When Energy Conservation Seems to Fail: The Prediction of the Neutrino

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Abstract A historical case study concerning the serious doubts that arose in early 1930s about the validity of the law of energy conservation in nuclear disintegrations, and the hypothesis of neutrino, will be closely analyzed with the goal of promoting understanding of the nature of science. This work is based upon primary archival and printed sources, with a particular focus on the proceedings of the first International Conference of Nuclear Physics which was held in Rome on October 1931.

History of physics; physics education; nature of science; conservation of energy; neutrino; Niels Bohr; Wolfgang Pauli; Enrico Fermi

There are more things in heaven and earth, [Horatio],

Than are dreamt of in [y]our philosophy

Ernest Rutherford, letter to Niels Bohr, November 19, 1929

William Shakespeare, Hamlet, Act 1, Scene 5

1 Introduction

When Ernest Rutherford, father of the nucleus, heard that Niels Bohr, father of the quantum mechanics, was “on the war path and wanting to upset the Conservation of Energy”, he was upset as well. Rather than to part with a law that played so prominent a role both in classical and modern physics, Rutherford much preferred to believe that what Shakespeare wrote in Hamlet, Act 1, Scene 5, could be extended also to the nuclear world. In a few years the physics took a path different of that expected by Bohr and, to Rutherford’s relief , Wolfgang Pauli’s hypothesis of the *neutrino* and Enrico Fermi’s *theory of beta decay* dispelled the doubts surrounding the conservation of energy.

This case-study has been often proposed within science education, e.g. by Fuller et al (1977) as a way to illustrate formal reasoning patterns among students, by Pantidos et al (2001) as an inspiration for the use of drama in physics teaching, and by Solbes & Tarìn (1998; 2004) and Solbes et al (2009) as a tool to overcome a learning difficulty of the principle of conservation of energy in upper secondary school education, namely the idea that this principle is limited to mechanical and thermodynamics phenomena. In this paper, the conservation of energy and neutrino case study will be instead closely analyzed, within the context of the nuclear electrons issue, with the goal of promoting understanding of the nature of science upon the basis of primary archival and printed sources, with a particular focus on the proceedings of the first International Conference of Nuclear Physics held in Rome on 11-17 October 1931 (figure 1). This conference, which was organized by Enrico Fermi under the aegis of the Royal Academy of Italy and the Volta Foundation with a budget of 200,000 lire (corresponding to about 200,000 of present day euros), gathered indeed the most distinguished scientists in the field of early 1930s nuclear physics (figure 2).

Figure 1. Proceedings of the Rome conference of nuclear physics (R. Accademia d'Italia 1932).

Figure 2. Participants in the Rome conference. Front (left to right): O.W. Richardson, R.A. Millikan, G. Marconi, N. Bohr, W. Bothe, B. Rossi, L. Meitner (partly hidden), and S. Goudsmit. Behind Marconi is M. Curie. Behind her is J. Perrin, and behind him is E. Fermi. P. Debye is behind Richardson. W. Pauli was not yet in Rome at the moment of the photograph.

2 Beware the Electron (In-the-Nucleus)

If a nuclear physicist was asked in the 1920s about the constitution of the nucleus, in all likelihood he would have replied that the nucleus itself is not an elementary particle, but is built up of elementary particles, namely protons and electrons. To believe that protons were inside the nucleus did not require a great leap of faith, since Ernest Rutherford had discovered in 1919 that protons could be knocked out of light elements by alpha particles bombardment. On the other hand, electrons also were likely inhabitants of the nuclear world as it was known for several years that they appeared to be ejected by the nuclei during the radioactive beta decay of some heavy elements.

This simple proton-electron nuclear model neatly explained why nuclei have masses that are nearly an integer. So, if A was the mass of a nucleus, such a nucleus had to contain A protons. In order to explain why a nucleus had a given atomic number Z, the model assumed also that the nucleus had *A-Z* electrons, beyond *Z* orbital electrons surrounding the nucleus. For example, fluorine has an atomic mass number of 19 and an atomic charge of 9. The nucleus of a fluorine atom must therefore contain 19 protons, to give the correct atomic mass, and 19 – 9 = 10 electrons to give the correct charge.

As it was established by the study of the band spectrum of the hydrogen molecule, both protons and electrons were known to possess an angular momentum equal to

$$I = \frac{1}{2} h/2\pi$$

which in turn could congregate into alpha particles. Thus, according to this model the alpha particle was made up of 4 protons and 2 electrons, in order to ensure the charge (equal to two positive units).

If, on the one hand, by this model of the nucleus, the nuclear origin of the electrons present in the radioactive beta decay was immediately ensured, on the other hand, the presence of the electrons in the nucleus as well the mechanism of their expulsion in radioactive processes posed serious theoretical problems.

2.1 The Confinement of the Electron in the Nucleus

According to Heisenberg's uncertainty principle, if the electrons, whose mass is about 2000 times smaller than proton's, are confined to an orbit of nuclear size (i.e. 10^{-12} cm), they would travel to a relativistic speed very close to the speed of light, that is v = 0.9998 c (Gamow 1931, p. 3), and would get a total energy close to 20 MeV. Consequently, the electrons' energy would be far greater than their rest-mass energy (0.51 MeV) and "far greater than the energy that they actually exhibit" (Bohr 1932a; Rossi 1931) as beta decay particles (that is a few MeV). In addition, because of this enormous kinetic energy, the electron mass would be no longer negligible and possibly become sensitive to the atomic weight of the element, in contrast to experimental data (Fermi 1932; 1933a).

