helium was derived from the α-particles fired out by the α-ray products of radium and made an approximate estimate of the rate of production of helium by radium. It was calculated that the amount of helium produced per gram of radium should lie between 20 and 200 cubic millimetres per year and probably nearer the latter estimate. The data available for calculation at that time were imperfect, but it is of interest to note that the rate of production of helium recently found by Sir James Dewar, in 1908, viz. 134 cubic millimetres per year, is not far from the value calculated as most probable at that time.

These estimates of the rate of production of helium were later modified as new and more accurate data became available. In 1905, I measured the charge carried by the α-particles from a thin film of radium. Assuming that each α-particle carried the ionic charge measured by J.J. Thomson, I showed that 6.2×10^{10} α-particles were expelled per second per gram of radium itself and four times this number when radium was in equilibrium with its three α-ray products. The rate of production of helium calculated on these data was 240 cubic millimetres per gram per year.

In the meantime, by the admirable researches of Bragg and Kleeman in 1904, our knowledge of the character of the absorption of the α-particles by matter had been much extended. It had long been known that the absorption of α-particles by matter was different in many respects from that of the β-rays. Bragg showed that these differences arose from the fact that the α-particle, on account of its great energy of motion, was not deflected from its path like the β-particle, but travelled in nearly a straight line, ionizing the molecules in its path. From a thin film of matter of one kind, the α-particles were all projected at the same speed and lost their power of producing ionization suddenly, after

traversing a certain definite distance of air. The velocity of the α-particles in this view were reduced by their passage through matter by equal amounts. These conclusions of Bragg were confirmed by experiments I made by the photographic method. As a source of rays, a thin film of radium C, deposited from the radium-emanation on a thin wire, was used. By examining the deflection of the rays in a magnetic field, it was found that the rays were homogeneous and were expelled from the surface of the wire at an identical speed. By passing the rays through a screen of mica or aluminium, it was found that the velocity of all the α-particles were reduced by the same amount and the issuing beam was still homogeneous.

A remarkable result was noted. All α-particles apparently lost their characteristic properties of ionization, phosphorescence and photographic action, at exactly the same point while they were still moving at a speed of about 9,000 kilometres per second. At this critical speed, the α-particle suddenly vanishes from our ken and can no longer be followed by the methods of observation at our command.

The use of a homogeneous source of α-rays like radium C at once suggested itself as affording a basis for a more accurate determination of the value of *e/m* for the α-particle and for seeing whether the value was consistent with the view that the α-particle was a charged atom of helium. In the course of a long series of experiments, I proved that the α-particles, whether expelled from radium, thorium or actinium, were identical in mass and must consist of the same kind of matter.

The velocity of expulsion of the α-particles from different kinds of active matter varied over comparatively narrow limits but the value of *e/m* was constant and equal to 5,070. This value was not very different from the one originally found. A difficulty at once arose in interpreting this result. We have seen that the value of *e/m* for the hydrogen atom is 9,650. If the α-particle carried the same positive charge as the hydrogen atom, the value of e/m for the α-particle would indicate that its mass was twice that of the hydrogen atom, i.e. equal to the mass of a hydrogen molecule. It seemed very improbable that hydrogen should be ejected in a molecular and not an atomic state as a result of the atomic explosion. If, however, the α-particle carried a charge equal to twice that of the hydrogen atom, the mass of the α-particle would work out at nearly four, i.e. a mass nearly equal to that of the atom of helium.

I suggested that, in all probability, the α-particle was a helium atom which carried two unit charges. On this view, every radioactive substance which emitted α-particles must give rise to helium. This at once offered an explanation of the fact observed by Debierne

that actinium as well as radium produced helium. It was pointed out that the presence of a double charge of helium-atom was not altogether improbable for reasons to be given later (p. 138).

