"Rutherford's experiment" on alpha particles scattering: the experiment that never was

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Abstract

The so-called *Rutherford's experiment*, as it is outlined in many physics textbooks, is a case in point of the flaws around the history at the educational level of one of the decisive event of modern physics: the discovery that the atom has a nucleus. This paper shows that this alleged experiment is a very approximate and very partial synthesis of a series of different particle scattering experiments, starting with that carried out by Rutherford in 1906 and ending with Geiger and Marsden's 1913 experiments.

1. Introduction

As it is well known, school and university physics textbooks often include "a bit of history", either in an introductory chapter or, more often, in scattered references, biographical inserts, or schematics representations of alleged crucial experiments. Although the history of physics might be useful in physics education of students and teachers for a number of reasons, e.g. its power to promote understanding the *nature of science*, to provide scientific clarification of the concepts to be taught and to overcome conceptual difficulties,[1] the standard textbook history is rarely satisfying as an educational tool. Less than accurate accounts of historical episodes, selection biases in the choice of topics, unclear pictures of the theory-experiment relationship are just some of the "crimes" of which textbook history is often guilty.

The *Rutherford's experiment*, as it is outlined in many physics textbooks, is a case in point of the flaws around the history of one of the decisive event of modern physics: the discovery that the atom has a nucleus. Our analysis of the original documents reveals a very different picture, a picture that tells a story far more interesting and instructive than one could expect from distorted textbooks accounts.

2. "Rutherford's experiment"

The development of the nuclear atomic model, by Ernest Rutherford in 1911, is explained in many school and university textbooks, and in many popular science monographs, web sites and blogs, by

referring to the so-called *Rutherford's experiment* (Fig. 1). A beam of alpha particles is made to collide on a gold foil. A circular fluorescent screen, located around the foil, detects the position of the particles after they have been scattered from the foil. Through this experiment it is noted that some particles are deflected to very large angles, even greater than 90 degrees (backscattering). According to these textbook accounts, to explain the large scattering angles Rutherford assumed that the positive atomic charge is concentrated at the center of the atom in an extremely small volume, the nucleus. This model predicts that the electric field is very high near the nucleus and, specifically, it is many orders of magnitude larger if compared to the electric field expected by the then current J.J. Thomson model (where a positive charge is uniformly distributed throughout the atomic volume). According to Rutherford's model, the electric field is able to scatter an alpha particle by a large angle even after one single atomic collision.

Actually, this experiment, as described above, has never been done neither by Rutherford nor by his collaborators. As we will show, the *Rutherford's experiment* outlined by many textbooks is a very approximate and very partial synthesis of a series of alpha particle scattering experiments, starting with that carried out by Rutherford in 1906, which we could define as *the true Rutherford's experiment*, and ending with Geiger and Marsden's 1913 experiments.
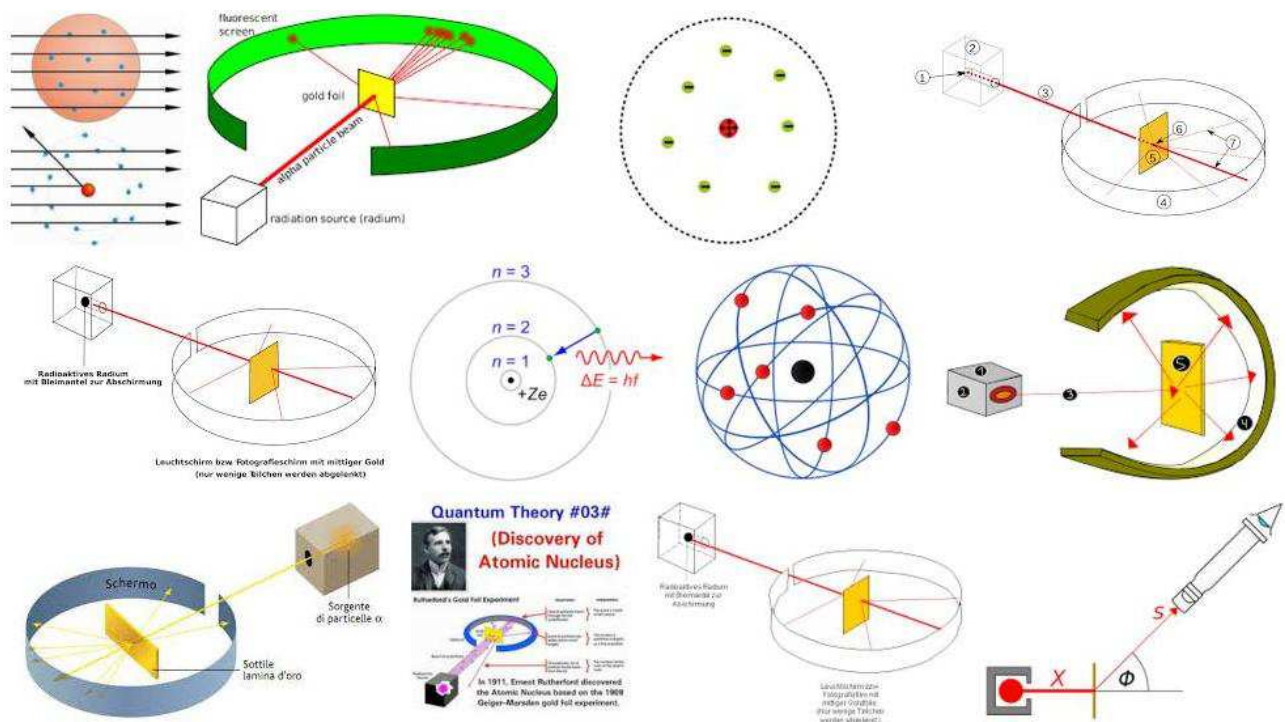
Figure 1. This figure displays the first results of a Google Images search for free-to-use images about "Rutherford's experiment". Analogous schematics are found in most physics textbooks.

