PREHISTORY OF NUCLEAR PHYSICS*

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A summary is given of the attempts to understand the structure of the atom from the discovery of radioactivity until the discovery of the neutron.

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In an essay on nuclear physics prepared for the centenary of the American Physical Society Hans Bethe wrote: "Nuclear physics started in 1894 with the discovery of the radioactivity of uranium by A. H. Becquerel" [1].

This statement can not be left without some comments. Firstly, Becquerel's discovery took place in 1896, not in 1894. Secondly, while we know today that radioactivity is a nuclear phenomenon, it took quite a few years after its discovery before it became an established knowledge. At the turn of the XX$^{\mathrm{th}}$ century no notion of the atomic nucleus existed, and even the very structure of the atom was a vague concept.

I am of the opinion that nuclear physics, as we know it now, began only in 1932 with the discovery of the neutron. In the first 35 years after Becquerel's discovery we had just an empirical science of radioactivity and radioactive radiations related with the structure of the atom. This period may be treated as "early nuclear physics" [2], but I prefer to call it "prehistory of the nuclear physics". The present article, therefore, gives a summary of the attempts to understand the structure of the atom before the discovery of the neutron. The summary is necessarily biased because it is not possible to cover all aspects of the development of subatomic physics of that period in a short presentation.

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In the history of science it is indispensable to learn the opinions of past scientists from their own words, hence this article contains extensive quotations from the original papers.

1. Early views on the source of energy of radioactive elements

Large and apparently inexhaustible energy of radioactive transformations was hard to explain without assuming some external source of energy. Thus, William Crookes [3] proposed that the heavy atoms of radioactive elements have the property of absorbing the kinetic energy of the fastest molecules of the air. He calculated that the air within a room 12 feet high, 18 feet wide, and 22 feet long contained energy enough to propel a one-horse engine by more than twelve hours. The hypothesis of Crookes was soon contradicted by Julius Elster and Hans Geitel [4] who proved experimentally that uranium radiation was the same at normal atmospheric pressure and in a vacuum, and also in a mine at the depth of 853 meters.

Other scientists speculated that the radioactive atoms could absorb some unknown radiation from space, and re-emit it in form of penetrating radiation. In her first paper on radioactivity [5] Marie Skłodowska-Curie wrote: "To interpret the spontaneous radiation of uranium and thorium one might imagine that all space is constantly traversed by rays analogous to Röntgen rays, but much more penetrating and able to be absorbed only by certain elements of high atomic weight, such as uranium and thorium". The Curies attempted to see whether the sun could be the source of that unknown radiation, but they found no diurnal variation in the activity of uranium [6]. The mystery deepened when Pierre Curie and Albert Laborde [7] measured the rate of emission of energy by a known quantity of radium. They again considered an unknown exterior source of energy. Lord Kelvin was also convinced that the energy can not originate inside the atom: "It seems to me absolutely certain that if emission of heat can go on month after month... energy must be supplied from without" [8]. The external source of radioactive energy was discussed as late as 1919 [9].

2. Early atomic models

In 1901 Jean Perrin suggested [10] that atoms might look like miniature planetary systems with one or more positively charged "suns" and small negatively charged "planets". The corpuscles farthest from the centre could be very weakly held by electric attraction and possibly easily detachable. It sounded as a plausible explanation of the spontaneous radioactivity of matter.

Lord Kelvin proposed that the negative electrons in atoms form groups inside a homogeneous spherical cloud of the positive charge [11]. This loose proposal was elaborated in 1904 by Joseph John Thomson [12] in the "plum pudding model" in which the electrons move in a plane, distributed with equal angular intervals over one or more rings. Thomson based his considerations upon observations of Alfred Marshall Mayer [13] who experimented with magnetized steel needles. When a number of such small magnets thrust through small disks of cork were floated in a vessel of water in a magnetic field, they formed stable configurations in form of regular polygons. The first polygon was formed when there were just five magnets. The sixth and subsequent magnets moved to the centre while the other five remained on the polygon. This went on until there were fourteen magnets forming two polygons. The fifteenth magnet would start to build a third polygon, and so on. Thomson calculated that the radiation from the moving rings of corpuscles is much reduced compared with the radiation of a single moving charge. This provided explanation of why atoms built with moving charges could be stable. Thomson also attempted to draw analogies between properties of chemical elements and periodicity in the arrangement of corpuscles.

In 1903 Philipp Lenard [14] proposed a hypothesis that atoms consisted of "dynamids" — pairs of opposite electric charges about 10,000 times smaller than atomic radii, so that the atom was supposed to be almost completely empty. He drew this conclusion from the fact that cathode rays easily traverse large number of atoms in thin foils. His model, however, failed to attract the interest of physicists. In 1904 Hantaro Nagaoka [15, 16] proposed a "Saturnian" atom model in which electrons distributed in a concentric ring circulated around a positively charged central attracting mass.

"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 present case will evidently be approximately realized if we replace these satellites by negative electrons and the attracting centre by a positively charged particle..." [15].

Nagaoka calculated that the oscillations perpendicular to the plane of the electron ring led to a spectrum having a band-like structure and the oscillations in the plane — to a kind of line spectrum. The α- and β-rays were assumed to be emitted when the electron ring and the atomic nucleus broke up because of large disturbances. It was soon realized [17], however, that Nagaoka's atom cannot serve its purpose. Rutherford nevertheless acknowledged his indebtedness to Nagaoka in his first paper on the structure of the atom.

