

Original Paper

The Role of Models in the Discovery of the Nucleus:

Ernest Rutherford and his School

Andrea Durlo^{1*}

¹ Italian Group of History of Physics, Italy

* Andrea Durlo, Italian Group of History of Physics, Italy

Received: May 19, 2020

Accepted: May 30, 2020

Online Published: June 7, 2021

doi:10.22158/eshs.v2n2p21

URL: <http://dx.doi.org/10.22158/eshs.v2n2p21>

Abstract

Ernest Rutherford is remembered as the scientist who proposed a planetary atomic model that would overcome the atomic structure of the early 20th century, proposed by J.J. Thomson, and based on a volume of positive charge within which the negative charge was considered to be uniformly distributed. Reading Rutherford's original paper published in 1911—allows us to compare the models of these two physicists and discuss the concept of the model itself.

Keywords

rutherford, bohr, atom model, α particles, history of physics, epistemology

1. Introduction

From the beginning of civilizations, curiosity has driven Man to investigate himself and Nature, and the principal means of tracing the why of things has very often been to “enter”, physically or through speculation and conjecture, into them. The atom has been no exception; ever since it was first defined by Leucippus, Epicurus, Democritus and Titus Lucretius Carus, it has been the ultimate term of investigation of matter in Man’s quest to unlock its secrets.

What atoms are and how they are made up are two questions that particularly marked the history of science between the end of the nineteenth century and the beginning of the twentieth, not only as simple questions whose purpose was to provide answers that would enhance experience, but above all to broaden the intellectual horizon, suggest new combinations of concepts and embark on untried experimental paths.

In Science and Physics, moreover, the role of models has always been very important in reconstructing phenomena and their properties through known structures and relationships. Models have the task of recreating correspondences between a natural object and an artificial one, but also of structuring a set

of relations that describe—usually in the language of mathematics—the relations that exist between the elements that constitute an object and the description of it in formal terms. The model thus becomes a simplified version of reality that allows certain structural and functional relations to be isolated.

2. Ernst Rutherford: Notes about the Man

“In science there is only physics: all the rest is stamp collecting”. Lord Kelvin Ernest Rutherford is remembered in manuals as the one who, thanks to a solar system atomic model, was able to overcome J. J. Thomson’s vision of an atom made up of a positive charge diffused in a spherical volume and within which the negative charge was dispersed.

However, to notice how behind the new idea of the atomic model a figure of absolute prominence stands, both as a scientist and as a man, we only need to recall what Niels Bohr said about him.

«Although Rutherford was always intensely occupied with the progress of his own work, he had the patience to listen to every young man, when he felt he had any idea, however modest, on his mind. At the same time, with his whole independent attitude, he had only little respect for authority and could not stand what he called “pompous talk”. On such occasions he could even sometimes speak in a boyish way about venerable colleagues, but he never permitted himself to enter into personal controversies, and he used to say: “There is only one person who can take away one’s good name, and that is oneself!” (Bohr, 1963)»

In 1913, Bohr himself sent Rutherford a memoir, drafting his first work on the atomic constitution and his quantum theory; Bohr fondly recalls that the response was not long in coming and could not be ignored, neither from a scientific nor from a human point of view.

«Dear Dr. Bohr, I have received your paper safely and read it with great interest, but I want to look over it again carefully when I have more leisure. [...] There is one criticism of minor character which I would make in the arrangement of the paper. I think in your endeavour to be clear you have a tendency to make your papers much too long, and a tendency to repeat your statements in different parts of the paper. [...] I do not know if you appreciate the fact that long papers have a way of frightening readers, who feel that they have not time to dip into them. [...] I shall be very pleased to see your later papers, but please take to heart my advice, and try to make them as brief as possible consistent with clearness [ibidem].»

These words give an idea of the human depth behind the scientist; Bohr himself recalls how Rutherford – as well as holding his learned colleagues in high esteem—took to heart all the young physicists who had the opportunity to work with him, whether for short or long periods. Rutherford, who would never claim for himself the authorship of someone else’s work, always seemed to be able to guess where the talent was: an inexhaustible source of encouragement and strength, eleven Nobel Prize winners would emerge from his school.