3. The real Rutherford's experiment

In 1906, after having studied a number of properties of natural radioactivity,[1] Rutherford directed his research programme to study the interaction of alpha particles with matter by means of a photographic method and soon discovered that when alpha particles pass through matter, some of them are deviated from their original direction of motion and undergo a scattering process [5,6]. Rutherford's apparatus was made of a vessel from which air could be evacuated, to create a vacuum (P), an alpha source (A), a screen with a narrow slit to collimate the beam (B), and a photographic plate to detect the alpha particles (C). The whole experimental arrangement was immersed in a magnetic field (LL), whose sign was reversed every 10 minutes (Fig. 2). The exposure time was 2 hours.
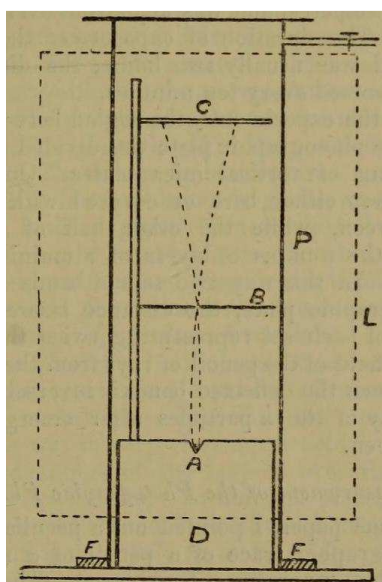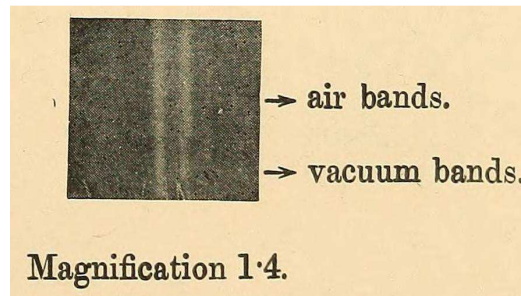

Figure 2. The real Rutherford's experiment [6]

Rutherford discovered that the image of the slit produced by the alpha particles beam had sharply defined edges when the experiment was performed in a vacuum. If, on the contrary, air was admitted into the apparatus, or if the slit was covered with a thin sheet of matter (a screen of mica, 3×10^{-3} cm thick), the photographic trace of the pencil of α rays was broadened and the

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[1] In 1898 he discovered that the radiation emitted by Uranium is made of "at least two distinct types of radiation": "one that it 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" [3]. The following year he discovered that the β radiation is made of electrons. As for the α radiation, in 1903-1904 he discovered the alpha particles are very fast (about 2.5 x 10^9 cm/s) and very heavy (the charge/mass ratio was estimated to be 6 x 10^3 u.e.m., i.e. about half the charge/mass ratio of H^+) positively charged particles. He was awarded the 1908 Nobel Prize in Chemistry "*for his investigations into the disintegration of the elements, and the chemistry of radioactive substances*".

intensity of the photographic effect faded off slowly on either side of the centre (Fig. 3). As it was concluded by Rutherford: "the greater width and lack of definition of the air-lines […] show evidence of an undoubted scattering of the rays in their passage through air" [5, p. 174].