2.2 The Electron Spin

Another issue concerned the inherent angular momentum (spin) of the alleged electrons in the nucleus. According to quantum mechanics, the electron had a spin. As for the bound electrons in the atom, the idea that the electron had a mechanical momentum and a magnetic moment seemed to work. Moreover, this idea fitted well within Dirac's relativistic theory of the electron since it was one of the consequences of such a theory. It might be expected, therefore, that the electron would preserve this property also within the nucleus. However, as soon as this property was attributed to the nuclear electrons, serious difficulties arose both from a theoretical point of view and from an experimental point of view.

Under the theoretical point of view, as was pointed out by Neville Francis Mott in his report to the Rome International Conference of Nuclear Physics, if the Dirac theory was applied to the case of the nuclear electron, for which the speed must be considered approximately equal to that of light, the existence of this property could no longer be detected. If the electrons were thought to be contained within the nuclei they appeared to lose this property. If, on the other hand, this property was kept as a property to the electron, one had to conclude, as Mott did in his report, that "it is not possible to use the Dirac equations to describe the behavior of the electrons in the nucleus" (Mott 1932, p. 32).

No less serious were the experimental difficulties caused by the application of the spin concept to nuclear electrons. As Samuel Goudsmit neatly showed in his report to the Rome conference, there was indeed a number of experimentally verifiable properties where the contribution of nuclear electron spins would be manifest, and it was not.

a) The amplitude of the separation of the hyperfine structure

The ordinary *fine structure*, that is the splitting of spectral lines into a number of components due to energy changes produced by the electron spin – orbit coupling, could be observed by an ordinary spectroscope. Besides this, a much more fine line splitting effect, thereby called *hyperfine structure*, was known.

On the basis of quantum mechanics, the amplitude of the separation of the hyperfine structure (which was about three orders of magnitude smaller than the splitting due to the fine structure and required therefore spectrographs of high resolving power) was deemed to depend on the interaction between the electron's total angular momentum and the nuclear spin, which in turn depended directly from the magnetic moments of the electrons and protons contained in the nucleus.

Since it was known that the magnetic moment of the electron is equal to 1 μ_B (Bohr magneton) while that of the proton is 1/1838 μ_B, that is 1838 times smaller than that of the electron, it was expected a small separation in the hyperfine structure of the atoms with an even number of electrons. This expected outcome was due to the fact that the electron magnetic moments would cancel each other, and that there would be only the very small effect of the proton magnetism. Vice versa, it was expected a very large fine structure separation for the atoms with an odd number of electrons, since in these cases there would be a predominant effect of the electron magnetism, i.e. magnetism of the order of one $\mu_{B.}$

Instead, as emphasized by Goudsmit, the experimental data available at the time showed that “the magnitude of the hyperfine structure agrees with a nuclear magnetism of the order of that of a proton, even in cases where there are an odd number of electrons in the nucleus” (Goudsmit 1932, p. 40).

b) Values of nuclear moments

As for the values of nuclear moments, these could be calculated via the hyperfine structure, as previously suggested by Fermi, for example, or as it was shown in 1927 by Friedrich Hund, through the molecular spectra.[1]

Considering the nucleus composed of protons and electrons, which obey the Pauli principle and have an angular momentum equal to ½ (h/2 π), it was expected a half-integer nuclear moment when the nucleus contained in the total (proton and electrons) an odd number of particles. Vice versa, it was expected an integer nuclear moment when the nucleus contained an even number of particles. However, as stressed by Goudsmit (1932, p. 40) through the study of the hyperfine structures of some nuclei, it was found that nuclei that should consist of an even number of particles had a half-integer angular momentum. In particular, all the isotopes of cadmium (even charge equal to 58) and lead (Z = 82), while containing an even number of particles in the nucleus, have an half-integer nuclear spin.

It is clear that, if the nucleus consists of protons and electrons, the fact that the total number of particles was even or odd depended on the fact that the positive charge was even or odd. (Of course the situation will change when, in 1932, following the discovery of the neutron, the nucleus is considered to be made of protons and neutrons).
A similar situation was shown by the study of the molecular spectra, in particular of the nitrogen ion (N_2). The nitrogen (A = 14, Z = 7) should have an odd number of particles in its nucleus (21, that is 14 protons and 7 electrons). Its nuclear moment must therefore be a half-integer multiple of h/2π. Instead, experimentally it was known that nitrogen nuclei have integer spin (Kronig 1928, Ornstein & van Wijk 1928).

It is interesting to observe that the nitrogen anomaly was reported for the first time by Heitler and Herzberg (1929) on the basis of some measurements made in the same year

[1] Hund (1927) demonstrates that, in the case of a diatomic molecule, it is possible to determine the value of the nuclear moment I, starting from the ratio between the intensities of the strong and weak lines in a spectral band. Let R be this ratio and J the nuclear moment, it was found indeed: R = (J +1) / J). By this method, applied to the hydrogen molecule, it was for example obtained that the angular momentum of the proton was ½ (h/2π).

by Franco Rasetti (during a fellowship abroad) on the Raman effect in the ammonia molecule. As we know through Giulio Racah review paper about the Rome conference (Racah 1931), while Rasetti actually reported about this work in a communication to the conference, no report was published in the proceedings.[2]

c) Statistics laws

Another problematic issue of the nuclear electron was the contribution of its spin to the statistics laws.

According to general principles of quantum mechanics, if it was admitted that all of the atomic nuclei were composed of protons and electrons, since both protons and electrons obeyed the Fermi-Dirac statistics and had an intrinsic mechanical moment equal to ½, one could deduce that the nuclei had to follow the Fermi-Dirac or the Bose-Einstein statistics depending on whether the total number of particles within them was odd or even.

