Rutherford and the structure of the nucleus

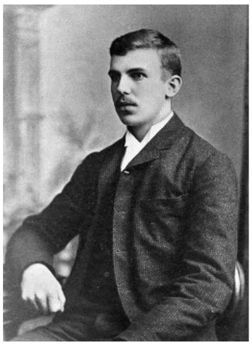
In a lecture to the French Physical Society on 20 April 1922, Sir Ernest Rutherford presented his latest experiments.

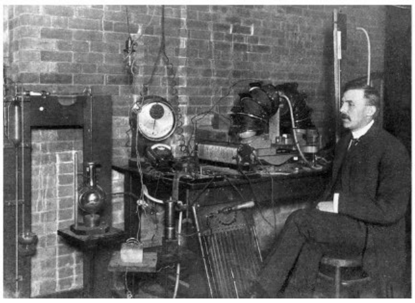
Rutherford begins by summarising current knowledge: each atom has an extremely small, positively charged central nucleus of approximately 10-12 cm in diameter. This contains almost the entire atomic mass and is surrounded by a cloud of electrons about 2x10-8 cm in diameter. The nuclear charge is identical to the atomic number, from 1 for hydrogen to 92 for uranium, and to the number of "planetary" electrons that drive the ordinary chemical properties. Electrons can be torn out temporarily, after which the atom quickly captures a new electron and returns to its original structure, but the nucleus remains unaltered.

He points out that any permanent change in the atom requires breaking the nucleus itself. Unstable, radioactive elements are rare: apart from uranium, thorium and their descendants, only potassium and rubidium show – much less – radioactivity. All other atoms have apparently remained unaltered for billions of years. Radioactivity is a property of the nucleus, manifested by the emission of fast alpha particles (helium nuclei) and sometimes fast electrons. The nuclei of heavy atoms can be seen as assemblies of electrons, hydrogen nuclei and helium nuclei (which are secondary units, each consisting of four hydrogen nuclei and two electrons (1)).

The forces holding the parts of a nucleus together are extremely powerful and much energy is required to break its structure. Among known energy sources, the fast alpha particles emitted by radium and thorium seem to be the most effective, although even they can penetrate heavy nuclei but not break them.

Rutherford stresses that the hydrogen nucleus cannot be broken by collision with an alpha particle: the scintillations produced indicate that hydrogen particles are emitted in different directions and do not correspond to collisions between point-like particles. He concludes that the alpha particle forms a spheroid with axes of 8x10-13 and 5x10-13 cm where forces are extreme. He describes this model as "probably artificial", but one that can provide the probable dimensions of the region where new powerful forces are acting. Similarly, he believes that “ordinary” laws no longer apply at small distances for a collision between a fast alpha particle and a more complex nucleus.





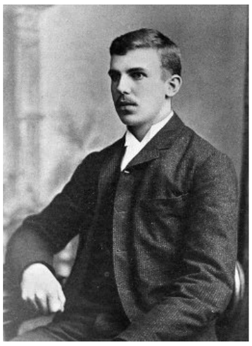
He points out that three or four times as many scintillations are observed when an alpha ray passes through dry air than through gaseous oxygen or carbonic acid, and even more are observed in nitrogen. Therefore, he assumes they are produced by charged hydrogen atoms due to the disintegration of the nitrogen nucleus.

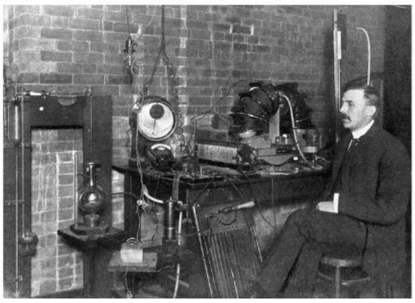
Rutherford then describes his new experimental device that allows the circulation of dried gas, the detection of scintillations on a zinc sulphide screen, and how absorbent mica screens can be inserted, varying the distance between the screen and the radioactive source of radium-C (2). Through successive experiments, he analyses the scintillations caused by alpha rays on dry hydrogen, dry air, oxygen and then metal foils (copper, iron, silver, gold and aluminium). He concludes that the number of scintillations observed for a given absorption depends only on the quantity of hydrogen and not at all on its chemical state, that the particles coming from nitrogen have a path of 40 cm and that aluminium causes strong scintillations with a very long path (90 cm).