Figure 3. Rutherford's discovery of the alpha particles scattering by air [5]

After this experiment, that for the first time proved the existence of the scattering of alpha particles, Rutherford no longer worked on this specific subject, but continued to deal with nature and properties of alpha particles.

As Rutherford later recalled, "a detailed examination of the amount and character of the scattering of the α particles in passing through matter was first made by [Hans] Geiger"[16, p. 191], young Rutherford's Ph.D student at the University of Manchester, later assisted by Ernest Marsden, still an undergraduate student under Rutherford's guidance.

The great leap in quality of Geiger's and Geiger and Marsden's experiments was due to the introduction of a much more precise method for detecting the particles, the scintillation method. It was based on an effect first discovered by William Crookes [3] and by Julius Elster and Hans Geitel [4] in 1903: if a small crystal of phosphorescent zinc sulphide (ZnS) is exposed to alpha rays and is observed with a magnifying glass, scintillating points of light are briefly observed over the surface of the crystal. Erich Regener was the first to devise, in 1908, a quantitative method to detect and count alpha particles out of this effect by means of a microscope of suitable magnification and aperture [7].
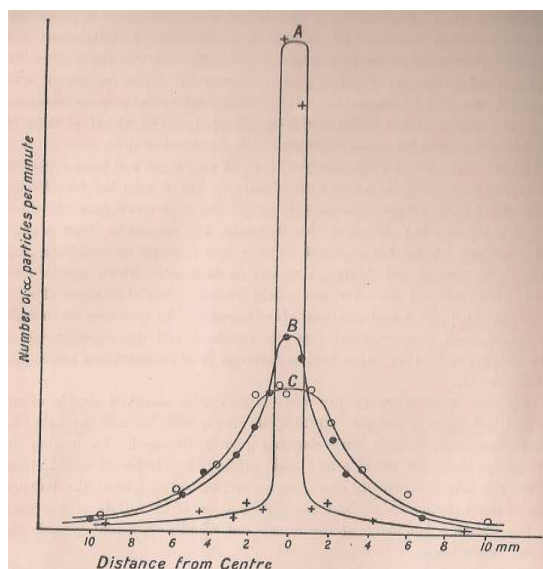
4. Geiger's 1908 experiment

In 1908, Geiger made the first attempt to determine the magnitude of the scattering of the alpha particles in passing through matter by using the scintillation method and Regener's method of counting scintillations. The main part of Geiger's apparatus consisted of a glass tube about 2 meters in length and 4 cm in diameter. The alpha particles from a strong source of "radium emanation"

(i.e. gas radon) placed at R passed through a narrow slit S and produced an image of this slit on a phosphorescent screen Z, cemented to the end of the glass tube. The numbers of scintillations at different points of the screen were counted directly by means of a suitable microscope M, of 50 times magnification (Fig. 4) [8].
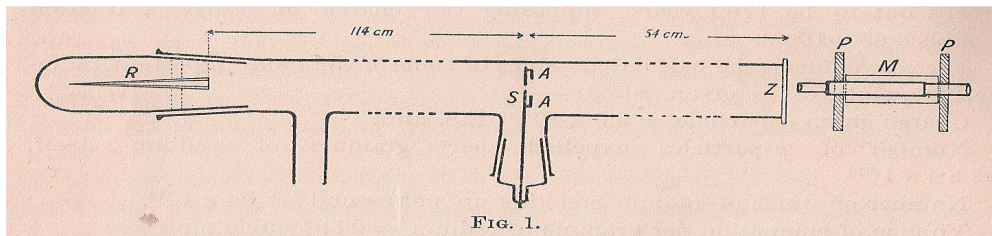
Figure 4. Geiger's 1908 apparatus [8]

By this apparatus Geiger discovered that, if the tube was exhausted, "hardly any scintillations were observed outside of the geometrical image of the slit". On the contrary, by "allowing a little air into the tube, the area where scintillations were observed greatly increased". Similar results were obtained if the tube was exhausted and if the slit were covered with leaves of gold or aluminum (put into a slide AA connected with the slit S). The curve A in Fig. 5 shows the distribution of the scintillations in a vacuum. The curve B shows the effect if the slit is covered with one gold leaf: the area over which the scintillations were observed was much broader. The curve C shows the effect of two gold leaves together.