Following this rule the nitrogen, that as above reported was supposed to contain an odd number of elementary particles (14 protons and 7 electrons), should obey the Fermi-Dirac statistics. However, as it was experimentally determined by studying its molecular spectrum, the nitrogen obeys Bose-Einstein statistics, that is, as noted by Goudsmit (1932, p. 39), "as if the nucleus contained an even number of particles."

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[2] Rasetti, former Fermi classmate at the Scuola Normale Superiore in Pisa, was at that time Professor of Spectroscopy at the Institute of Physics of Rome. He had "spent the academic year 1928-29 at the California Institute of Technology in Pasadena, under a grant from the Rockefeller Foundation." (Rasetti undated, p. 8). In particular, he had obtained an "International Education Board" fellowship with the goal of "undertaking experiments on the Raman effect in diatomic gases, that is measuring their rotational energy levels from their band spectra" (Stuewer 1983, p. 35). Among the various gases studied by Rasetti was the ammonia. In this regard, Rasetti (1929) made the following observations, immediately reported by Heitler and Herzberg: "it is significant for the properties of the nuclei that N_2 and H_2, which have a similar electronic structure […], behave in opposite ways as to the relative weight of odd and even rotational states." It should be stressed that Rasetti's measurements, as also the ones he made in 1930 (which confirmed the previous results), took place in a context completely foreign to nuclear physics. For example, at the 1930 Congress of the Italian Society for the Advancement of Science, he reported about this work without making mention of the nuclear physics issues (Rasetti 1930), even though during the next session of the same congress, Fermi faced the issue of the nuclear moments (Fermi 1930). As we have discussed, others (e.g. Heitler and Herzberg) will note for the first time that Rasetti's results represent a serious difficulty for the issue of a statistics of nuclei based on a proton-electron nuclear model.

As the number of protons was even, while that of the electrons was odd, it was as if the electrons did not contribute to the statistics of nucleus.

After having discussed all these difficulties for the electrons inside the nucleus in relation to their spin, Goudsmit concluded as follows:

> [The] laws which hold for the outside electron configurations, cannot be applied to the nucleus. The results about the nuclear moment can be remembered by saying that the electrons in the nucleus seem to lose their spin and magnetic properties and that only the protons determine the spin moment and the magnetic moment of the nucleus. (Goudsmit 1932, p. 40)

2.3 The Continuous Spectrum of Beta Rays

Another problem related to the presence of electrons in the nucleus concerned the so-called continuous spectrum of beta rays.[3]

The history of the discovery of the continuous energy spectrum in beta decay dated back to Chadwick's 1914 experiment (Chadwick 1914). Although this experiment did not firmly establish that the spectrum of beta rays shows a continuous spectrum, nevertheless it did provide important experimental evidence later to be much debated.

In Chadwick's apparatus, by varying a magnetic field successive portions of a radon source spectrum (the source is fixed at Q in figure 3) entered a counter (T) and the amount could be determined by the frequency of the throws of the string electrometer attached to the counter. Chadwick's measurements are shown in figure 4, where curve A represents the number of beta particles of a given energy, and curve B is the ionizing action of the particles when a ionization chamber is used in place of the counter. These curves showed clearly that the beta ray emission fell into two parts: a small line spectrum superimposed on a broad continuous spectrum (Rutherford, Chadwick & Ellis 1930, p. 399-401).

[3] See for example Brown (1978), Guerra & Robotti (2009), Jensen (2000), Pais (1986).

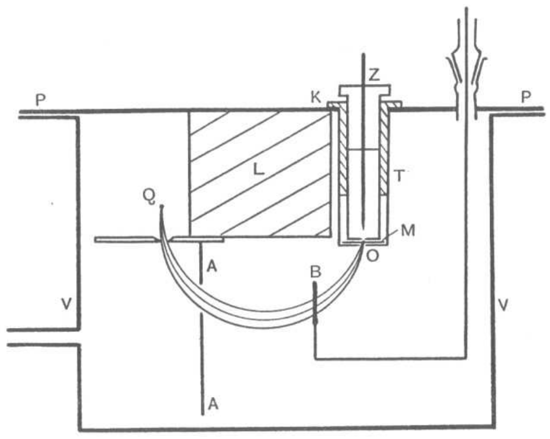

Figure 3. Chadwick’s apparatus enabling the discovery of the continuous spectrum of beta rays. Radioactive source (Q) and counter (T) are placed inside an evacuated box (V). (Rutherford, Chadwick & Ellis 1930, p. 400).

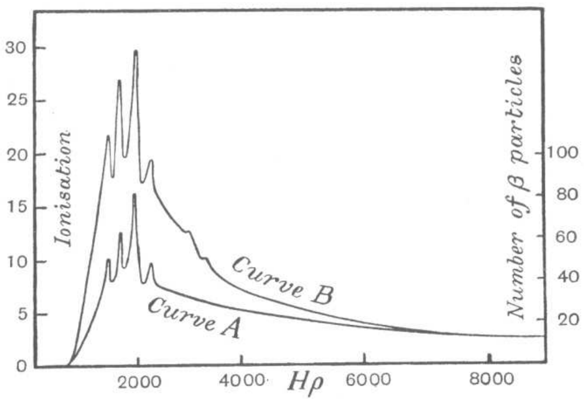

Figure 4. Number of beta particles (curve A) and ionizing action (curve B) as a function of velocity as obtained by Chadwick’s measurement. (Rutherford, Chadwick & Ellis 1930, p. 400).

While the line spectrum was later explained by Rutherford as a secondary effect due to the conversion of γ rays, the continuous spectrum seemed difficult to reconcile with the discrete quantum states of the nucleus.

