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THE CENTENNIAL OF THE ATOMIC NUCLEUS*

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In May 1911 Ernest Rutherford published a paper *The Scattering of α- and β-particles by Matter and the Structure of the Atom*. Now it is usually considered to be the birth certificate of the atomic nucleus. Rutherford's results are presented and discussed in a wider context of physics views of that time.

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1. Introduction

In the second half of the XIXth century many physicists and chemists regarded the idea of atoms with suspicion and those who accepted it imagined atoms to be indivisible and indestructible entities. Thus Ernest Rutherford, who was born in 1871, recollected [1]:

> I was brought up to look at the atom as a nice hard fellow, red or gray in colour, according to taste.

However, around 1900 the experiments with the cathode rays (discovered in 1869) and radioactive substances (discovered in 1896), as well as the studies of atomic spectra, led to conclusions which could be summarized as follows:

1. Matter is quite transparent.
2. Atoms are electrically neutral but are composed of charged parts.
3. Negative particles much smaller than atoms exist.
4. Some atoms undergo transformations and emit energetic radiation (radioactivity).
5. Atoms emit or absorb electromagnetic radiation of frequencies characteristic to each chemical element.

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Thus, attempts to portrait the structure of the atoms had to provide at least a qualitative explanation of these facts as well as of the existence of the periodic system of elements.

2. Early models of the atom

In some early models the atoms were pictured as miniature planetary systems. In 1901 Jean Perrin suggested that atoms might consist of the central mass, charged with positive electricity and a certain number of negatively charged corpuscles held in orbits by electrical forces. Some of these corpuscles could be easily detachable because of weak binding which sounded as a plausible explanation of the spontaneous radioactivity of matter [2].

In a *Saturnian* atom model proposed by the Japanese physicist Hantaro Nagaoka (1904) all negatively charged corpuscles were assumed to form a single ring [3]:

> The system, which I am going to discuss, consists of a large number of particles of equal mass arranged in a circle at equal angular intervals and repelling each other with forces inversely proportional to the square of distance; at the centre of the circle, place a particle of large mass attracting the other particles according to the same law of force. If these repelling particles be revolving with nearly the same velocity about the attracting centre, the system will generally remain stable, for small disturbances, provided the attracting force be sufficiently great.

The proposal by Philipp Lenard that atoms were composed of pairs of positive and negative charged parts which he called *dynamids* [4] did not attract the interest of physicists.

Much more appealing was a suggestion by Lord Kelvin that the negative corpuscles (electrons) in atoms form groups inside a homogeneous cloud of the positive charge [5]. Kelvin's idea was elaborated in the *plum pudding model* by Joseph John Thomson who had been studying the cathode rays since 1897. Already in his first paper on the subject he declared [6]:

> I regard the atom as containing a large number of smaller bodies which I will call corpuscles ... the space through which the corpuscles are spread acts as if it had a charge of positive electricity equal in amount to the sum of the negative charges on the corpuscles ...

In a later paper [7] J.J. Thomson worked out a reasonable explanation of the quasi-stability of atoms by showing that the intensity of radiation by electric charges moving as a ring could be reduced by many orders of magnitude due to destructive interference.

Thomson's *plum pudding model* seemed to explain, at least qualitatively, several properties of atoms and was widely popularized. As an example, we quote below an excerpt from the book *The Radioactive Substances* by Walter Makower [8]:

> According to the scheme proposed by J.J. Thomson, negative corpuscles are supposed to be in rapid rotation in orbits within the sphere of positive electricity. Under these circumstances the corpuscles form themselves into concentric rings, and it can be shown that there are only quite definite configurations of the corpuscles within the atom which are stable. Thus it can be shown that with less than five corpuscles within the atom these corpuscles would arrange themselves in a single ring. On adding a sixth, a discontinuity of arrangement would occur, and the stable system would now consist of a ring of five corpuscles with one at the centre.
>
> On further increasing the number of corpuscles the two-ring system would persist until there were fifteen corpuscles within the atom, when a three-ring system would be formed, and so on for greater numbers. This, then, is in general principle the conception of the constitution of the atoms which we are considering, and in support of this view J.J. Thomson has shown that many of the facts of chemistry can be explained by considering the atoms of the various elements as made up of such systems containing different numbers of corpuscles.
>
> ... it can be shown that if the velocity of rotation is increased above a certain critical value, other configurations may suddenly become stable. Suppose, then, that we have a system of corpuscles rotating with velocities above this critical value, certain configurations will be stable which could not exist if the velocity were reduced below the critical velocity. Now it can be demonstrated that such a system will continually radiate out energy, though possibly at a very slow rate, and this energy will be derived from the energy of rotation of the corpuscles. The velocity of the corpuscles will thus be slowly reduced, and must inevitably reach the critical value below which they are no longer in stable equilibrium.
>
> A complete rearrangement of the corpuscles in the atom will suddenly occur, and during the violent disturbance which must thereby be caused, certain portions of the atom may break free which manifest themselves as radiations from the atom. This is what may be conceived to be taking place with the radioactive elements. If such

> explosions of the atoms occur frequently we have a strongly radioactive element. If they occur less frequently, or not at all, we have a feebly radioactive or non-radioactive substance, as the case may be.
>
> ... It is remarkable that a theory of matter which has been devised to explain the physical and chemical behaviour of atoms in general should be capable of interpreting the recently discovered property of radio-activity possessed to an appreciable extent by certain forms of matter only.

3. Probing the atom

In 1906 Ernest Rutherford obtained the first evidence [9] that the α particles emitted by radioactive sources undergo scattering in passing through matter. He covered a part of the slit between the radiant source and the photographic plate by a mica screen. The band representing the trace of the rays which have not passed through the mica was well defined whereas the trace of the rays after passing through mica was diffuse. If there were no scattering of the rays, the two bands should be equally well defined.

Prompted by Rutherford, his collaborator Hans Geiger studied this phenomenon in more details. His results [10] suggested that the scattering of the α particles may occur at considerable angles. As Rutherford later recollected [11]:

> One day Geiger came to me and said. 'Don't you think that young Marsden whom I am training in radioactive methods ought to begin a small research?' Now I had thought so too, so I said, 'Why not let him see if any alpha-particles can be scattered through a large angle?' The result was quite extraordinary.

The amazing outcome of the Geiger–Marsden experiment [12] was that of the incident α particles about 1 in 8000 particles was reflected at large angle. It was in obvious conflict with the *plum pudding* model of J.J. Thomson in which scattering of α particles occurred predominantly at very small angles. Rutherford always declared that it was the most surprising result he had known, and he coined a graphic phrase which he often used [11]: "It was as though you had fired a fifteen-inch shell at a piece of tissue paper and it had bounced back and hit you".

One has to remember that before 1932 the only two fundamental interactions known were gravitational, responsible for phenomena involving large masses, and electromagnetic which bound electrons and nuclei in atoms as well as protons and electrons in atomic nuclei. Thus, in his speech during the BAAS meeting at Winnipeg (Canada) in August, 1909 Rutherford said [13]:

> The general experimental evidence indicates that electrons play two distinct roles in the structure of the atom, one as lightly attached and easily removable satellites or outliers of the atomic system, and the other as integral constituents of the interior structure of the atom. The former ... probably play an important part in the combination of atoms to form molecules, and in the spectra of the elements, the latter, which are held in place by much stronger forces, can only be released as a result of an atomic explosion ...
>
> While there can be no doubt that electrons can be released from the atom or molecule by a variety of agencies and, when in rapid motion, can retain an independent existence, there is still much room for discussion as to the actual constitution of electrons, if such a term may be employed, and of the part they play in atomic structure.
>
> There is, so to speak, no time for the atom to get out of the way of the swiftly moving α particle, but the latter must pass through the atomic system. On this view, the old dictum, no doubt true in most cases, that two bodies can not occupy the same space, no longer holds for atoms of matter if moving at a sufficiently high speed.