Figure 5. Distribution of particles in a vacuum (curve A), with one gold leaf (B) and with two gold leaves (C) obtained with Geiger's 1908 apparatus [8]

According to Geiger, this experiment provides a direct confirmation that alpha particles are scattered by matter and that this scattering can also reach an appreciable angle:

> The observations just described give direct evidence that there is a very marked scattering of the α-rays in passing through matter, whether gaseous or solid. It will be noticed that some of the α-particles after passing through the very thin leaves - the stopping power of one leaf corresponded to about 1 mm. of air - were deflected through quite an appreciable angle [8, p. 177].

5. Geiger and Marsden's "surprising" result (1909)

Though "appreciable", the scattering suffered by alpha particles was nonetheless limited to a small angle: a few mm of broadening vs. a 54 cm distance between S and Z (Fig. 3). However, less than one year later, Geiger and Marsden reported a striking discovery. Inspired by the recent observation of Heinrich Willy Schmidt [9], that when beta particles fall on a plate, a strong radiation emerges from the same side of the plate as that on which the beta particles fall, Geiger and Marsden wondered if the same could be true also for the alpha particles. The previous experiments carried out by Rutherford [5,6] and Geiger [8] made this possibility unlikely:

> For α-particles a similar effect has not previously been observed, and is perhaps not to be expected on account of the relatively small scattering which α-particles suffer in penetrating matter [10, p 495].

Yet, Geiger and Marsden found "conclusive evidence […] of the existence of a diffuse reflection of the α-particles". A small fraction of the α-particles falling upon a metal plate, they discovered, have indeed their directions "changed to such an extent that they emerge again at the side of incidence" [10, p. 495]. Their apparatus consisted in: an alpha particle source (radium active deposit on plate A), a platinum reflector (R) of about 1 cm^2 area, a ZnS screen (S). The arrangement was such that the alpha particles arriving on S did not come directly from A, but had to be backscattered from R (Fig. 6).
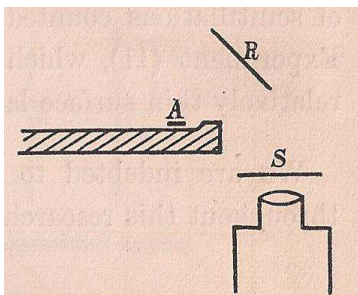
Figure 6. Experimental arrangement of Geiger and Marsden experiment [10]

By this experiment Geiger and Marsden discovered "that of the incident α-particles about 1 in 8000 was reflected". Besides this, by studying the relative amount of reflection from a metal of varying thickness, they also discovered that the backscattering "is not a surface but a volume effect" and that this effect "is confined to a relatively thin layer" such as to require the presence within the atom of very intense forces:

> about half of the reflected particles were reflected from a layer ,equivalent to about 2 mm. of air. If the high velocity and mass of the α-particle be taken into account, it seems surprising that some of the α-particles, as the experiment shows, can be turned within a layer of 6 x 10^{-5} cm. of gold through an angle of 90°, and even more. To produce a similar effect by a magnetic field, the enormous field of 10^{9} absolute units would be required [10, p. 498].

6. Geiger's 1910 experiment: the multiple scattering mechanism does not work

Nine months later, Geiger, alone again, published the results of his work undertaken with the goal of obtaining "a quantitative measurement of the scattering by determining the most probable angle through which an α-particle of definite range is turned by passing through a given thickness of matter" [11, p. 492]. Since the amount of α-particles scattered is comparatively small, Geiger understood that accurate measurements "could only be obtained […] by the use of a very narrow beam of α-particles" [11, p. 492]. Consequently, it was necessary to employ "a very small and intense source" [11, p. 492]. Although the source used in his previous experiments, i.e. a tube filled with gas radon, fulfilled the condition of being intense and narrow, its radiation was not homogeneous because of the different α-ray products originating from it and because of the absorption by the gas inside the tube. To overcome this difficulty, Geiger modified its apparatus in such a way that the radiation source consisted mainly of a single product of decay of gas radon, deposited on the conical glass tube A (Fig. 7).