Actually, there was not a general consensus from the scientific community about the results of Chadwick's experiment. As it is remarked by Franklin (2004, p. 50), this was partly because no other experiment had replicated Chadwick's results, and partly because there were others, such as Lise Meitner, who had suggested that the inhomogeneity of the electron energies was introduced after the actual expulsion from the nucleus, e.g. by a γ-rays emission in the passage of the electrons through the intense electric field of the atom (Meitner 1922a, 1922b). Meitner suggested also that the resolution of Chadwick's apparatus was not enough to resolve many discrete lines and that this accounted for his observed continuous spectrum (Franklin 2004, p. 50). Soon after Meitner's work, Chadwick's experiment was replicated by Chadwick and Charles D. Ellis (1922), with a result supporting the view that "the continuous spectrum is emitted by the radioactive atoms themselves" rather than due to electrons ejected by γ-rays or backscattered electrons.

As remarked by Rutherford, Chadwick & Ellis in their influential 1930 radioactivity textbook,

> [it] would be a long task to analyse the various ways in which the heterogeneity [of electron energies] might be introduced if sufficient freedom in the choice of hypotheses were allowed, but all such hypotheses would have as their one object to make the total energy the same for each disintegration. If the continuous spectrum extends from an upper limit of energy E_{max}, then this energy of disintegration could not be less than E_{max}. If on the contrary the disintegration electrons were actually ejected from the nucleus with various energies, then the average energy of disintegration should correspond to the mean energy of the continuous spectrum. A final decision between the two views would thus be reached by measuring the total energy of disintegration of a β ray [nuclide] whose continuous spectrum was known. (Rutherford, Chadwick & Ellis 1930, p. 401-402)

Ellis and William A. Wooster suggested just this kind of experiment in 1925 and reported about their definitive experimental results in 1927. Ellis and Wooster made use of "radium E" (Bismuth-210), whose continuous spectrum has a maximum energy of 1.05 MeV and an average energy of 0.39 MeV (Figure 5). A measurement of the heating effect given by the radioactive source provided a crucial experiment to distinguish between the two hypotheses, one predicting a value of 0.39 MeV per disintegration, the other 1.05 MeV. The heating effect was measured through a calorimeter (Figure 6a) which consisted of a lead tube of rather more than 1 mm thickness so that all the beta rays were absorbed. To avoid external disturbances, a second identical calorimeter was constructed into which a dummy non activated wire was lowered (Figure 6b), and the steady temperature difference set up between the two calorimeters was measured by a system of thermocouples attached to a sensitive galvanometer. The result of this experiment gave 0.35 ± 0.04 MeV, that is a value entirely incompatible with the value predicted by the alternative theory that the energy of disintegration is always the same (Ellis and Wooster, 1925, 1927). (Ellis and Wooster's experimental result on the heating effect was later supported by Meitner and Orthmann (1930), who found a value of 0.337 ± 0.04 MeV per disintegration through an improved apparatus).

This result seemed to contradict the fact that, despite this difference of energy between the electrons emitted during the same process of beta decay, in the end there was always one type of radioactive product. In other words, the law of decay, for a given atomic species, was always the same, that is all the nuclei of the same species decayed in the same way.

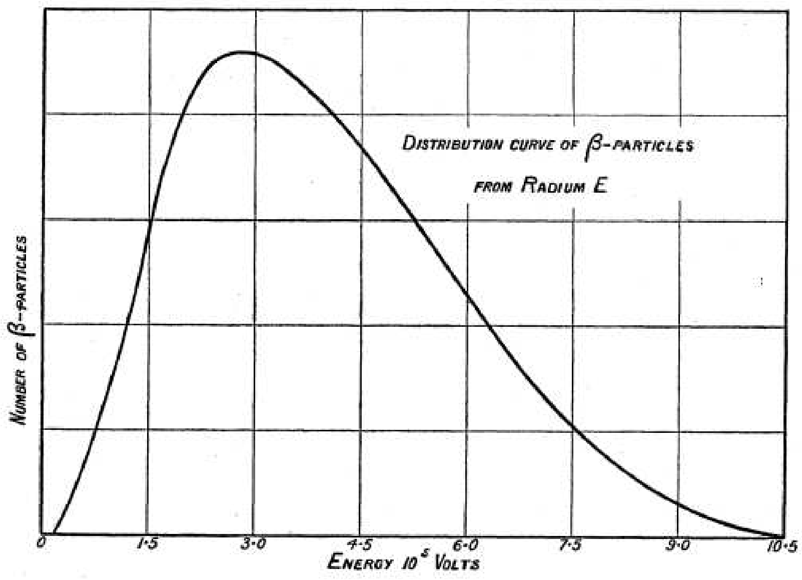

Figure 5. Radium E’s beta particles spectrum (Ellis & Wooster 1927, p. 111).

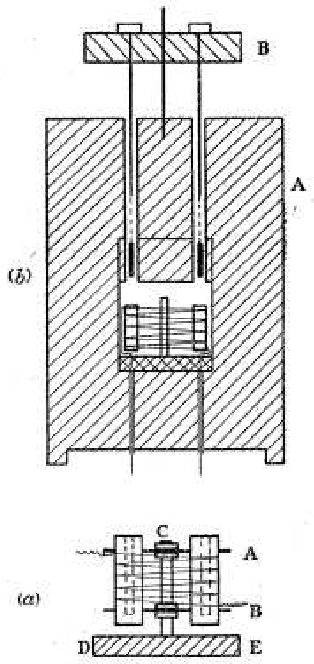

Figure 6. Apparatus for measuring the heating effect of radium E (Ellis & Wooster 1927, p. 113).