While the evidence as a whole strongly supported the view that the α-particle was a helium atom, it was found exceedingly difficult to obtain a decisive experimental proof of the relation. If it could be shown experimentally that the α-particle did in reality carry two unit charges, the proof of the relation would be greatly strengthened. For this purpose an electrical method was devised by Rutherford and Geiger for counting directly the α-particles expelled from a radioactive substance. The ionization produced in a gas by a single α-particle is exceedingly small and would be difficult to detect electrically except by a very refined method. Recourse was had to an automatic method of magnifying the ionization produced by an α-particle. For this purpose it was arranged that the α-particles should be fired through a small opening into a vessel containing air or other gas at a low pressure, exposed to an electric field near the sparking value. Under these conditions the ions produced by the passage of the α-particle through the gas generate a large number of fresh ions by collision. In this way it was found possible to magnify the electrical effect due to an α-particle several thousand times. The entrance of an α-particle into the testing vessel was then indicated by a sudden deflection of the electrometer needle. This method was developed into an accurate method of counting the number of α-particles fired in a known time through the small aperture of the testing vessel. From this was deduced the total number of α-particles expelled per second from any thin film of radioactive matter. In this way it was shown that 3.4×10^{10} α-particles are expelled per second from one gram of radium itself and from each of its α-ray products in equilibrium with it.

The correctness of this method was indicated by another, quite distinct method of counting. Sir William Crookes and Elster and Geitel had shown that the α-particles falling on a screen of phosphorescent zinc sulphide produced a number of scintillations. Using specially prepared screens, Rutherford and Geiger counted the number of these scintillations per second with the aid of a microscope. It was found that, within the limit of experimental error, the number of scintillations per second on a screen agreed with the number of α-particles impinging on it, counted by the electrical method. It was thus clear that each α-particle produced a visible scintillation on the screen, and that either the electrical or the optical method could be used for counting the α-particles. Apart from the purpose for which these experiments were made, the results are of great interest and importance, for it is the first time that it has been found possible to detect a single atom of matter by its electrical and optical effect. This is of course only possible because of the great velocity of the α-particle.

Knowing the number of α-particles expelled from radium from the counting experiment, the charge carried by each α-particle was determined by measuring the total positive charge carried by all the α-particles expelled. It was found that each α-particle carried a positive charge of 9.3×10^{-10} electrostatic units. From a consideration of the experimental evidence of the charge carried by the ions in gases, it was concluded that the α-particle did carry two unit charges, and that the unit charge carried by the hydrogen atom was equal to 4.65×10^{-10} units. From a comparison of the known value of e/m for the α-particle with that of the hydrogen atom, it follows that an α-particle is a projected atom of helium carrying two charges, or, to express it in another way, the α-particle, after its charge is neutralized, is a helium atom.

The data obtained from the counting experiments allow us to calculate simply the magnitude of a number of important radioactive quantities. It was found that the calculated values of the life of radium, of the volume of the emanation, and of the heating effect of radium were in excellent agreement with the values found experimentally. A test of the correctness of these methods of calculation was forthcoming shortly after the publication of these results. Rutherford and Geiger calculated, on the assumption that the α-particle was a helium atom, that one gram of radium in equilibrium should produce a volume of 158 cubic millimetres of helium per year. Sir James Dewar in 1908 carried out a long experimental investigation on the rate of production of helium by radium, and showed that one gram of radium in equilibrium produced about 134 cubic millimetres per year. Considering the difficulty of the investigation, the agreement between the experimental and calculated values is very good and is strong evidence in support of the identity of the α-particle with a helium atom.

While the whole train of evidence we have considered indicates with little room for doubt that the α-particle is a projected helium atom, there was still wanting a decisive and incontrovertible proof of the relationship. It might be argued, for example, that the helium atom appeared as a result of the disintegration of the radium atom in the same way as the atom of the emanation and had no direct connection with the α-particle. If one helium atom were liberated at the same time that an α-particle was expelled, experiment and calculation might still agree and yet the α-particle might be an atom of hydrogen or of some unknown substance.

In order to remove this possible objection, it is necessary to show that the α-particles, collected quite independently of the active matter from which they are expelled, give rise to helium. With this purpose in view some experiments were recently (1908) made by Rutherford and Royds. A large quantity of emanation was forced into a glass tube which

had walls so thin that the α-particles were fired right through them, though the walls were impervious to the emanation itself. The α-particles were projected into the glass walls of an outer sealed vessel and were gradually released into the exhausted space between the emanation tube and the outer vessel. After some days a bright spectrum of helium was observed in the outer vessel. There is, however, one objection to this experiment. It might be possible that the helium observed had diffused through the thin glass walls from the emanation. This objection was removed by showing that no trace of helium appeared, when the emanation was replaced by a larger volume of helium itself. We may thus confidently conclude that the α-particles themselves give rise to helium, and are atoms of helium. Further experiments showed that when the α-particles were fired through the glass walls into a thin sheet of lead or tin, helium could always be obtained from the metals after a few hours' bombardment.