From this experiment, Geiger found that for small thicknesses of gold the most probable angle of scattering increases at a rate proportional to the square root of the thickness of matter traversed (Fig. 8), in agreement with the theory of multiple scattering, according to which the scattering of a beam of particles through a thin metal layer is due to many little scatterings due to each atom traversed.
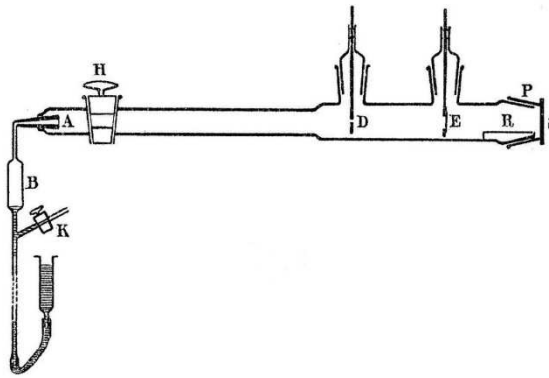
Figure 7. Experimental arrangement of Geiger experiment [11]
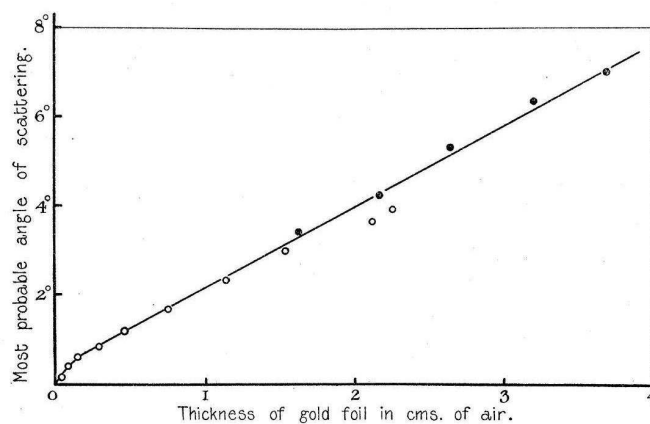
Figure 8. Most probable angle of scattering [11]

Upon the basis of these new data it was possible to arrive at an interpretation of the previous Geiger and Marsden's results on the alpha particles backscattering (1 out of 8000 alpha particles reflected of an angle larger than 90° by a gold layer of thickness equivalent to 5 mm. of air). According to fig. 8, the most probable angle of scattering Φ in Geiger and Marsden's experiment (thickness of gold equivalent to 5 mm of air) was about 1°. A simple calculation, assuming the ordinary probability law, shows, as remarked by Geiger, that the probability of an α-particle being scattered through an angle exceeding 90° "is extremely small, and of a different order from that which the reflection experiment suggests" [11, p. 500], i.e. 1 out 8000 alpha particles. According to the law of probability, the probability that an alpha particle was scattered of angle β larger than 90° was indeed exp $(-\beta^2/\Phi^2)$. The expected probability was therefore vanishingly small (8×10^{-40}). Geiger's analysis demonstrated that the standard interpretation, based on the multiple scattering theory, did not work for large angles of scattering. However, according to Geiger "it does not appear profitable at present to discuss the assumption which might be made to account for this difference". A different mechanism was required. But this problem was left to Rutherford.

7. Rutherford's theory of atomic nucleus (1911)

In view of the impossibility of reconciling large angles of scattering of alpha particles with the theory of multiple scattering, Rutherford suggested in 1911 a new theory of scattering based on the assumption that the large angle of scattering are due to a single atomic collision. A brief account of this theory was first communicated by Rutherford to the Manchester Literary and Philosophical Society at the 7 March 1911 ordinary meeting of the society [12]. A full account of this theory was later submitted by Rutherford to the Philosophical Magazine in April 1911 [14]. According to Rutherford:

> It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter, for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter [14, p. 669].