3. The discovery of the atomic nucleus

The idea of the central atomic charge was proposed by Ernest Rutherford in the paper "The Scattering of α and β Particles by Matter and the Structure of the Atom", published in May 1911 [18]. His aim was to explain the results obtained by Hans Geiger and Ernest Marsden on the scattering of α-particles by thin metal foils published in June 1909 [19]. Preliminary results of the scattering of α-particles were reported a year earlier by Geiger [20].

Rutherford himself liked to repeat a story: "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?' I may tell you in confidence that I did not believe that they would be, since we knew that the α-particle was a very fast massive particle, with a great deal of energy, and you could show that if the scattering was due to the accumulated effect of a number of small scatterings the chance of an α-particle's being scattered backwards was very small. Then I remember two or three days later Geiger coming to me in great excitement and saying, 'We have been able to get some of the α-particles coming backwards ... ' " [21].

Rutherford always declared that it was the most surprising result he had known, and he coined a graphic phrase which, again, he often used: "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"[21].

It took Rutherford two years to develop a nuclear model of the atom, which could explain the results on α scattering. It is interesting to note that in 1909 he enrolled as a student to attend the elementary lectures on probability given by Horace Lamb and that he took extensive notes like any first-year student [22]. At first he was undecided as to the charge of the central core. In a letter to William Henry Bragg [23] he wrote: "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 [24] he was undecided: "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". By that time he knew that the results are independent of the charge so he wrote in his epoch-making paper: "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 ... . It has not so far been found possible to obtain definite evidence to determine whether it be positive or negative ...” [18].

But three years later he seemed to have forgotten his initial hesitation: “...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” [25].

One should note that Rutherford used initially the words “central core” or “central charge”, and the word “nucleus” was first used by John Nicholson [26].

Rutherford's theory explained the scattering of α-particles and hardly anything else, therefore it did not arouse much interest. It was not even mentioned at the First Solvay Conference on Physics (October 30–November 3, 1911). The Second Solvay Conference on Physics took place in October 1913, just few months after Niels Bohr's first paper on the quantum theory of the atomic constitution had been published. Apparently the discovery of the atomic nucleus was not yet appreciated by physicists at that time, since the only reference to it was made by Rutherford himself in the discussion following J.J. Thomson's report “Structure of the atom”. Furthermore, Rutherford's discovery was not mentioned in Campbell's *Modern Electrical Theory* (1913), and Richardson's *The Electron Theory of Matter* (1914). Rutherford himself mentioned the nucleus briefly in a short section in his *Radioactive Substances and Their Radiations* (1913).

Only much later, at the Third Solvay Conference (1–6 April 1921), Rutherford's nuclear model of the atom and Bohr's atomic theory were central in the discussion of “Atoms and electrons”, which was the main theme of the meeting.

4. The wonder year 1913

One has to remember that at the turn of the XX$^{\text{th}}$ century the number of electrons in atoms was believed to be very large. As reported by Rutherford in 1902 [27]: “The electron thus appears to be the smallest definite unit of mass with which we are acquainted. The view has been put forward that all matter is composed of electrons. On such a view an atom of hydrogen for example is a very complicated structure consisting possibly of a thousand or more electrons. The various elements differ from one another in the number and arrangement of electrons, which compose the atom”.

Later Thomson devised a method to determine this number from arguments based on the scattering of X-rays and the dispersion of light in gases and also on the absorption of cathode rays and β-rays in matter. In 1906 he concluded that the number of electrons was comparable with the atomic weight [28]. After 1910 it was generally accepted that the number of electrons in an atom was of the same order as its atomic number, although as late as 1911, H.A. Wilson maintained that a hydrogen atom contained eight electrons [29].

In 1912 the origin of radioactive transformations was still uncertain. For example Rutherford considered "...the instability of the central nucleus and the instability of the electronic distribution. The former type of instability leads to the expulsion of an α-particle, the latter to the appearance of β- and γ-rays ..." [30]. Thus, only in that year α-decay was for the first time correctly identified as a nuclear process.

In 1913 various pieces of the atomic jigsaw puzzle began to fall into proper places. Antonius van den Broek correctly interpreted the atomic number A as the nuclear charge Z, and proposed the proton-electron model of the nucleus [31–33]. Geiger and Marsden presented [34] splendid quantitative confirmation of Rutherford's scattering theory. Niels Bohr published his famous trilogy on the constitution of atoms and molecules [35], and Henry Moseley [36] found the formula for the frequency of characteristic X-radiation, which led to the definitive interpretation of the periodic table. Also Kasimir Fajans [37], Georg v. Hevesy [38], Alexander Smith Russell [39], and Frederick Soddy [40] independently discovered the Displacement Law for radioactive decays, and Soddy elaborated the concept of the isotopes [41]. It truly was a wonder year, *annus mirabilis.*

Van den Broek, a Dutch lawyer, was also an amateur theoretical physicist, interested mostly in numerical regularities. Starting from 1907 he tried to find proper arrangement of elements in the periodic system by including the newly discovered radioactive substances. His various planar and cubic versions of the periodic system extended it up to 120 elements, the last place being that of uranium.