In early 1929 George Paget Thomson, then Professor of Natural Philosophy at the University of Aberdeen, stressed that Ellis and Wooster's experiment posed a serious problem to contemporary physics. According to Thomson:

> We are […] reduced to suppose either that the conservation of energy does not apply to each individual process, or that among the atoms either of the Radium E or of its product Radium F (or both) there are some individuals with a million volts more energy than others, or that there is some way at present unknown by which the atoms can equalize their energy. (Thomson 1929, p. 405)

As a matter of fact, the first road (inapplicability of the conservation of energy), had been formerly suggested, but rejected by Ellis and Wooster themselves. As they wrote in 1925,

> if we were to consider the energy to be conserved only statistically there would no longer be any difficulty in the continuous spectrum. But an explanation of this type would only be

> justified when everything else had failed, and although it may be kept in mind as an ultimate possibility, we think it best to disregard it entirely at present (Ellis & Wooster 1925, p. 858).

As we will show in next sections, such an "ultimate possibility" was pursued by Bohr and the hypothesis of another way to equalize the energy by Pauli. As for the other hypothesis suggested by Thomson, that is the idea that individual atoms of a given radioactive product are essentially different, it was not pursued further. Under such an hypothesis, as later emphasized Bohr himself, "it would be difficult to understand [the] common rate of decay" for radioactive elements and to account for "the essential identity of any two nuclei containing equal numbers of protons and electrons" (Bohr 1932a, p. 129-130).

3 A Departure from the Law of Energy Conservation

The main supporter of the idea that the puzzle of the continuous energy spectrum of the electrons in β-decay might be explained through "a departure from the law of energy conservation in nuclear disintegrations" was Niels Bohr (1932a).[4] As early as July 1, 1929, Bohr, stimulated by Thomson's views,[5] sent a note to Wolfgang Pauli discussing the possibility of energy conservation being violated in β-decay and its possible relevance to the physics mechanisms occurring in the interior of the stars, while admitting that "little basis we possess at present for a theoretical treatment of the problem of β-ray disintegrations" (Bohr 1985, p. 443; Bohr 1986, p.

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[4] As it is well known in the history of modern physics literature, Bohr had previously assumed that the law of conservation of energy has only statistical validity within the context of the so-called BKS theory (after the names of Niels Bohr, Hendrik Kramers, and John Slater) of the wave-particle dualism (Bohr et al 1924). The doubts about the validity of the conservation of energy had been expressed much earlier by Bohr, e.g. in his 1919 correspondence with Charles Galton Darwin, a grandson of the biologist (Stolzenburg 1984). The validity of the conservation of energy in each elementary process involving the interaction between radiation and matter, and therefore the refutation of BKS theory, was demonstrated one year later by Bothe and Geiger (1925) and by Compton and Simon (1925).

[5] Besides stressing the problem posed by Ellis and Wooster's experiment, Thomson advocated also the view that this was a "natural consequence of the wave theory of matter" (Thomson 1929, p. 406). While Bohr thought that "any simple explanation of the continuous β-spectra based on the ordinary ideas of wave mechanics", as Thomson's one, was unlikely, he did not conclude that energy must be conserved in beta decay (Bromberg 1971).

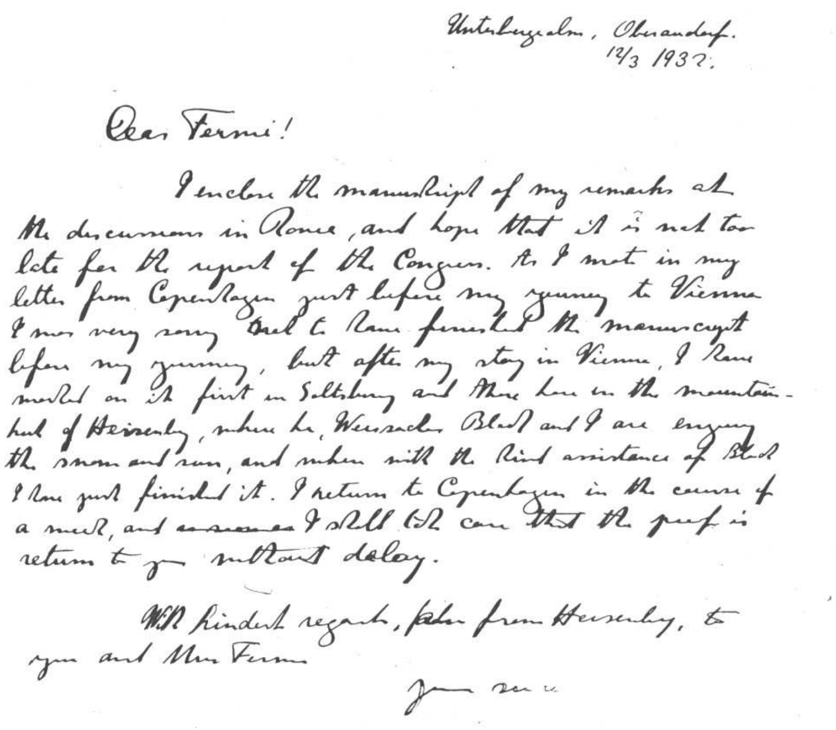
[5]). Pauli's reply was very negative – e.g. "we really *don't* know what is the matter here. You don't know either, and can only state reasons *why* we understand nothing. […] *In any case let this note rest for a good long time and let the stars shine in peace!*" (Bohr 1986, p. [6]) – and in fact Bohr never published his note.

Actually, Bohr openly advocated this idea for the first time during a Faraday Lecture to the Chemical Society in London delivered on May 8, 1930. Yet, as remarked in Bohr's *Collected Works*, the published text of the lecture, where he wrote that "we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations, and are even led to complications and difficulties in trying to do so" (Bohr 1932b), was written only in 1932. In the transcript of the lecture there is only a single sentence near the end, "referring to possible limitations in the applicability of such ideas as energy and momentum in nuclear physics" (Bohr 1986, p. [7]).

