The role of Rutherford, the father of nuclear physics

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Abstract.   In this article, I will give a short account of Rutherford's contributions to the birth and early developments of nuclear physics.

1. Introduction: annus mirabilis

Up until the most recent centenary celebrations in physics, 1905 was called the *annus mirabilis* mostly because of two turning points: relativity and quantization. No doubt, these are remarkable changes in the development of the foundations of physics. But it is true that even considering the exceptional advent of the phenomenological models of microscopic objects it introduced a new unprecedented picture of the world. Only in 1906 did Jean Perrin give a persuasive proof of the existence of atoms with no mention of their internal structure; the first speculative model of atomic structure was Thomson's pancake of a spherical positive charge distributed in space with electrons oscillating inside at special frequencies corresponding to the spectral lines. Probably, this period was one of the most exciting for physicists throughout the world.

2. Lord Rutherford of Nelson

Ernest Rutherford (1871 – 1937) came to the Cavendish Laboratory (UK) from his native New Zealand thanks to a grant; he spent a short time in and around that period at McGill University in Canada. In 1900 he made an extremely important discovery [1, 2]: the data of radioactive decays can be ordered by assuming that each emitting species has a characteristic "probability per unit time" of generating "Becquerel rays". Intrinsically casual phenomena enter the classical scene dominated by deterministic mechanical theories. Accurate measurements showed at this point that the time distribution of decays is Poissonian; this was clearly reported in the famous text *Radiation from radioactive substances* by Rutherford, Chadwick and Ellis ([3], p. 172). I think that this excellent and deep sample of the "change of paradigm" is not sufficiently underlined in the current teaching of physics. Rutherford did not interrupt his analysis at this result: he was a true Galilean and immediately moved to "sensate experience", to sensible tests for investigating the positive charges in atoms. The most plausible route to this end is scattering. Despite his reluctance to use theoretical calculations, he himself made the exercise of computing the coulomb scattering between two point charges; since then, we call his result the Rutherford cross section [4]. He deliberately neglected the electron cloud (he only knew that electrons were a small part of the atomic mass). But he immediately got confirmation of his ideas: an amount of back-scattered alpha particles compatible with his calculations showed that the atoms have a heavy nearly point-like central nucleus. This marked the birth of the so called planetary model

that was quantized by Niels Bohr and Arnold Sommerfeld after a short period of time (1913). It may be useful to list the problems on which Rutherford worked since then (with more or less success):

- Isotopes: the meaning of A (the mass number) and Z (the atomic number) and nuclear stability.
- Beta decay and the nuclear emission of energetic electrons.
- The mechanism of alpha decay.
- The experiments performed by German physicists.
- The sources of subatomic particles.
- Inelastic reactions.
- Nuclear electromagnetic radiation.

Following on the classification of the years prior to 1930, in epistemological terms, Sir Ernest was a "classical realist"; very conservative indeed. He is extremely diffident of theoretical physicists. There is a lucky accident in his favour: the Rutherford cross section has no quantization problems in the sense that the classical "collision parameter method" produced exactly the same results as the dominating first order Born approximation amplitude of the quantum theory of scattering.

3. A short review of the problems

The existence of isotopes is clear. The number A (the "mass") is very close to an integer multiple of the hydrogen mass (proton = hydrogen nucleus). The measured electron mass in cathode rays was known to be 2000 times smaller than that of a proton. An unstable nucleus emitted electrons in beta decay. It was very natural to think that a nucleus consisted of A protons and $A - Z$ electrons; altogether $2A - Z$ particles (fermions). The nuclear electrons should be tightly bound to protons in states unpredicted by current atomic models. Theory was in serious difficulty, for many reasons.

i)   It could not account for the electron-proton bound state;

ii)   Why should these states be unstable so as to produce beta decay?

iii)   Why was the spectrum of beta decay electrons continuous up to a maximum energy?

These problems occupied nearly thirty years of nuclear physics. In 1928, Franco Rasetti noticed that according to the theory of Raman molecular spectra a system of $2A - Z$ fermions should have a half-integer spin in the case of nitrogen ($A = 14, Z = 7$), contrary to the experimental evidence obtained by Rasetti himself. The imagination of physicists exploded; but the idea of a neutron is not so easily conjectured up. Some nuclear reaction events in which neutrons are emitted were confused with gamma ray emission. As far as the electron spectra are concerned, Bohr, Kramers and Slater proposed resurrecing an idea by Exner according to which a microscopic energy conservation might be a statistical law; even Schrödinger proposed this, years later. Many physicists had been infected by the seemingly open mindedness of theoretical physics, notwithstanding the difficulties of the Heisenberg representation of the mathematics of the time; that mathematics was mostly based on a deep understanding of partial differential equations, determining the immediate success of the Schrödinger approach especially after the interpretation of the "probability amplitudes" by Max Born. The tunnel effect, as proposed by George Gamow in 1928, gave a convincing explanation of alpha decay as a completely non-classical phenomenon in the penetration of forbidden potential barriers. Gamow imagined that an attractive short range nuclear potential added to the Coulomb repulsion formed a barrier of finite thickness; then he computed by the Schrödinger equation the probability of the transition in which an alpha particle is emitted by a nucleus (A, Z) leaving a nucleus $(A - 4, Z - 2)$ and