Then, in 1913, he made a lucky hit. It is worth to quote the text of his ground-breaking proposal almost in its entirety: "In a previous letter to *Nature* (July 20, 1911, p. 78) the hypothesis was proposed that the atomic weight being equal to about twice the intra-atomic charge ... Charges being known only very roughly (probably correct to 20 per cent), and the number of the last element Ur in the series not being equal even approximately to half its atomic weight, either the number of elements in the Mendeleeff's system is not correct (that was supposed to be the case in the first letter), or the intra-atomic charge for the elements at the end of the series is much smaller than that deduced from the experiment (about 200 for Au). Now,

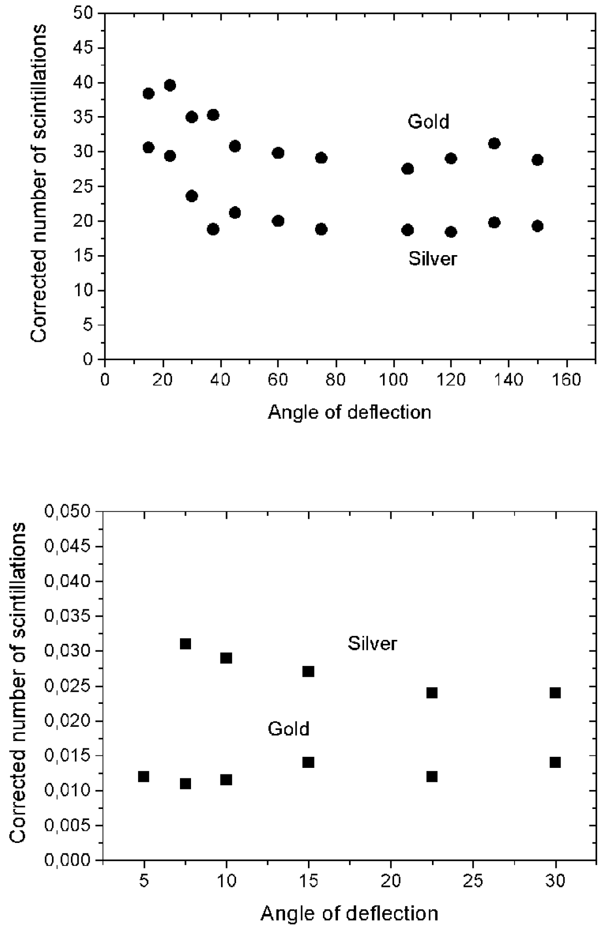


Fig. 1. The results on the scattering of α-particles obtained by Geiger and Marsden. The data were taken from [34].

according to Rutherford the ratio of the scattering of α-particles per atom divided by the square of the charge must be constant. Geiger and Marsden (*Phil. Mag.* **XXV**, pp. 617 and 618) putting the nuclear charge proportional to the atomic weight, found values, however, showing not constancy, but systematic deviations from (mean values) 3,885 for Cu to 3,25 for Au. If now in these values the number M of the place each element occupies in Mendeleeff's series is taken instead of A, the atomic weight, we get a real constant (18,7$\pm$ 0,3); hence the hypothesis proposed holds good for Mendeleeff's series, but the nuclear charge is not equal to half the atomic weight. Should thus the mass of the atom consist for by far the greatest part of α-particles, then the nucleus must contain electrons to compensate this extra charge ..." [32].

Geiger and Marsden studied the scattering of α-particles by thin metal foils in order to check the scattering formula proposed by their boss two years earlier [18]: "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.

... considering the enormous variation in the numbers of scattered particles, from 1 to 250,000, 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 $\mathrm{cosec}^4\varphi/2$" [34].

Moseley carried out precise measurements of the wavelengths of K_α-lines of 21 elements. Inspired by van den Broek he found a beautiful regularity in that the wave number $\nu(Z)$ of K_α for element Z changed in a regular way when passing from one element to the next, and using the chemical order of elements in the periodic system.

"We have here a proof that there is in the atom a fundamental quantity, which increases by regular steps as we pass from one element to the next. This quantity can only be the charge on the central positive nucleus, of the existence of which we already have definite proof. Rutherford has shown, from the magnitude of the scattering of α-particles by matter, that this nucleus carries a + charge approximately equal to that of $A/2$ electrons, where A is the atomic number. Barkla, from the scattering of X-rays by matter, has shown that the number of electrons in an atom is roughly $A/2$, which for an electrically neutral atom comes to the same thing. Now atomic weights increase on the average by about 2 units at a time, and this strongly suggests the view that N increases from atom to atom always by a single electronic unit. We are therefore led by experiment to the view that N is the same as the number of the place occupied by the element in the periodic system ... This theory was originated by Broek and since used by Bohr" [36].

No wonder that Rutherford was enthusiastic when he wrote: "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" [42].

Once the presence of negative electrons in atomic nuclei was accepted as a working hypothesis, the question remained about the nature of the positive charges situated there. Rutherford thought that these might be positive electrons:

"The exceedingly small dimensions found for the hydrogen nucleus add weight to the suggestion that the hydrogen nucleus is the *positive electron*, and its mass is entirely electromagnetic in origin. According to the electromagnetic theory, the electrical mass of a charged body, supposed spherical, is $2e^2/3a$ where e is the charge and a the radius. The hydrogen nucleus consequently must have a radius about $1/1830$ of the electron if its mass is to be explained in this way. There is no experimental evidence at present contrary to such an assumption. The helium nucleus has a mass nearly four times that of hydrogen. If one supposes that the positive electron, *i.e.* the hydrogen atom, is a unit of which all atoms are composed, it is to be anticipated that the helium atom contains four positive electrons and two negative" [43].