The first, full, open announcement of Bohr's idea on this matter occurred in October 1931 during the Rome international conference of nuclear physics.

In the section "problems of intra-nuclear electrons" of his paper *Atomic stability and conservation laws* (Bohr 1932a) sent to Fermi for inclusion in the proceedings of the Rome conference (Bohr 1932c), Bohr discussed the β-decay puzzle after having reported about how quantum mechanics can explain the nuclear disintegrations in which alpha particles are emitted.

> Just like the α-ray products, all β-ray products have a well-defined rate of decay, but nevertheless for each product the energy of the emitted β-particle varies continuously within wide limits. If energy were conserved in these processes, it would imply that the individual atoms of a given radioactive product were essentially different, and it would be difficult to understand their common rate of decay. If, on the other hand, there is no energy balance, it is possible to explain the law of decay by assuming that all nuclei of the same product are essentially identical. […] Still, we must remember, after all, that the essential stability of atoms is an implicit assumption in the whole classical description of natural phenomena, and we cannot therefore be surprised if classical concepts fails in accounting for their own foundation. Just as we have been forced to renounce the ideal of causality in the atomistic interpretation of the ordinary physical and chemical properties of matter, we may be led to further renunciations in order to account for the stability of the atomic constituents themselves. (Bohr 1932a, p. 129-130)



Unterbergalm, Oberaudorf.
12/3 1932.

Dear Fermi!

I enclose the manuscript of my remarks at the discussions in Rome, and hope that it is not too late for the report of the Congress. As I wrote in my letter from Copenhagen just before my journey to Vienna I was very sorry not to have finished the manuscript before my journey, but after my stay in Vienna, I have worked on it first in Salzburg and then here in the mountain-hut of Heisenberg, where he, Weizsäcker, Bloch and I are enjoying the snow and sun, and where with the kind assistance of Bloch I have just finished it. I return to Copenhagen in the course of a week, and I shall take care that the proof is return to you without delay.

With kindest regards, also from Heisenberg, to you and Mrs Fermi

Yours ever

Figure 5. Bohr’s letter to Fermi accompanying his manuscript for the Rome conference proceedings (from the library of the “Accademia Nazionale delle Scienze detta dei XL” in Rome, repository of Source for History of Quantum Physics).

As it occurred in the Faraday lecture, Bohr’s paper to the Rome conference was actually written months after the meeting (as shown in Figure 7, it was sent to Fermi on March 12, 1932; see Bohr 1932c). However, the available scientific accounts written soon after the end of the Rome conference (Racah 1931, Rossi 1931) show that Bohr entered into some details on October 17 (in the discussion section following Max Delbrück’ speech about Gamow’s quantum theory of the nuclear structure), and that his words much impressed the audience. Among the concepts discussed by Bohr figured the idea of renouncing to the principle of conservation of energy in order to explain the continuous beta spectrum and the fact that this distribution does not correspond to different excitation states of the nuclei neither before nor after the disintegration. Also, Bohr actually drew a parallel, later echoed by the latest sentence of his paper, between our being forced to renounce the conservation of energy in nuclear physics as in the past we were forced to renounce the ideal of causality in the atomic physics field. Furthermore, it is highly significant the contents of the letter written from Rome by Marie Curie to her daughter, Irene on October 13, 1931, that is the day of Goudsmit’s lecture. In this letter, Madame Curie briefly reported about the conference and stressed that “I have hitherto very little to say to you except that Bohr strongly emphasized the impossibility of actually applying [quantum] mechanics inside the nucleus” (Curie-Sklodowska to Curie 1931).

As regards the impossibility of applying quantum mechanics to the nucleus, another letter, written by Bohr to Rutherford on May 2, 1932, is of particular significance. After reporting to Rutherford about his special interest "in the foundation of the new mechanics and its limitations", Bohr also suggested to him a possible way to experimentally test this hypothesis:

> At the end of my Faraday lecture [...] I introduced a few remarks about the possible failure of energy conservation as regards electrons in nuclei, and in an account to the Rome congress, which I hope to send you soon, I have entered into more detail of the theoretical side of this problem. If it should be possible to excite electron emission from nuclei by means of the recently discovered powerful agencies, it would perhaps be possible to set this fundamental problem (Bohr 1932d).

By this suggestion, Bohr was thinking about the possibility of obtaining electrons out of the nuclei according to a process similar to that leading to the ejection of protons through the alpha particles bombardment of light nuclei. And, of course, by "recently discovered powerful agencies" Bohr was mainly referring to a new particle discovered in late February 1932 by James Chadwick, at the Cavendish Laboratory in Cambridge, through the alpha particles bombardment of beryllium. This new particle, which was understood to be a new uncharged constituent of the nucleus, was about as massive as the proton, and was named by Chadwick as "*neutron*". In spite of its being a nearly ideal "nuclear bullet", no electron could be ejected by its use. As a matter of fact, the "neutron" was the key to the solution of the nuclear electrons puzzle. However, "Chadwick's neutron" was not the only one available in the market…

4 A New Particle (Or Two?)

By the time Chadwick reported about the *experimental* discovery of a new nuclear constituent called neutron (1932), another *theoretical* neutron had entered the picture of nuclear physics thanks to Pauli.