It took Rutherford two years to develop a nuclear model of the atom which could explain the result on the scattering of α particles. In a letter to Otto Hahn on April 26, 1911 he wrote [14]:

> I have been working recently on scattering of alpha and beta particles and have devised a new atom to explain the results, and also a special theory of scattering. Geiger is examining this experimentally, and finds so far it is in good agreement with the facts. I am publishing a paper on the subject to appear shortly.

For quite some time Rutherford was undecided as to the charge of the central core of the atom. In a letter to William Henry Bragg of February 9, 1911 he wrote [15]:

> I am beginning to think that the central core is negatively charged, for otherwise the law of absorption for beta rays would be very different from that observed ...

A month later he gave the following abstract of a paper read in Manchester [16]:

> The scattering of the electrified particles is considered for a type of atom which consists of a central electric charge concentrated at a point and surrounded by a uniform spherical distribution of opposite electricity equal in amount.

When writing his epoch-making paper [17] Rutherford left the question of the central charge open:

> Consider an atom which contains a charge $\pm\, Ne$ at its centre surrounded by a sphere of electrification containing $\mp\, Ne$ supposed uniformly distributed throughout a sphere of radius R ...
>
> 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. 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.

Rutherford started his calculations from assessing the influence of the negative charge in the atom.

> ... Consider an atom containing a positive charge Ne at its centre, and surrounded by a distribution of negative electricity Ne uniformly distributed within a sphere of radius R. The electric force X ... at a distance r from the centre of an atom for a point inside the atom is given by
>
> $$X = Ne\left[\left(1/r^2\right) - \left(r/R^3\right)\right] .$$

Rutherford assumed that the central charge is $100\,e$, and calculated that the α particle of velocity $2.09 \times 10^9\,\mathrm{cm/s}$ will be brought to rest at about $3.4 \times 10^{-12}\,\mathrm{cm}$ from the centre, hence the field due to the uniform distribution of negative electricity may be neglected. Then followed the familiar derivation of Rutherford's formula for the probability p of deflection at angle θ, $p \sim \mathrm{cosec}^4\,(\theta/2)$.

4. The reception of the Rutherford's model

The general theme of the First Solvay Council on Physics which took place in Brussels from October 30 to November 3, 1911, was *Radiation and Quanta*. Thus, it is not surprising that atomic models were not discussed during the sessions. Rutherford might have discussed privately his ideas with some participants, but if so, there was no evidence of it left. One should remember that Rutherford's theory published several months before the conference explained the scattering of α particles and hardly anything else, therefore it did not arouse much interest.

In 1913 Rutherford's book *Radioactive Substances and Their Radiations* [18] was published. In this book of 700 pages there is only a two-page summary of the 1911 paper, giving the sign of the central charge as positive or negative. The word 'nucleus' occurs just once, in general 'central charge' is used — it is indexed under *scattering of α-rays, theory of.* There is yet another reference at the end of the book, and it is indexed under *Atom, structure of, to explain scattering.* The word *nucleus* is not present in the Index.

The theme of the Second Solvay Council on Physics (October 27–31, 1913) was *The structure of matter.* The conference started with a long talk by J.J. Thomson entitled *The structure of the atom.* The author tried to convince the audience that his *plum pudding model* adequately explained many features of atoms. In the long discussion after Thomson's talk Rutherford mentioned briefly that he had another model of the atom with a concentrated central charge. He was supported by Marie Skłodowska-Curie. No conclusion was however reached.

Meanwhile, Norman Campbell's *Modern electrical theory* [19] published in 1913 had a chapter *The structure of the atom* all dedicated to Thomson's atom model. Rutherford's model, then two years old, was not even mentioned. In another book published that year [20] we find only an incorrect statement that "Rutherford therefore conceives the atom, like Thomson, as a positive nucleus (but of very small dimensions) surrounded by an electronic system probably rotating in rings".

Several important papers were published in 1913. In the first place, Hans Geiger and Ernest Marsden announced a very convincing quantitative confirmation of Rutherford's model.

> Professor Rutherford has recently developed a theory to account for the scattering of α particles through these large angles, the assumption being that the deflexions are the result of an intimate encounter of an α particle with a single atom of the matter traversed. In this theory an atom is supposed to consist of a strong positive or negative central charge concentrated within a sphere of less than 3×10^{-12} cm radius, and surrounded by electricity of the opposite sign distributed throughout the remainder of the atom of about 10^{-8} cm radius.