Van den Broek also tried to estimate the dimensions of the positive charges: "Should the α-particle be composed of $4(H^+) + 2$ electrons, then the number of nuclear electrons should be for U 142, that of the positive units 238, and, 380 particles occupying about 2.7×10^{-35} c.cm., the positive unit must be of equal size, if not identical with the electron (0.5×10^{-37}), but in a different state" [44].

By that time Rutherford already realized that "... 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 ..." [45].

5. The first artificial nuclear transmutation

The outbreak of the World War slowed down or interrupted physics investigations. In the end of 1917 Rutherford was able to resume studies of the interactions of α-particles with matter. The best known result of these experiments, published in 1919, was the identification of the first artificially induced nuclear transformation.

"It is difficult to avoid the conclusion that the long-range atoms arising from collision of α-particles with nitrogen are not nitrogen atoms but probably atoms of hydrogen, or atoms of mass 2 … . We must conclude that the nitrogen atom is disintegrated under the intense forces developed in a close collision with a swift α-particle, and that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus …" [46].

At that time Rutherford developed a model of the structure of atomic nuclei as built up of three smaller basic units. He best explained his ideas in the famous Bakerian lecture on June 3, 1920 [47]:

"We should expect the H nucleus to be the simplest of all and, if it be the positive electron, it may have exceedingly small dimensions compared with the negative electron … .

In considering the possible constitution of the elements, it is natural to suppose that they are built up ultimately of hydrogen nuclei and electrons. On this view the helium nucleus is composed of four hydrogen nuclei and two negative electrons with a resultant charge of two … .

We have shown that atoms of mass about 3 carrying two positive charges are liberated by α-particles both from nitrogen and oxygen, and it is natural to suppose that these atoms are independent units in the structure of gases dots . We have seen that so far the nuclei of three light atoms have been recognised experimentally as probable units of atomic structure, *viz.* H_1^+, X_3^{++}, He_4^{++}, where the subscript represents the mass of the element".

Thus Rutherford speculated that: "We should anticipate from radioactive data that the nitrogen nucleus consists of three helium nuclei of atomic mass 4 and either two hydrogen nuclei or one of mass 2. If the H nuclei were outriders of the main system of mass 12, the number of close collisions with the bound H nuclei would be less than if the latter were free, for the α-particle in a collision comes under the combined field of the H nucleus and of the central mass … The general results indicate that the H nuclei … are distant about twice the diameter of the electron (7×10^{-13} cm) from the centre of the main atom" [46].

"The expulsion of an H atom carrying one charge from nitrogen should lower the mass by 1 and the nuclear charge by 1. The residual nucleus should thus have a nuclear charge 6 and mass 13, and should be an isotope of carbon. If negative electron is released at the same time, the residual atom becomes an isotope of nitrogen.

The expulsion of a mass 3 carrying two charges from nitrogen, probably quite independent of the release of the H atom, lowers the nuclear charge by 2 and the mass by 3. The residual atom should thus be an isotope of boron of nuclear charge 5 and mass 11. If an electron escapes as well, there remains an isotope of carbon of mass 11 … The data at present available are quite insufficient to distinguish between these alternatives dots" [47].

The reactions considered by Rutherford can be written in modern notation as

^{4}He + ^{14}N → ^{4}He + ^{1}H + ^{13}C
^{4}He + ^{14}N → ^{4}He + ^{1}H + ^{13}N+e^{-}
^{4}He + ^{14}N → ^{4}He + ^{3}X + ^{11}B
^{4}He + ^{14}N → ^{4}He + ^{3}X + ^{11}C+e^{-}

These schemes are of course quite different from the present interpretation. The reason was that Rutherford considered the ^{4}He to be one of the building blocks of matter and hence could not accept that it also might be subject to disintegration.

Rutherford and James Chadwick systematically studied disintegration of various elements by α-particles and published the results in a series of papers [48–50]. Disintegration was found in many elements, but some (*e.g.* H, He, Li, C, and O) failed to show the effect.

Meanwhile, Hans Pettersson, a Swedish physicist working in Vienna, claimed that the disintegrability of atomic nuclei is universal and not a property of a limited number of elements [51]. He doubted the satellite theory of nuclear disintegration proposed by Rutherford and advanced an "explosion theory" according to which the encounter of an α-particle with a nucleus caused its disruption. A prolonged controversy erupted in which Rutherford's experimental results were proven correct, although Pettersson's attack on the satellite theory was justified.

In 1925 Partick Blackett published the results of the study of interactions of α-particles in the cloud chamber [52]. In about 23,000 photographs with roughly 420,000 tracks of α-particles there were found eight „forks" undoubtedly representing the ejection of a proton from a nitrogen nucleus according to the now well-known scheme ^{14}N + ^{4}He → ^{17}O + ^{1}H.

Rutherford did not easily give up his ideas. Thus, in commenting on Blackett's paper, he pointed out the existing inconsistency in experimental results: "... The fine track of the proton was clearly visible, also that of the recoiling nucleus, but there was no sign of a third track to be expected if the α-particle escaped after the collision ... In 1923 Prof. W.D. Harkins and R.W. Ryan (*Journ. Amer. Chem. Soc.*, **45**, p. 2095) ... recorded a photograph of a collision in which the α-ray track broke into three distinct branches — indicating a disintegration in which two high speed particles appear in addition to the recoiling nucleus. My attention has recently been directed to another interesting photograph recorded by M. Akiyama (*Jap. Journ. Phys.*, **2**, p. 272, 1923), which also shows three branches ... It is, of course, difficult to reconcile these photographs with the eight obtained by Blackett in which no third branch has been noted ... It is obvious that there is still much work to be done to clear up these difficulties ..." [53].