On December 4, 1930, Pauli wrote indeed a letter, later to become famous, headed to "Dear radioactive ladies and gentlemen" gathered at a physics meeting in Tübingen, Germany (for an English translation of Pauli's letter see Brown, 1978). Besides explaining that he was unable to attend to the meeting because he was expecting much more from a ball which he wished to attend in Zurich, Pauli wrote in this letter that he had hit upon a "desperate remedy" to save statistics and conservation of energy, namely

> the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. The continuous β-spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant. (Brown 1978, p. 27)

The contents of Tubingen letter shows that Pauli, in order to face the issue of continuous beta-spectrum, invented one particle that he named, as Chadwick will, about one year later, "*neutron*". Interestingly, "Pauli's neutron" was deemed by Pauli to be a genuine neutral spin ½ *nuclear constituent* (as "Chadwick's neutron" will be one year later), much lighter than the other *known* nuclear constituents, protons and electrons.

By the hypothesis of "Pauli's neutron" the problem posed by the continuous beta-spectrum was immediately solved. Also all the problems raised at the experimental level by the spin of the nuclear electron which, as we have seen, concerned exclusively nuclei that were thought to consist of an odd number of electrons (in which the contribution of the electrons seemed to be missing), appeared to be resolved. Since the number of "Pauli's neutrons" was equal to that of the electrons, the spin of these particles "neutralized" indeed the spin of electrons, and then, in the case of an odd number of electrons, it was as if the electrons were not present. On the other hand, when the nucleus had an even number of electrons, as we have seen, everything kept working by adding one "Pauli's neutron" for each electron present. In this case, also the neutrons would be equal in number, and therefore their spin would cancel each other out.

Pauli repeated his suggestions about the "neutron" at the 88th meeting of the American Association for the Advancement of Science and associated societies, held in Pasadena, California, from June 15 to 20, 1931. Differently from what Pauli later recalled in a lecture delivered in Zurich in 1957 (Pauli 1961,1964), in June 1931, Pauli still considered his "neutron" to be a nuclear constituent and kept referring to them as "neutrons". As outlined in the physics section of the Pasadena meeting (AAAS 1931), Pauli delivered his speech within the second symposium, presided by W.F.G. Swann and devoted to *The present status of the problem of nuclear structure*:

> Dr. W. Pauli, of Zurich, Switzerland, pointed out that the two chief difficulties in nuclear theory are the breakdown of the alternation rule and the existence of a continuous beta-ray spectrum. A number of elements such as nitrogen do not obey this rule. Dr. Pauli attempted to overcome this difficulty and at the same time provide for the possibility of a continuous beta-ray spectrum by the introduction of a third kind of particle called the neutron. If the

> neutron can be assumed to have a spin angular momentum of one half quantum, and a mass less than one one-hundredth the mass of a proton, all known experimental results can be explained. (AAAS 1931, p. 111)

Pauli's speech in Pasadena was followed by the one delivered by Goudsmit, who reviewed recent successes and failures of theories of hyperfine structure. As a matter of fact, two months later Goudsmit himself reported about Pauli's hypothesis in his paper (written in August 1931) for the Rome conference. After pointing out the difficulties associated with the presence of electrons in the nucleus, he continued indeed as follows:

> At a meeting at Pasadena in June 1931, Pauli expressed the idea that there might exist a third type of elementary particles besides protons and electrons, namely "neutrons". These neutrons should have an angular momentum ½ $h/2\pi$ and also a magnetic moment, but no charge. They are kept in the nucleus by magnetic forces and are emitted together with β-rays in radioactive disintegration. This, according to Pauli, might remove present difficulties in nuclear structure and at the same time in the explanation of the β-ray spectrum, in which it seems that the law of conservation of energy is not fulfilled. If one would find experimentally that there is also no conservation of momentum, it would make it very probable that another particle is emitted at the same time with the β-particle. The mass of these neutrons has to be very much smaller than that of the proton, otherwise one would have detected the change in atomic weight after β-emission. Pauli also believes that neutrons may throw some light on the nature of cosmic rays. (Goudsmit 1932, p. 41)

Certainly, as emphasized by Goudsmit, Pauli's "neutron" solved the problem of the continuous spectrum of beta rays and the experimental problems raised by the nuclear spin of the electron. Furthermore, it provided a theoretical explanation of the sharp upper limit of the continuous β-ray spectrum that, by late 1920s, has been determined "in a considerable number of cases and appears to be quite definite" (Sargent 1933, p. 659). As later recalled by Pauli himself, he had many private discussions in Rome on the issue of his neutron, and "from an empirical point of view, it seemed to me decisive, whether the beta spectra of electrons showed a sharp upper limit or whether they showed a Poisson distribution dropping off toward infinity. In the first case, in my opinion, my idea of new particles would be established" (Pauli 1961/2000, p. 6). Actually, we do not have primary sources dating back to the time of Rome conference corroborating Pauli's memories. In fact, this matter was settled only by the end of 1932 by B.W. Sargent (1933) who experimentally provided a "strong indication that the end-point is one of the characteristics of the [β-ray] spectrum", and by Ellis (present in Rome as well) and N.F. Mott, who in May 1933 provided a theoretical interpretation.

> According to our assumption, [if P→Q is a β-disintegration], the β particle may be expelled with *less* energy than the difference of energies $E_P - E_Q$ of the two nuclei, but not with *more* energy. We do not wish […] to dwell on what happens to the excess energy in those disintegrations in which the electron is emitted with less than the maximum energy. We may, however, point out that if the energy merely disappears, implying a breakdown of the principle of energy conservation, then in a B-ray decay energy is not even statistically conserved. Our hypothesis is, of course, also consistent with the suggestion of Pauli that the excess energy is carried off by particles of great penetrating power such as neutrons of electronic mass (Ellis & Mott 1933, p. 502-503).[6]

It must be said, however, that the hypothesis of "Pauli's neutrons" did not solve all the problems posed by the nuclear electrons. In fact, not only it completely left open the subject of electron confinement within the nucleus, but extended this problem to "Pauli's neutron" itself since even this latter particle would had to be confined within the nucleus.