a fast helium nucleus. This was immediately a great success; Condon and Gurney reached the same conclusion just few weeks later. Also the Geiger and Nuttall law, known since 1912, and giving a simple relation between the lifetime and the alpha energy, was easily reproduced by the model.

Let me add a short comment on what the Italians (I already mentioned the important contribution by Rasetti) were doing at the time. Rutherford hesitated in believing such a possibility as the tunnel effect. He had devised a model in which the alpha particles were like satellites around an unstable nucleus to which they were bound by polarization forces; he had presented such a model at the conference held in Como in 1927 to celebrate Alessandro Volta. Giovanni Gentile jr., who had just completed the physics course at university and worked with a student, Ettore Majorana, showed that the Rutherford satellite model was unsustainable. Gentile also wrote a popular book [5], *Fisica Nucleare*, issued in 1937 which is still very up to date. Rutherford had excellent collaborators: among them, James Chadwick. At that time in Germany, Bothe and Becker, using electric counters, had explored the possible existence of energetic gamma rays. They actually found a neutral component; but the assumption that it was a gamma ray required that it have too large an energy. Chadwick repeated the German experiment and showed clearly that what was emitted was a "neutral proton", to be rebaptized "neutron" shortly afterwards. One of the first to understand thet there was a neutron in these events was Ettore Majorana.

4. Amaldi about the Cavendish group

Edoardo Amaldi wrote and published in 1984 an important review [6]: *From the discovery of the neutron to the discovery of nuclear fission*. In that report, the paragraphs from 1.4 to 1.6 are dedicated to the Cavendish group, particularly to Rutherford and Chadwick, but also to Feather and Dee. On June 3, 1920, Rutherford gave a "Bakerian Lecture" to the Royal Society; on that occasion, he mentioned the neutron for the first time as a short for the electron-proton tightly bound state. Amaldi recounts that throughout the twenties the word neutron was improperly used many times, always referring to an exotic bound state. So did Nernst, in 1898 speaking of electrolytic solutions, as referred by Johannes Stark, in a conjecture about radioactivity. Many people were impressed by the regularity of isotopic masses as evidenced by Aston using mass spectrometers. I also list some amusing speculations in the literature:

- The famous Dutch lawyer Antonius Johannes van den Broek was very interested in the periodic system of Mendelejev and speculated on electrons and protons. In 1921, Van den Broek proposed a model with neutral particles constituted by alpha particles bound with two electrons; this possibility was reconsidered by Rutherford in 1927.

- Working on the Aston data, the Chicago chemist William Draper Harkins proposed in 1915 a model in which beryllium was a bound state of a neutron and two alpha particles.

- Dimitri Ivanenko in the USSR was perhaps the first to conceive of a model with protons and neutrons as genuine different nucleons.

When Chadwick produced the experimental evidence of the neutron, in 1932, the theoretical difficulties of the electron-proton bound state appeared unsurmountable. The notion of the De Broglie wave length of a particle indicated that the nuclear size implied relativistic energies for the bound electrons. For instance, even for a large nucleus with $A = 210$ the bound electron should possess 210 MeV. Nevertheless, Werner Heisenberg and his assistant Guido Beck insist on e-p bound states. The most impressive changes will occur in the thirties.

- The Heisenberg-Majorana exchange forces, based on concepts developed for molecular dynamics, were accepted by the nuclear community as fundamental forces.

- Pauli proposed the neutrino and shortly after Fermi invented the theory of weak interactions. A new dedicated mathematics was invented by Pascual Jordan, in which the introduction of creation and destruction operators, made the physics of quantum fields much easier.

- Frederic Joliot and Irene Curie discovered the transmutation reactions of light nuclei.

- Fermi understandood the efficiency of slow neutrons in destabilizing nuclear structures; he failed to understand the most dramatic result: Uranium fission.

Sir Ernest Rutherford, Lord of Nelson, died in October 1937. Forgive my too short account of his enormous history: he was the reference head of a community which is one of the most impressive in the history of science. Thus, the father of nuclear physics.

References

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