6. Models galore

While Rutherford and others tried to probe the properties of the atomic nucleus through systematic experimentation, many physicists attempted to devise models of its structure. These numerous electron-proton nuclear models have been long forgotten but it is worth to mention at least some of them because they constitute an important part of the history of physics.

In the period 1914–1932 it was generally accepted that the nucleus contained negative electrons and positive charges, usually identified with the protons. The model-builders were aware of the Earnshaw's theorem that a system of particles interacting by forces varying as the inverse square of the distance cannot be in stable static equilibrium, hence the components of the nucleus were assumed to be in motion.

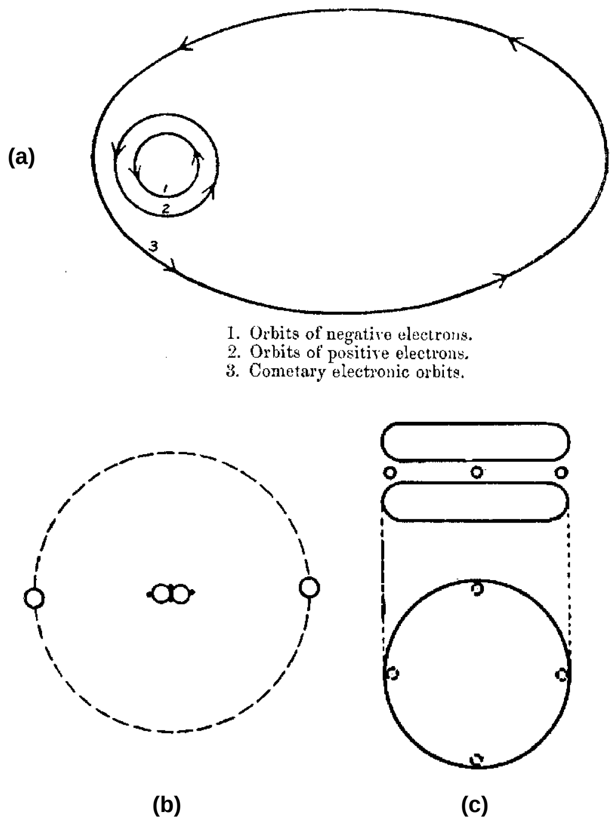


Fig. 2. (a) Stewart's model of atomic nuclei [54], (b) the structure of the α-particle according to Gehrcke [57]; the negative electrons are shown by large open circles and the positive charges by small black dots; (c) Harkins' model of the α-particle [55].

Thus in 1918 Alfred Stewart [54] proposed that: "At the centre of the structure is a group of negative electrons travelling in closed orbits which, for the sake of clearness, may be assumed to be circular. Closely surrounding this negative group lies another series of orbits occupied by positive electrons which, in some cases, are associated with negative electrons in a manner to be dealt with later. These orbits are assumed to be circular also; their extreme diameter may be taken, according to Rutherford's view, as not being greater than 10^{-12} cm.; and, as in the Rutherford atom, the mass of the system is assumed to be concentrated in this portion. Further still from the centre, other electrons move in orbits of an elliptical character, the ellipses being much elongated, so that the electrons travel in paths like those of comets in the solar system ...".

Much attention was paid to the nucleus of helium (see Fig. 2). In the model devised by William Harkins [55]: "The helium nucleus is assumed to consist of two negative electrons which have the form of rings, or discs, or spheres flattened into ellipsoids. The rings or discs lie with their greatest dimension perpendicular to the axis of the nucleus, and far from each other relative to their dimensions, between the two discs near their edges are the positive electrons in a symmetrical arrangement, that is at the corners of a square".

Still more complicated was the "triplane model" by R. Hargreaves [56]. He assumed that: (a) The atomic weight p is the number of positive electrons contained in the nucleus; (b) The atomic number q is the number of negative electrons moving as satellites in orbits external to the nucleus, and controlled by the positive residue of the nucleus.

"The difference $p - q$ is the number of negative electrons engaged in binding together the positive units so as to form a structure. The nucleus is taken to be a structure in the sense that all units contained revolve about a common axis, with their relative positions unaltered, under attractions and repulsions following electrostatic law. Further it is supposed that nuclear orbits are on a much smaller scale than those of satellites.

In the upper and lower of three parallel equidistant planes equal circles are described by positive electrons, in the middle plane a circle of smaller radius is described by negative electrons, all circles having their centres on a common axis perpendicular to the planes. Each circle contains n elements equally spaced; positive lies over positive, but negative elements are in azimuth halfway between the positive. The circles are described with a common angular velocity ..." [56].