3. The Model Issue

“Making a comparison between a piece of machinery and its model is like going to a restaurant to eat the menu”. Anonymous

The full reading of Ernest Rutherford’s article “LXXIX. The scattering of α and β particles by matter and the structure of the atom”, as published in *Philosophical Magazine Series 6*, 21:125, 669–688, is absolutely fundamental to understand the importance of the concept of model.

What immediately strikes the reader is the complexity of the writing and the number of ad hoc hypotheses that are invoked from time to time as needed. At the same time, Rutherford is able to establish some remarkable symmetries (p. 671):

«[...] It will be shown that the main deductions from the theory are independent of whether the central charge is supposed to be positive or negative. For convenience, the sign will be assumed to be positive (Rutherford, 1911).»

and he confirms them at the end of his dissertation (p. 688):

«The deductions from the theory so far considered are independent of the sign of the central charge, and it has not so far been possible to obtain definite evidence to determine whether it be positive or negative [ibidem].»

while he does not seem to be overly concerned about handling a stable model for his atom, at least not right away (p. 671):

«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 [ibidem].»

Nor does he seem to bother citing atomic models that have already been disproved or statements that proved not to be true (p. 688):

«It is of interest to note that Nagaoka has mathematically considered the properties of a “Saturnian” atom which he supposed to consist of a central attracting mass surrounded by ring of rotating electrons. He showed that such a system was stable if the attractive force was large [ibidem].»

Reading the original Rutherford’s text allows a comparison to be made between J.J. Thomson’s atomic model, cited by Rutherford in his paper as a point of comparison, and that of the New Zealand physicist himself; from the step-by-step analysis of the article it was possible to draw the following considerations.

The analysis of the hypotheses at the basis of the models proposed by Thomson and Rutherford reveals an anti-symmetry between the issues considered essential by one and the other scientist, as if different eyes were looking at the same experimental data to interpret them in the light of their own ideas.

The aspect that is untouchable for Thomson, the stability of the atomic nucleus in terms of Classical Mechanics, turns out—as already illustrated—to be unnecessary for Rutherford; for the latter, instead, the behaviour of α particles is of fundamental importance, a behaviour that Rutherford leads back to

the presence of a central nucleus, in accordance with his own hypothesis.

We would like to point out that the question of the α radiation was particularly dear to Rutherford; Rutherford himself said, on the occasion of the fragmentation of lithium nuclei by proton bombardment, which he carried out together with Cockcroft and Walton in 1932:

«Those scintillations look mighty like alpha-particle ones. I should know an alpha particle scintillation when I see one for I was in at the birth (Reeves, 2008).»

The question then arises of how to reconcile the phenomenon of scattering of large- and small-angle α and β particles according to the two models we have proposed to examine. For example, the large-angle scattering of α particles, which is fundamental in Rutherford's modelling of a central massive nucleus atom, is in fact an anomaly in Thomson's model, which does not agree with this phenomenon (p. 670):

«The theory of Sir J.J. Thomson is based on the assumption that the scattering due to a single atomic encounter is small, and the particular structure assumed for the atom does not admit of a very large deflexion of an α particle in traversing a single atom (Rutherford, 1911).»

The anomaly in Thomson's model could be explained by introducing forces of a different nature where the Coulombic interaction loses its validity: in this way it would be possible to safeguard the model according to the framework of Classical Mechanics. On the contrary, the scattering of the β particles becomes a phenomenon that can be adapted to both models: according to Thomson, the deflection is not appreciable, according to Rutherford, observable results would be obtained only if the atom were surrounded by thousands of electrons.

A fundamental difference between Thomson's and Rutherford's atomic description is the estimation of a measurable atomic radius of the order of 10^{-10} m, which Rutherford does not introduce.

The lack of a radius, that is the impossibility to obtain dimensionally a length with the quantities involved in the "planetary" modelling, makes the model irreconcilable with the laws of Classical Physics (an electron in motion on an orbit like the one proposed by Rutherford radiates energy, causing the inevitable collapse of matter).

Describing matter according to the planetary model leads to serious difficulties intrinsic to the instability of the electron system, difficulties which did not appear according to the model proposed by Thomson.