To measure the angular distribution of scattered particles the authors [21] used a "... metal box B which contained the source of α particles R, the scattering foil F, and a microscope M to which the zinc-sulphide screen S was rigidly attached. The box was fastened to a graduated circular platform A, which could be rotated ... By rotating the platform the box and microscope moved with it, whilst the scattering foil and radiating source remained in position.

> ... considering the enormous variation in the numbers of scattered particles, from 1 to 250000, the deviations from constancy of the ratio are probably well within the experimental error. The experiments, therefore, prove that the number of α particles scattered in a definite direction varies as $\text{cosec}^4\ \varphi/2$.

Other important papers published in 1913 were those of Niels Bohr [22] in which he incorporated Rutherford's nucleus into his planetary atom model, Antonius Van den Broek's suggestion [23] that the charge of the nucleus is equal to the atomic number and not to half the atomic weight, and Henry Moseley's measurements of the frequencies of X-rays of various elements [24]. The pieces of the jigsaw puzzle began to fall into proper places so that Rutherford was able to conclude in December of that year [25]:

> The original suggestion of van de Broek that the charge of the nucleus is equal to the atomic number and not to half the atomic weight seems to me very promising. This idea has already been used by Bohr in his theory of the constitution of atoms. The strongest and most convincing evidence in support of this hypothesis will be found in a paper by Moseley in Philosophical Magazine of this month. He there shows that the frequency of the X-radiations from a number of elements can be simply explained if the number of unit charges on the nucleus is equal to the atomic number. It would appear that the charge of the nucleus is the fundamental constant which determines the physical and chemical properties of the atom, while the atomic weight, although it approximately follows the order of the nuclear charge, is probably a complicated function of the latter depending on the detailed structure of the nucleus.

It appears that in 1914 Rutherford no longer had doubts concerning the charge of the atomic nucleus [26].

> ... I supposed that the atom consisted of a positively charged nucleus of small dimensions in which practically all the mass of the atom was concentrated. The nucleus was supposed to be surrounded by a distribution of electrons to make the atom electrically neutral, and extending to distances from the nucleus comparable with the ordinary accepted radius of the atom.

> ... the nucleus, though of minute dimensions, is in itself a very complex system consisting of a number of positively and negatively charged bodies bound together by intense electric forces ... [27].

Meanwhile, Rutherford's model of the atom was mentioned in other books published in 1914. Owen W. Richardson's *The Electron Theory of Matter* [28] had a long chapter IX entitled *The Structure of the Atom*, most of which was devoted to the J.J. Thomson's model. Rutehrford's model then three years old, and Bohr's fundamental work published in 1913 were introduced only in the last few pages.

> The deflections of the α rays through large angles and the scattering of X rays by light atoms . . . agree much better with Rutherford's view that the positive electricity in the atom is concentrated in a minute region of it than with the uniform sphere of positive electrification . . . It will be noticed that if the linear dimensions of the nucleus are small enough the whole mass of the atom may be of electromagnetic origin.

G.W.C. Kaye [29] in his book presented a twisted picture of a new development:

> Rutherford's theory of the constitution of matter, which is a development of that of J.J. Thomson, regards an atom as built up of a minute nucleus positively charged, surrounded by a cluster of negatively charged electrons which are grouped in rings.

Then came the Great War and the physicists had other worries than studying the atom. But the Third Solvay Council in 1921 was all devoted to the new picture of the nuclear atom of Ernest Rutherford.

5. Concluding remarks

Scientific discoveries seem to fall into two categories. The first one could be called *media type* events. A *media-type* discovery can be explained in 1–2 minutes in a TV or radio interview and thus it is readily accepted by the scientific community and the public. The examples of this type are *e.g.* X-rays, and superconductivity at high temperature. Other discoveries, such as Rutherford's atomic nucleus, require much longer time for acceptance, especially when they occur as a competition to "well established" view (J.J. Thomson's model).

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