According to a German physicist E. Gehrcke the two negative electrons in the helium nucleus were surrounded by four symmetrically placed positive charges, called "elementary nuclei" (*Elementarkernen*) [57]. Y. Takahashi [58] assumed that the nucleus of helium consisted of four protons in a circle

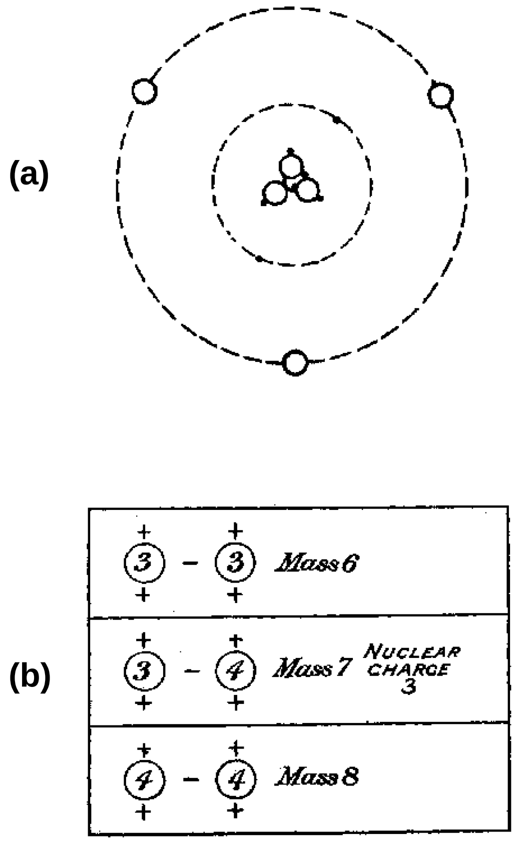
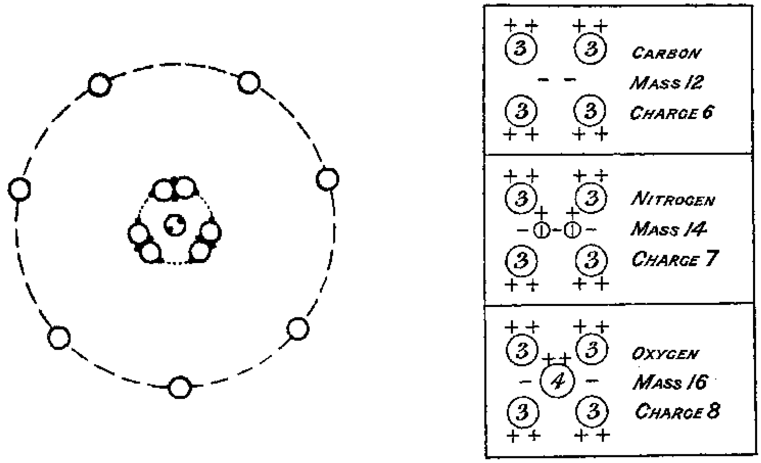


Fig. 3. (a) The structure of ^{6}Li according to Gehrcke [57]; the symbols are the same as in Fig. 2b, (b) Rutherford's models for the three isotopes of lithium [47].

and two electrons on the axis. To explain the observed stability of α-particles it was necessary to assume that Coulomb's law is not obeyed.

The models of the structure of heavier nuclei were quite complicated. According to Hans Wolff [59] the nucleus had a form of a circular disc, made up of concentric rings. Positively charged H and He particles described circular orbits around the midpoint of the atom as centre. Around each positive charge revolved the negative electrons. E. Gehrcke [60] proposed an "onion-like" structure of the nuclei of heavier atoms. Thus, the nucleus of Na was simply the nucleus of Li surrounded by the ring of 4 α-particles. The nucleus of Cu was composed of the nucleus of Na and the ring of 10 α-particles, and 2 nuclear electrons, the nucleus of Ag was formed of the nucleus of Cu and the ring of 11 α-particles, and 4 nuclear electrons, and so on.



(a) **(b)**

Fig. 4. (a) The model of ^{14}N according to Gehrcke [60], (b) Rutherford's models [47] for ^{12}C, ^{14}N, and ^{16}O. The building blocks are the hydrogen nuclei, α-particles and X_3^{++} particles.

In the model of S. Ono [61] the protons in an atomic nucleus lay in two zones, an inner one solid and spherical and in which each proton was accompanied by a single electron, and an outer spherical shell in which the protons form pairs, each pair with one electron. G.I. Pokrowski [62] was convinced that the nucleus is a system of differently charged concentric spheres, some positive and others negative.

The heavier the nucleus, the more intricate were the proposed models. A fanciful model for $Z = 44$, $A = 118$ proposed by Emil Kohlweiler [63] was so involved (see Fig. 5) that an eminent historian of science compared it to a Gothic cathedral [64].

In 1925 Rutherford also extended his "satellite" nuclear model of 1919. It now included "satellites" (negative electrons and positive protons), which formed closely spaced "neutral doublets". The new model used to explain why uranium freely emits relatively low energy α-particles (of range 2.7 cm), while α-particles of higher energy (of range 6.7 cm) are scattered away. The emission of low energy α-particles was explained as due to the break up of closely spaced "satellites" [65]. In 1927 Rutherford extended the model quantitatively by showing that a number of γ-ray lines could be interpreted as arising from transitions of such "satellites" (see Fig. 6). He did not give up this model even after Gamow's quantum theory of α-decay (1928).