Rutherford suggested therefore that the atom consists of a central charge supposed concentrated at a point, and that the large single deflexions of the α particles are mainly due to their passage through the strong central field.[2] According to this model, the atom is composed of a small, centrally located, positively charged nucleus surrounded by a sphere of equal but uniformly distributed negative charge whose effect on the scattering of the particles is negligible. The orders of magnitude for the nuclear radius is about 10^{-12} cm, and for the whole atom about 10^{-8} cm [14]. On Rutherford's theory of single scattering, the number of α particles scattered back by different foils containing the same number of atoms should be proportional to A^2, where A is the atomic weight of the radiator [14, p. 681]. This expectation was in good agreements with previous Geiger and Marsden's data about the number of scintillations using scattering materials of different atomic weight [10, p. 497].

In Rutherford's model, if E, m and u be the charge, mass and initial velocity of an alpha particle, Q be the total number of alpha particles falling on the scattering material, Ne be the central charge of the scattering atom and if n is the number of atoms per unit volume of the material, the number y of particles scattered to unit area of the ZnS screen placed at an angle Φ to the original direction of the particles is given by

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[2] With hindsight we know that, by Rutherford's model of central nucleus, the maximum electric field at the surface of a nucleus of gold was 2.3 x 10^{22} N/C. On the contrary, the maximum field in the then accepted Thomson's model of atom (supposed to consist of a number of negatively charged corpuscles, accompanied by an equal quantity of positive electricity uniformly distributed throughout a sphere), was nine order of magnitude lower (1.1 x 10^{13} N/C).

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

Since $b = \frac{2NeE}{mu^2}$, on Rutherford's theory the number of alpha particles per unit area at a given distance r from the point of scattering is proportional to $\cosec^4(\Phi/2)$ (or $1/\Phi^4$ if Φ is small), to t (thickness of scattering material provided this is small), to the square of the charge of nucleus Ne, and is inversely proportional to the fourth power of velocity if m be constant.

So much for Rutherford's model of single scattering. The general correctness of it remained to be experimentally confirmed.

## 8. Geiger's preliminary experimental test of the nuclear theory (1911)

A first preliminary corroboration of Rutherford's theory was reported by Geiger to the Manchester Literary and Philosophical Society on 7 March 1911, i.e. the very same day of Rutherford's brief account of his theory to the same learned society [13]. As reported by Geiger:

> [The] fraction of the α particles scattered through various angles by a thin gold foil has been experimentally determined by the scintillation method. […] The microscope to which the zinc sulphide screen was attached moved round the arc of a circle; the distance between the scattering material and the screen was constant and equal to about 2 cms. […] The number of α particles scattered through large angles up to 150° was first measured […]. The actual number of particles observed varied very approximately as $\cosec^4\varphi/2$ where φ is the angle of deflection. This is the relation theoretically deduced by Professor Rutherford in the foregoing paper [13, p. xx-xxi].

This apparatus is very similar to the one usually described as "Rutherford's experiment" (see section 2 above), the main difference being the fact that in Geiger's version the ZnS screen moves around the gold foil up to 150°, while most textbooks show the detector in Rutherford's experiment as a fixed full circle screen, and so are plainly wrong.

9. Geiger and Marsden's conclusive experimental tests of the nuclear theory (1913)

Later, Rutherford's theory was tested point by point by a series of experiments carried out by Geiger and Marsden as reported in their joint 1913 paper [15]. In analogy with Geiger's preliminary experiments, Geiger and Marsden used a rotating platform (A) to observe the alpha particles scattered by F in different directions by the ZnS screen S (Fig. 9). Observations were taken for angles of scattering between 5° and 150°.
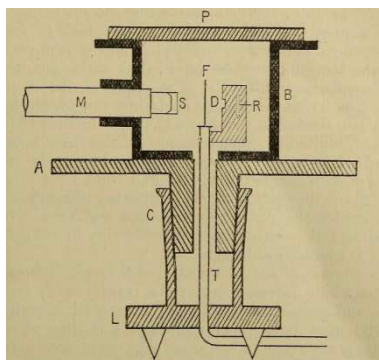
Figure 9. Geiger and Marsden's apparatus to test Rutherford's theory [15]

By suitably modifying this apparatus, Geiger and Marsden studied also how the scattering depends on the thickness of material, on its atomic weight, and on the velocity of the alpha particles. They found that the number of alpha particles emerging from a scattering foil at an angle Φ with the original beam varies as $\text{cosec}^4 (\Phi/2)$ and is directly proportional to the thickness of the scattering foil. Furthermore, the amount of scattering is found to be proportional to the square of the atomic weight and to the inverse fourth power of the velocity of the incident alpha particles. In short,

> all the results of our investigation are in good agreement with the theoretical deductions of Prof. Rutherford, and afford strong evidence of the correctness of the underlying assumption that an atom contains a strong charge at the centre of dimensions, small compared with the diameter of the atom [15, p. 606].