Considering the evidence together, we conclude that the α-particle is a projected atom of helium, which has, or in some way during its flight acquires, two unit charges of positive electricity. It is somewhat unexpected that the atom of a monatomic gas like helium should carry a double charge. It must not however be forgotten that the α-particle is released at a high speed as a result of an intense atomic explosion, and plunges through the molecules of matter in its path. Such conditions are exceptionably favourable to the release of loosely attached electrons from the atomic system. If the α-particle can lose two electrons in this way, the double positive charge is explained.

We have seen that there is every reason to believe that the α-particles, so freely expelled from the great majority of radioactive substances, are identical in mass and constitution and must consist of atoms of helium. We are consequently driven to the conclusion that the atoms of the primary radioactive elements like uranium and thorium must be built up in part at least of atoms of helium. These atoms are released at definite stages of the transformations at a rate independent of control by laboratory forces. There is good reason to believe that in the majority of cases, a single helium atom is expelled during the atomic explosion. This is certainly the case for radium itself and its series of products. On the other hand, Bronson has drawn attention to certain cases, viz. the emanations of actinium and of thorium, where apparently two and three atoms of helium respectively are expelled at one time. No doubt these exceptions will receive careful investigation in the future. It is of interest to note that uranium itself appears to expel two α-particles for one from each of its products. Knowing the number of atoms of helium expelled from the atom of each product, we can at once calculate the atomic weights of the products. For example, in the uranium-ionium-radium series, uranium expels two α-particles and each of the six following α-ray products one, i.e. eight in all. Taking the atomic weight of uranium as 238.5, the atomic weight of ionium should be

230.5, of radium 226.5, of the emanation 222.5, and so on. It is of interest to note that the atomic weight of radium deduced in this way is in close agreement with the latest experimental values. The atomic weight of the end-product of radium, resulting from the transformation of radium F (polonium) should be 238.5 – 8 x 4= 206.5, or a value close to that for lead. Long ago, Boltwood suggested from examination of analyses of old uranium minerals, that lead was in all probability a transformation product of the uranium-radium series. The coincidence of numbers is certainly striking, but a direct proof of the production of lead from radium will be required before this conclusion can be considered as definitely established.

It is very remarkable that a chemically inert element like helium should play such a prominent part in the constitution of the atomic systems of uranium and thorium and radium. It may well be that this property of helium of forming complex atoms is in some way connected with its inability to enter into ordinary chemical combinations. It must not be forgotten that uranium and thorium and each of their transformation products must be regarded as distinct chemical elements in the ordinary sense. They differ from ordinary elements in the comparative instability of their atomic systems. The atoms break up spontaneously with great violence, expelling in many cases an atom of helium at a high speed. All the evidence is against the view that uranium or thorium or radium can be regarded as an ordinary molecular compound of helium with some known or unknown element, which breaks up into helium. The character of the radioactive transformations and their independence of temperature and other agencies have no analogy in ordinary chemical changes.

Apart from their radioactivity and high atomic weight, uranium, thorium, and radium show no specially distinctive chemical behaviour. Radium for example is closely allied in general chemical properties to barium. It is consequently not unreasonable to suppose that other elements may be built up in part of helium, although the absence of radioactivity may prevent us from obtaining any definite proof. On this view, it may prove significant that the atomic weights of many elements differ by four – the atomic weight of helium-or a multiple of four. Time is too limited to discuss in greater detail these and other interesting questions which have been raised by the proof of the chemical nature of the or-particle.*

* The lecture was illustrated with lantern slides and experiments on the radium emanation.