Thus, the fundamental difference between Thomson's model and Rutherford's model is that the forces which Thomson says act on the electrons make possible certain electronic configurations and movements of the electrons, at which the system is in stable equilibrium: there are no such considerations in the Rutherford model. In other words, the character of the difference is more marked if we consider that among the quantities that refer to the first atom there is one, the radius of the positive sphere, which has the dimensions of a length and the same order of magnitude of the linear dimensions of the atom: this length does not appear among the quantities that characterise the second

model; it is not possible to go back to the length of the radius of the Rutherford model only through the masses and charges of the electrons and of the positive nucleus.

Only a little later, it will be Niels Bohr to reconsider this fundamental point, neglected by Rutherford in the exposition of his structure of the atom, and to establish the measure of a radius through Planck's constant, proving that the relation:

$$\sqrt{\frac{h^2}{mke^2}} \quad (3.1)$$

has the physical dimensions of a length.

This is the opening passage of his 1913 publication, and it is also interesting in virtue of the fact that it is, somehow, an "incipit" in dimensional terms of the quantities involved in the dissertation. Minus a factor of 4π that we would expect in the denominator, the numerical value obtained is about 20\AA , a generic order of magnitude of atomic dimensions. Bohr also realised that there must necessarily be a link between h and the structure of the atom itself, which is why h should appear in all equations relating to this structure.

«[...] the electron will approach the nucleus describing orbits of smaller and smaller dimensions, and with greater and greater frequency; the electron on the average gaining in kinetic energy at the same time as the whole system loses energy. This process will go on until the dimensions of the orbit are of the same order of magnitude as the dimensions of the electron or those of the nucleus. A simple calculation shows that the energy radiated out during the process considered will be enormously great compared with that radiated out by ordinary molecular processes. It is obvious that the behaviour of such a system will be very different from that of an atomic system occurring in nature. In the first place, the actual atoms in their permanent state seem to have absolutely fixed dimensions and frequencies. Further, if we consider any molecular process, the result seems always to be that after a certain amount of energy characteristic for the systems in question is radiated out, the systems will again settle down in a stable state of equilibrium, in which the distances apart of the particles are of the same order of magnitude as before the process. [...]

The way of considering a problem of this kind has, however, undergone essential alterations in recent years owing to the development of the theory of the energy radiation, and the direct affirmation of the new assumptions introduced in this theory, found by experiments on very different phenomena such as specific heats, photoelectric effect, Röntgen &c. The result of the discussion of these questions seems to be a general acknowledgment of the inadequacy of the classical electrodynamics in describing the behaviour of systems of atomic size. Whatever the alteration in the laws of motion of the electrons may be, it seems necessary to introduce in the laws in question a quantity foreign to the classical electrodynamics, i. e., Planck's constant, or as it often is called the elementary quantum of action. By the introduction of this quantity the question of the stable configuration of the electrons in the atoms is essentially changed as this constant is of such dimensions and magnitude that it, together with the mass

and charge of the particles, can determine a length of the order of magnitude required (Bohr, 1913).»

If we now make a comparison between Rutherford's and Bohr's models, we will observe that the introduction, in the calculation, of the "quantum of action" will allow Bohr to state that each emission or absorption of radiation by the atom is an individual process accompanied by a transfer of energy:

$$h\nu = hcR \left(\frac{1}{n_2^2} - \frac{1}{n_1^2} \right) \quad (3.2)$$

For the Rutherford atom we should not even expect a line spectrum, since, according to ordinary electrodynamics, the frequencies of radiation accompanying the electronic motion would change continuously with the energy emitted (Bohr, 1963).

Far from wishing to exhaust the whole theory of Bohr's model here, it is worth emphasising how—among the stumbling blocks it has allowed to be overcome—it also allows a visualisation of the atom as a small Copernican system, to some extent compatible with the classical conception. It overcomes, in this way, a sort of "horror vacui" of the mind, linked to the necessity of a graphic model of an imagination linked to classical connotations: it was possible to visualise the electrons on their stationary orbits as a Copernican system.

4. In Memoriam

We conclude this paper with the obituary Niels Bohr wrote in the 18 December 1937 supplement of the journal *Nature*. Bohr's words give a good description of Rutherford as a researcher, but at the same time underline the deeper aspects of his personality.