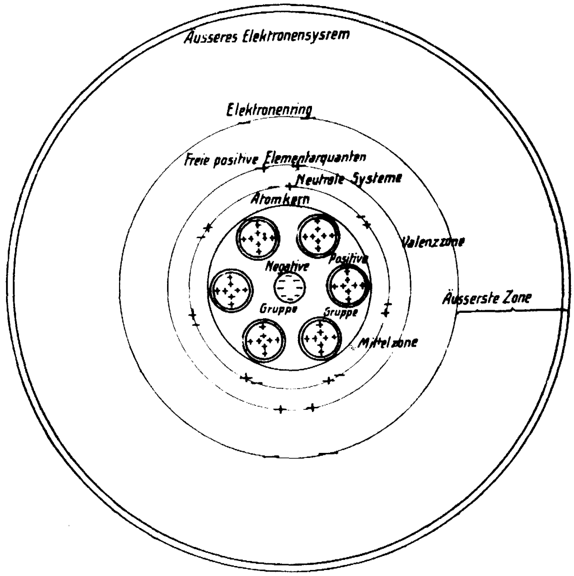


Fig. 5. Kohlweiler's model for atomic number 44 and atomic weight 118 [63].

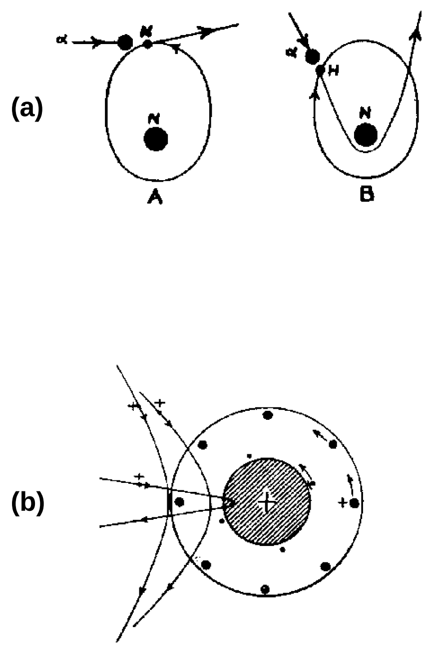


Fig. 6. (a) The disintegration of the ^{14}N nucleus by α-particles according to Rutherford [46], (b) Rutherford's extended "satellite model" of nuclei [65].

7. The "nitrogen catastrophe" and other controversies

The presence of electrons inside the atomic nuclei had been a commonly accepted fact by the physicists in the 1920s. But the development of quantum mechanics and experimental data on the band spectra of molecules quickly led to a controversy with the spin-statistics theorem.

For example, in the electron-proton model of atomic nuclei the nucleus of nitrogen 14 was thought to consist of 14 protons and 7 electrons, a total of 21 particles. The odd number of spin 1/2 particles ought to produce a half-integer total spin. But the studies of the Raman band spectra for O_2 and N_2 proved beyond doubt that both nuclei obeyed the Bose statistics. It was found shortly that the nucleus of lithium 6 also has the "wrong" statistics. There were various desperate attempts to find an explanation of this controversy. Experimental data were questioned [66]. In this connection it is worth citing Ralph de Kronig [67]: "One is therefore probably required to assume that in the nucleus the protons and electrons do not maintain their identity in the same way as in the case when they are outside the nucleus".

Another conceptual difficulty followed from the Heisenberg's uncertainty relation, because it could be demonstrated that an electron confined to nuclear dimensions would have to possess momentum, and hence energy, much larger than known nuclear binding energies.

The most serious problem was that of the energy in the β-decay. Already in 1914 James Chadwick discovered [68] that the beta-spectrum of radium $B + C$ is continuous with some lines superimposed on it. This finding was confirmed by other experimenters, the most precise being the result of Charles Drummond Ellis and William Alfred Wooster [69]. All attempts to find an explanation of why a two-body decay leads to a continuous spectrum were futile. Some part of the energy released in the decay seemed to disappear. Niels Bohr was even ready to accept non-conservation of energy in β-decay.

It is well known that in 1930 Wolfgang Pauli came out with another desperate solution by postulating the existence of a new particle. In a letter of December 4 to Hans Geiger and Lise Meitner participating in a physics conference in Tübingen, he wrote [70]:

"I have come upon a desperate way out regarding the 'wrong' statistics of the N- and the Li 6-nuclei, as well as to the continuous β-spectrum, in order to save the alternation law of 'statistics' and the energy law. To wit, the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin 1/2 and satisfy the exclusion principle, and which are further distinct from light quanta in that they do not move with light velocity. The mass of the neutrons should be of the same order of magnitude as the electron mass, and in any case not larger than 0.01 times the proton mass. The continuous β-spectrum would then become understandable from the assumption that in β-decay a neutron is emitted along with the electron, in such a way that the sum of the energies of neutron and electron is constant ...".

The name "neutrino" for Pauli's hypothetical particle was proposed by Enrico Fermi after the discovery of the neutron by James Chadwick in 1932.

8. The discovery of the neutron

I shall only briefly remind that the discovery of the neutron was the end result of the series of studies undertaken in order to understand the "beryllium radiation" discovered in 1930 by Walter Bothe and Herbert Becker [71]. They found out that by exposing beryllium to α-particles from polonium, a radiation, more penetrating than ordinary γ-rays, was produced. Irène Curie and Frédéric Joliot [72] concluded from their studies that this radiation in turn is able to eject protons from paraffin or other hydrogenous substance by means of a Compton scattering process. Their paper was published on January 18, 1932. Chadwick immediately understood that the proposed interpretation could not be correct. He decided to perform a series of experiments with various targets and obtained strong evidence that corpuscular radiation, not γ-rays, were being produced in beryllium by α-particles. On February 17 he sent a preliminary note [73] to *Nature*, which was followed by a full report on the discovery of the neutron [74].