1. E. Rutherford, Uranium radiation and the electrical conduction produced by it, *Phil. Mag.*, 47 (1899) 116.

2. E. Rutherford and F. Soddy, *Phil. Mag.*, 5 (1903) 106.

3. E. Rutherford and F. Soddy, *Phil. Mag.*, 4 (1902) 582.

4. E. Rutherford and F. Soddy, *Phil. Mag.*, 5 (1903) 453.

5. E. Rutherford, letter in *Nature*, 69 (Aug. 20, 1903).

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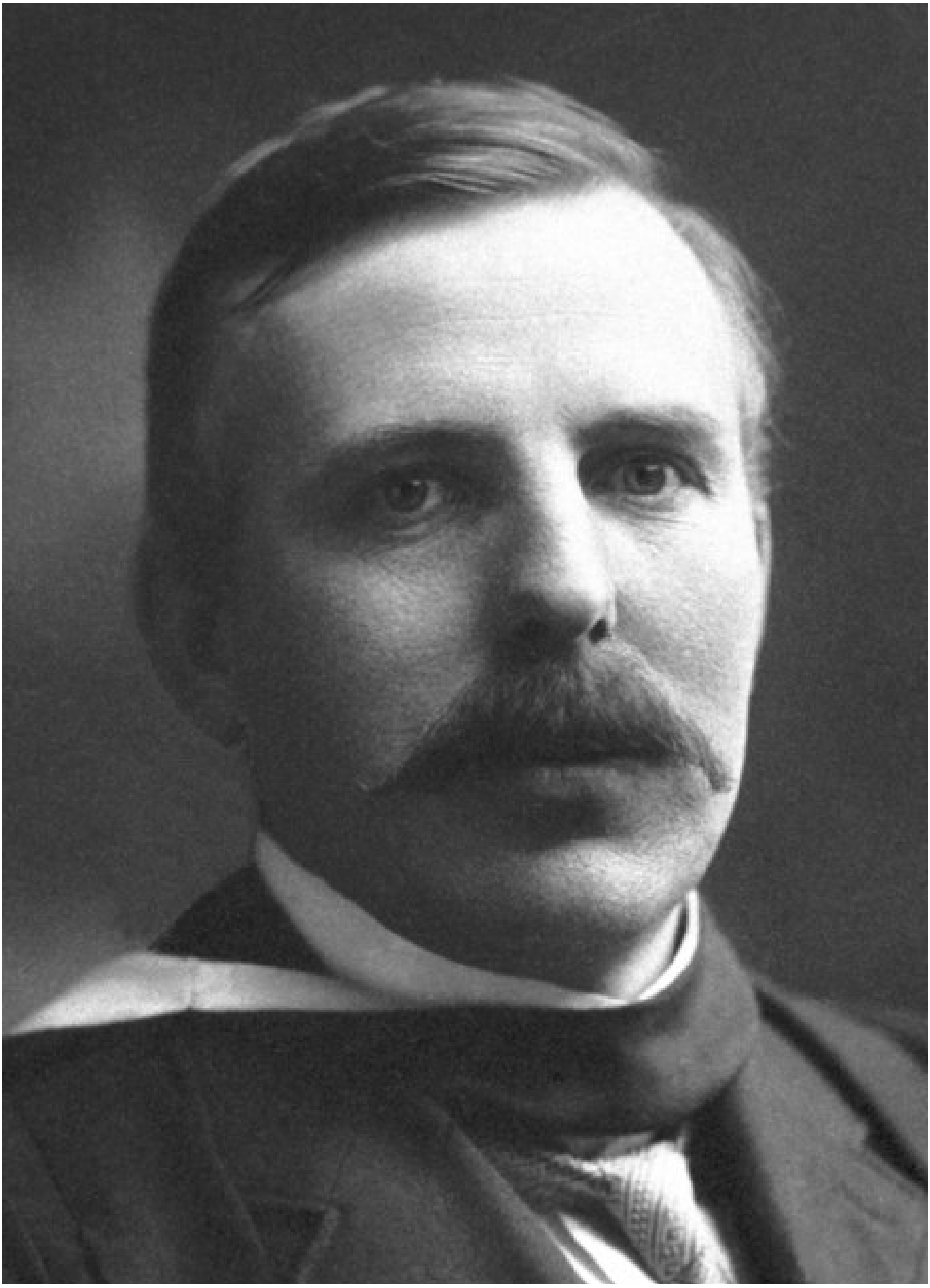

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Ernest Rutherford
The Nobel Prize in Chemistry 1908

Born: 30 August 1871, Nelson, New Zealand

Died: 19 October 1937, Cambridge, United Kingdom

Affiliation at the time of the award: Victoria University, Manchester, United Kingdom

Prize motivation: "for his investigations into the disintegration of the elements, and the chemistry of radioactive substances."

Prize share: 1/1

Work

The discovery of radioactivity in 1896 led to a series of more indepth investigations. In 1899 Ernest Rutherford demonstrated that there were at least two distinct types of radiation: alpha radiation and beta radiation. He discovered that radioactive preparations gave rise to the formation of gases. Working with Frederick Soddy, Rutherford advanced the hypothesis that helium gas could be formed from radioactive substances. In 1902 they formulated a revolutionary theory: that elements could disintegrate and be transformed into other elements.

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