«I am thankful for the invitation of the Editor of *Nature* to write a few words about my relations with Lord Rutherford that have been so decisive for my work and have filled so large a place in my life. Indeed, neither in the short article about Rutherford's relationship to his pupils, which I had the pleasure of contributing to the Cavendish Laboratory Supplement to *Nature* of December 19, 1926, nor in the short tribute to Rutherford's memory, which I had the sad duty of giving at the Galvani Congress in the announcement of his untimely death and which appeared in *Nature* of October 30, 1973, did I find opportunity to give a proper expression of my personal indebtedness to him, who was to me everything that an inspiring leader and a fatherly friend could be.

From the moment I was admitted into the group of students from very different parts of the world working under Rutherford's guidance in his laboratory in Manchester, he has to me appeared as the very incarnation of the spirit of research. Respect and admiration are words too poor to describe the way his pupils regarded the man whose discoveries were the basis of the whole development in which they were enthusiastically striving to partake. What we felt was rather a boundless trust in the soundness of his judgement, which, animated with his cheerfulness and good will, was the fertile soil from which even the smallest germ in our minds drew its force to grow and flourish. His simplicity and disregard of all external appearance perhaps never disclosed themselves more spontaneously than in

discussion with his students, who were through his straightforwardness even tempted in youthful eagerness to forget with whom they were talking until, by some small remark, the point of which they first fully understood after they left him, they were reminded of the power and penetration of his insight.

The stimulus Rutherford gave his pupils was, however, in no way limited to times of daily intercourse. Thus when, returned to Denmark, I pursued the line of work which I had taken up in Manchester, it was to me a most encouraging feeling to know that I could always count on his warm interest and invaluable advice. Indeed, looking through our correspondence from those days, I can hardly realize how in the midst of all his work he could find time and patience to answer in the kindest and most understanding way any letter with which a young man dared to augment his troubles. Especially close our relations became during my stay for the first years of the Great War as lecturer in Manchester and when, in times of full anxieties, he kept up the spirits of the small group left in the laboratory and, in the short moments of leisure from the great practical duties entrusted upon him, steadily went on preparing the road to new discoveries which should soon lead to such great results.

In later years, it was each time to me the greatest source of renewed encouragement to visit him in his home in Cambridge, where, in spite of never-ceasing work and ever heavier burden of duties, he shared so quiet and simple a life with the companion who, always in contact with what was deepest in his character, from early days stood by him in every joy and sorrow. With age the vigour of his spirit did not abate, but found outlet in every new ways, and his genial understanding and sympathy with all honest human endeavour gave to his advice in any scientific or practical matter a value treasured in wider and wider circles. To every one of us to whom he extended his staunch and faithful friendship an approving smile or a humorous admonition from him was enough to warm our hearts, and for the rest of our lives the thought of him will remain to inspire and guide us (Bohr, 1937).»

Acknowledgement

I would like to thank Prof. Alfio Briguglia, of the Italian Group for the History of Physics who, during the final reports at the 2018 annual meeting, allowed me to give the talk of his working group from which this paper originates. Deep thanks also go to Prof. Fabiano Minni, who in 2018 was the national coordinator of the Italian Group for the History of Physics and allowed me, together with the members of the board, to join this research group in the History of Physics.

To both of them goes my gratitude.

References

- Bohr, N. (1913). On the Constitution of Atoms and Molecules. *Philosophical Magazine Series*, 6(26), 1-25. <https://doi.org/10.1080/14786441308634955>
- Bohr, N. (1937). *Ernest Rutherford's Obituary*. Supplement to Nature, December 18, 1937.

- Bohr, N. (1963). *Essays 1958-1962 on Atomic Physics and Human Knowledge*. New York: John Wiley & Sons. <https://doi.org/10.1063/1.3051271>
- Rutherford, E. (1911). LXXIX. The scattering of α and β particles by matter and the structure of the atom. *Philosophical Magazine Series*, 6(21:125), 669-688. <https://doi.org/10.1080/14786440508637080>
- Reeves, R. (2008). *A Force of Nature*. New York: Atlas Book LLC.

Notes

Note 1. Nagaoka's atomic model, presented in *Phil. Mag.* vii, p. 445, 1904, had already been rejected on the grounds that it could not cope with the classical problem of the radiation of the electron in motion around the nucleus and therefore could not explain the non-collapse of matter.

Note 2. While Rutherford's model had no graphical description in the 1913 article, it is true that Bohr's model in turn did not allow the transitions of electrons from one orbit to another to be represented graphically.