According to a widespread story Chadwick was mentally prepared for the neutron because its possible existence had been suggested by his master, Ernest Rutherford, in the Bakerian Lecture [47]. As reported by Rutherford's biographer, Arthur Eve [75]: "Prof. Joliot told me an interesting story of his work with his wife, Irène Curie, on the effect of α-rays on beryllium. Although they both followed all publications with care and interest they had not read Rutherford's second Bakerian Lecture, because 'in such lectures it is rare to find anything novel which has not been published elsewhere'. Joliot stated that if he and his wife had read Rutherford's prophetic suggestion about the neutron in the Bakerian Lecture, it is possible or probable that they would have identified the neutron in place of Chadwick".

This explanation does not hold water. The Bakerian Lecture by Rutherford was not the only place where the neutron was mentioned. The existence of this particle was considered by several other authors in the leading periodicals [76], so that it was hard to miss it.

The discovery of the neutron did not change physicists' views on the constituents of atomic nuclei overnight. Rutherford imagined a hypothetical neutron to be a very close combination of a proton and an electron. Chadwick held the same opinion. In this connection it is interesting to recall some opinions expressed during the discussion on the structure of atomic nuclei held at the Royal Society on April 28, two months after Chadwick's paper was published [77]:

"... It is generally supposed that the nucleus of a heavy element consists mainly of α-particles with an admixture of a few free protons and electrons, but the exact division between these constituents is unknown ... It appears as if the electron within the nucleus behaves quite differently from the electron in the outer atom ... it now seems clear that the nuclear γ-rays are due to the transition of an α-particle between energy levels in an excited nucleus ... .

The idea of the possible existence of "neutrons", that is, of a close combination of a proton and an electron to form a unit of mass nearly 1 and zero charge is not new ..." (Rutherford).

"The neutron may be pictured as a small dipole, or perhaps better, as a proton embedded in an electron. On either view the 'radius' of the neutron will be between 10^{-13} cm and 10^{-12} cm ..." (Chadwick).

"It must not be forgotten that there are other particles in the nucleus besides α-particles and electrons. Fowler has suggested that the presence of protons may be responsible for certain peculiarities of the spectrum, and recent work shows that we may even have to consider neutrons of one or more kinds ..." (Ellis).

"We must examine how the neutron fits into the scheme of modern physics. From the point of view of the classical quantum theory, it is difficult to see how it can exist ..." (Lindemann).

Soon, however, it became obvious that Chadwick's discovery indicated a new direction in the study of atomic nuclei. Dmitri Iwanenko [78] and Werner Heisenberg [79] initiated the neutron–proton model of atomic nuclei. A new type of interaction, which we now call strong, found its place in physics. The story of its gradual acceptance by the physics community has been told in detail by Roger Stuewer [64].

9. The true birth of nuclear physics

Before 1929 the papers on radioactivity and related studies were classified in *Science Abstracts* [80] either in the section entitled "Molecular physics, Matter and Ether" or in "Radiation". In the 1929 edition the name of the former section was changed to "Molecular and Atomic Physics", while the "Radiation" section remained unchanged. More significant change took place in 1932. The section "Atomic and Molecular Structure" was divided into eight subsections, of which the first three were: "Atomic Structure", "Periodic System", "Isotopes and Isobares". Also a new subsection, called "Nucleus (Synthesis and Disintegration)", was introduced in the "Radioactivity" section.

One has to remember that 1932 was another *annus mirabilis*, which brought besides the neutron also the discoveries of the positron by Carl D.

Anderson [81]], and the deuterium by Harold Urey, Ferdinand Brickwedde and George Murphy [82]. John Cockroft and Ernest Walton achieved the first nuclear disintegration, $p + {}^7\mathrm{Li} \to \alpha + \alpha$, initiated by artificially accelerated particles [83], while Ernest Lawrence, Stanley Livingston succeeded to operate an 1.2 MeV cyclotron and later reported [84] on the first nuclear reaction studied with that accelerator.

Thus, it is not surprising that the following year (1933) in the "Atomic and Molecular Structure" section we find subsections such as: "Nuclear Constitution", "Artificial Disintegration of Elements", "Isotopes and Isobares", and "Neutrons". The number of papers on nuclear physics rocketed up, as shown in Fig. 7.

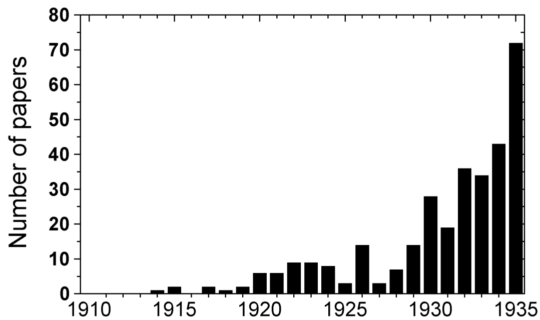


Fig. 7. The number of papers listed in Science Abstracts [80] with key words "nucleus" or "nuclear".

Thus the study of the atomic nucleus has finally come of age. Nuclear physics was born and started to be of central interest to physicists. Understandably, the theme of the Seventh Solvay Conference from October 22 to 29, 1933 was "Structure and Properties of Atomic Nuclei".

It was, however, still rather new and little known, as illustrated by an amusing story reported by Charles Weiner [85]: "In the early thirties Max Born had prepared a paper on quantum theory of the nucleus. He wrote the paper long-hand labelling it "For the Conference of Nuclear Physics". He made his "n"'s and "u"'s very much alike so that his stenographer in copying it wrote 'For the Conference of Unclear Physics' ".

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