Working with his former PhD student, James Chadwick, he then examined particles produced by different elements with paths > 32cm. All elements from Li to S with an atomic mass of less than 40 except the noble gases were studied, as well as some heavier elements in compounds, and metals in foils. They observed scintillations only for nitrogen, fluorine, aluminium and phosphorus, and to a lesser extent for boron and sodium.

Rutherford observes numerous scintillations up to 40 cm for nitrogen (air); up to 20 cm for a mixture of hydrogen and carbon dioxide, far fewer scintillations for dry oxygen; and, for aluminium, relatively numerous released particles capable of long trajectories. The number of scintillations decreases rapidly with the speed of the alpha particles, particularly for aluminium: there, no more scintillations are observed as soon as the speed decreases by 11%. Therefore, he emphasises, alpha particles require minimal energy to tear a hydrogen atom out of the aluminium nucleus. He also notes that particles released by aluminium are projected backwards as well as forwards, contrary to the case for nitrogen; he believes that phosphorus will behave in a similar way.

Rutherford then looks at the nature of the long-range expelled particles. Those from nitrogen behave like fast, positively charged hydrogen atoms. More recent experiments with Chadwick have since confirmed that hydrogen can be torn out of the nuclei of nitrogen, fluorine, phosphorus and aluminium.

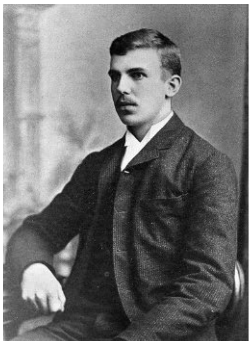


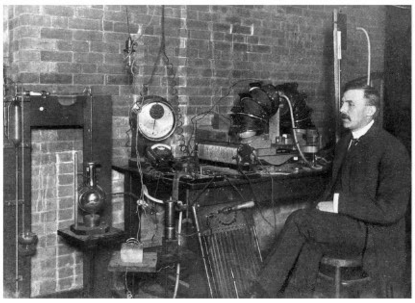


The maximum velocity of the projected hydrogen has been evaluated using the law of proportionality between the velocity of the alpha particles and the cube root of hydrogen's path length. This calculation, confirmed experimentally, shows that the maximum velocity of a hydrogen freed by direct collision with an alpha particle of velocity v is l.6v, while its path in the air is about 28 cm. Rutherford concludes that this maximum velocity is 1.8v for nitrogen (40 cm) and 2.37v for aluminium (90 cm). As an alpha particle gives 64% of its energy to a free hydrogen atom in the direction of collision, he estimates that hydrogens expelled with paths greater than about 56 cm have higher energy than the incident alpha particles. He adds that the disintegration of the nucleus therefore results in an energy gain: part of the hydrogen's energy arises from the disintegrated nucleus, like the energy gain that occurs when an alpha particle exits a radioactive nucleus. Furthermore, alpha particle disintegrations occur on a small scale: only two in a million approach the aluminium nucleus closely enough to free a hydrogen atom. This cannot be detected by ordinary chemical means, but only via scintillations on a zinc sulphide screen.

Moving on to the mechanism of disintegration, Rutherford says the alpha particle (or helium nucleus, mass 4) is considered one of the units of atomic structure. These experiments suggest that hydrogen nuclei could also be structural units because they are only released from elements with atomic masses fitting the formulae (4n + 2) or (4n + 3), n being an integer, and not from "4n" elements such as carbon and oxygen. Thus, in nuclei made of helium and hydrogen nuclei (mass 1), the hydrogen can be released if it is a satellite of the main nucleus and direct collision with an alpha particle provides it with enough energy to escape. They are closer to the main nucleus in aluminium than in nitrogen, and therefore need more energy to escape.

He also suggests a reason why hydrogen is expelled from aluminium in all directions, and with a much lower speed 'backward' than 'forward'. With hydrogen orbiting the central nucleus, its final direction would depend on its position relative to the nucleus when the collision occurs. So, if the nucleus is not in the trajectory of the incident alpha particle, the hydrogen escapes in the direction of that particle but, if the incident particle trajectory is aligned with both the hydrogen satellite and the nucleus, the hydrogen goes around the nucleus, U-turns and then escapes in the opposite direction. Rutherford points out that this assumes that the short-range forces between satellites and nuclei, both positively charged, are attractive ones. This hypothesis is supported by the fact that this change in the sign of the short-range forces explains the stability of the nuclei.