Rutherford was aware that this model of atom was unstable but chose to ignore this difficulty for the time being. For Rutherford, "the question of the stability of the atom proposed need not be considered at this stage, for this will obviously depend upon the minute structure of the atom, and on the motion of the constituent charged parts" [14, p. 671].

Indeed the way out of this difficulty required a quantum mechanical interpretation, then emerging. In the same year of Geiger and Marsden's experiments (1913), Bohr succeeded in ensuring the stability of Rutherford's model within quantum mechanics and the idea of an atomic nucleus quickly obtained total acceptance in the scientific community.

Conclusions

As we have seen, Rutherford's establishment of the nuclear model of the atom in 1911 had a lengthy and complex history. Although Rutherford was the great protagonist of this story, Geiger played a prominent role that deserves to be valued and recognized.

Though including some simplified history of physics in physics teaching, particularly for secondary school students, has some merits at the meta-cognitive level and it is indeed almost inevitable, a

misleading "pseudo-history" [1] does a disservice to students since it does not fully exploit the power of history for developing the key competences in the school curriculum.

The usual practice of reducing everything to an alleged *Rutherford's experiment*, has indeed a number of negative implications. First, by taking an experiment out of context and by neglecting its origins, this approach does not contribute to a fuller understanding of physics. Actually, this practice cancels seven years of history around a epochal turning point in physics, the hypothesis of an atomic nucleus. Second, this practice trivialises the relationship between theory and experiment, thus giving a distorted image of the nature of science. Finally, by a caricature portrait like *Rutherford's experiment*, physics education misses a good opportunity to show students that the path of physics is not always straightforward.

References

[1] Matthews M 2015 *Science Teaching: The Contribution of History and Philosophy of Science*, 2nd edition (Rutledge: New York)

[2] Rutherford E 1899 Uranium radiation and the electrical conduction produced by it *Phil. Mag. 47*, 109-163

[3] Crookes W 1902 The emanations of Radium *Proc. Roy. Soc. Lond.*, 71, 405-408

[4] Elster J and Geitel H 1903 Über die durch radioactive emanation erregte scintillierende phosphoreszenz der sidot-blende *Phys. Zeit.* 4, 439-40

[5] Rutherford E 1906 Some properties of the α rays from Radium *Phil. Mag.* Series 6, 11, 166-176

[6] Rutherford E 1906 Retardation of the α particle from Radium in passing through matter *Phil. Mag.* Series 6, 12, 134-146

[7] Regener E 1908 Über Zählung der α-Teilchen durch die Szintillation und die Grösse des elektrischen Elementarquantums *Verhandlungen der deutschen physikalischen Gesellschaft zu Berlin*, 10, 78-83

[8] Geiger H 1908 On the scattering of the α-particles by matter *Proc. Roy. Soc. Lond.* Series A, 81, 174-177

[9] Schmidt H W 1908 Bericht über den Durchgang der β-Strahlen durch feste Materie *Jahrb. d. Radioaktivität u. Elektronik* 5, 451-492

[10] Geiger H and Marsden E 1909 On a diffuse reflection of the α-particles *Proc. Roy. Soc. Lond.* Series A, 82, 495-500

[11] Geiger H 1910 The scattering of the α-particles by matter *Proc. Roy. Soc. Lond.* Series A, 83, 492-504

[12] Rutherford E 1910-11 The scattering of the α and β rays and the structure of the atom *Manchester Lit. & Phil. Soc.* 55, xviii-xx

[13] Geiger H 1910-11 The large scattering of the α particles *Manchester Lit. & Phil. Soc.* 55, xx-xxi

[14] Rutherford E 1911 The scattering of α and β particles and the structure of the atom *Phil. Mag.* Series 6, 21, 669-688

[15] Geiger H and Marsden E 1913 The laws of deflexion of α particles through large angles *Phil. Mag.* Series 6, 25, 604-623

[16] Rutherford E, Chadwick J and Ellis C D 1930 *Radiation from radioactive substances* (University Press: Cambridge)