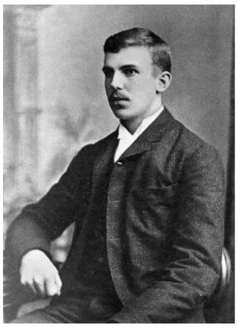
It is difficult to prove that the helium nucleus consists of four hydrogen nuclei and two electrons. Nevertheless, the mass loss of this assembly compared to the sum of its component masses indicates, according to the modern understanding of matter and energy, that the energy of formation of a helium nucleus is more than 3-4 times the energy of the fastest alpha particle emitted from radium. It therefore seems obvious that alpha particles are not able to break helium nuclei, consistent with all experiments to date. In nitrogen, hydrogen could be released by a slow alpha particle because it is not attached to the nucleus as strongly as in helium. The mass of this nuclear hydrogen would then be similar to that of the hydrogen nucleus (1.0077), and the atomic mass of nitrogen, made of three helium nuclei and two hydrogen nuclei, would not be 14.00 but about 14.01. Rutherford concludes that the effective mass of protons in light nuclei probably varies from 1.000 to 1.007 depending on how tightly bound they are.

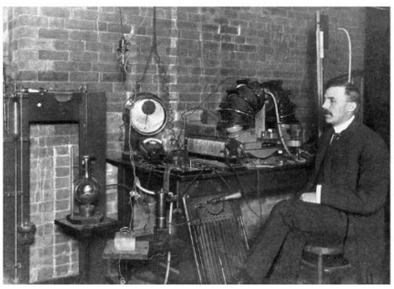
Are other particles freed by alpha rays? Rutherford has already observed brilliant scintillations in nitrogen and oxygen, with a maximum path of 9cm in the air. He first assumed that they were a new kind of alpha rays coming from the radium-C source, and afterwards that they were particles of mass 3 produced within the gases. He now envisages that these particles would indeed arise out of the radioactive source and would be of mass 4. He stresses that further experiments are required to definitively establish the nature of this radiation: perhaps a new transformation of radium-C.

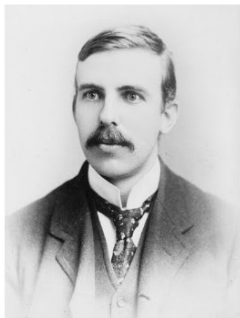
Rutherford's experimental methods prevent him from detecting decays that release short-path alpha particles. However, experiments by a young Japanese visitor Takeo Shimizu at the Cavendish laboratory reveal very clear forks towards the end of the alpha particle's path, although these cannot yet be interpreted.

Rutherford also considers the possibility that alpha particles can sometimes tear a helium atom out of a complex nucleus made up exclusively of helium nuclei, because the forces binding these nuclei are weaker than those binding the hydrogen constituents in the helium nucleus itself. Charged particles of mass 2 or 3 could also be secondary constituents of the nuclei. He has also investigated whether fast beta or energetic gamma rays can produce similar effects, but this is unlikely: hydrogen is not energetic enough to produce scintillations and he believes they are not able to release fast hydrogen from a complex nucleus either.

Looking back at several experiments that claimed a disintegration of ordinary atoms, Rutherford cited Sir William Ramsay's studies of the effect of uranium's alpha rays in which







Ramsay claimed that neon and lithium are obtained from the disintegration of copper. But he is now sure that such a transformation could not have been characterised by the usual chemical methods. Similarly, the formation of helium or hydrogen in a discharge tube was often interpreted as a transformation of aluminium nuclei in the electrodes during intense electrical discharges. However, because of the very high energy required by an alpha particle to produce such transformations, Rutherford favours the hypothesis that these gases were initially within the electrodes.

In conclusion, Rutherford states that only energy sources as concentrated as alpha particles can attack the stable structure of nuclei, and disintegrations rarely occur because only a few alpha particles out of a million are effective. However, charged atoms containing 10x the energy of the alpha particle might penetrate, and perhaps even disintegrate, the nuclear structure of all atoms.

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[1] Neutrons were discovered ten years later, in 1932, by the same James Chadwick who Rutherford mentions here. He was awarded the 1935 Nobel Prize for this discovery.

[2] Radium-C was the name for the element we now know as Polonium 210

Original article:

La désintégration artificielle des éléments, E. Rutherford, Radium (Paris) 3, 133-148 (1922)

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