Not surprisingly, the hypothesis of "Pauli's neutron" did not immediately proved popular, nor was further discussed during the Rome conference. For example, Goudsmit himself, after having publicly announced it, did not state the hypothesis. What's most important, Peter Debye, in the final report of the conference, made no mention of this hypothesis, but instead emphasized Bohr's position on the possibility of "a departure from the law of energy conservation in nuclear disintegrations." In the digest of Debye's closing speech at the Rome conference, not published in the Proceedings, but preserved by the *Accademia dei Lincei* archives in Rome, we read as follows:

> The difficulties arise, however, when it comes to investigate the properties of the nuclei and their constituent parts. The speaker refers to all the difficulties of the investigation that were exposed during the discussions, and finally focuses on the observations of Prof. Bohr, that starting from the behavior of electrons inside the nucleus and the continuous spectrum of beta rays, seem to attack the very base of physics itself, coming up to question the principle of conservation of energy. These speculations, however bold, seem to offer the easiest way to get out of difficulties in the interpretation of experimental facts, which otherwise seem insurmountable. (Debye 1931)

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[6] On the support provided by this explanation of the upper limit to the hypothesis of neutrino see also Mott (1933, p. 284).

Despite the great difficulties that the early 1930s nuclear physics was facing, an important result seemed to have been reached through the Rome conference: the tracing out of a neat line between issues that seem solvable with quantum mechanics and those who could not hope for any help from this theory. This boundary line was outlined by Gamow at the beginning of his report (actually written by Delbrück) for the Rome conference and on which all the speakers were found at the end to agree with. As it was observed by Gamow:

> We know that there are two rather differing kinds of constituent part of atomic nuclei, we may call them *heavy* and *light* constituents parts. To the first class belong the protons and also complex constituents parts such as alpha-particles. For these particles we can estimate that, due to the relatively great masses, their motion may be described according to unrelativistic mechanics and the nuclear processes involving these particles only can be treated in detail by means of the present quantum theory.
>
> On the other hand the light constituent parts, the nuclear electrons, move in the nucleus with velocities near to that of the light and relativistical treatment is necessary. This is just the point where the present means of theoretical physics fail to help us. (Gamow 1931, p. 65)

5 Toward the Theory of Beta Decay

The controversial subject of the continuous energy spectrum of the electrons in β-decay was discussed again during the Fifth International Conference on Electricity, which was held in Paris between 5 and 12 July 1932. Enrico Fermi was invited to deliver a speech there and he chose as a subject the nucleus (Fermi 1932).

Although the Paris conference was held about one year after the Rome conference, Fermi did not make reference in his speech about the major nuclear physics developments that had occurred over the past months, e.g. no reference was made about April 1932 J.D. Cockroft and E.T.S. Walton's first artificial disintegration of a nucleus through the bombardment with a beam of accelerated protons. Even more significant is the fact that no reference was made about February 1932 discovery of Chadwick's neutron. Only at the end of his written report, Fermi very briefly reported about these two findings, by specifying that "since this manuscript was written, important nuclear physics experiments were made". It should be noted that Chadwick's discovery dates back to five months earlier, and that during the same conference Madame Curie had extensively reported about the neutron.

Although his paper was written long before the conference, at first Fermi had clearly shown little interest in this new constituent of the nucleus. One possible reason for this attitude may be due to the fact that the neutron represented a new heavy constituent of the nucleus, for which we could rely on quantum mechanics. According to Fermi, however, the main problems to be solved concerned instead the light components of the nucleus, i.e. the nuclear electrons. As for the problem of the confinement of electrons within the nucleus, Fermi suggested that “the conceptions of ordinary quantum mechanics are not applicable to the study of the dynamics of the nuclear electrons”.

This position, however, did not prevent Fermi to positively consider the hypothesis of “Pauli’s neutron”, which until then had received almost no attention from the international scientific community. According to Fermi, this particle could be a solution to a series of problems that seemed insurmountable, such as the continuous spectrum of beta rays and the spin of nuclear electrons:

> One might think for example, following a suggestion by Pauli, that some “neutrons” are present in the atomic nucleus, and that these ones are emitted simultaneously with the β particles. These “neutrons” could pass through large thicknesses of matter losing a small part of their energy and thus virtually escaping observation. The existence of the “neutron” would undoubtedly give a simple explanation of certain phenomena that are currently poorly understood. (Fermi 1932/1962, p. 498)

As Pauli had done, Fermi called the new particle “neutron”. In this respect, in the discussion section following Fermi’s communication in Paris there was an exchange with the polish physicist Wertenstein:

> Mr. Wertenstein asked for an explanation of the possibility of the emission of radiation accompanying the beta rays of naturally radioactive bodies and re-establishing the conservation of energy. He did not believe that these rays could be [Chadwick’s] neutrons because of their mass. Mr. Fermi answered that such [Pauli’s] neutrons are not those that have been discovered, but that they would have a much lighter mass. (De Valbreuze 1932, as translated by Segrè 1970, p. 69)

As remarked by Segrè (1962), this exchange shows that Pauli’s hypothesis by then had become known to physicists interested in beta decay. Of course, this does not mean that it had gained a broad acceptance.[7]

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[7] Among those who took seriously Pauli’s hypothesis figured J.F. Carlson and J.R. Oppenheimer from Berkeley who, coincidentally, a few days after the Paris conference, submitted a paper to *Physical Review*

At the October 12 to 18, 1933 Italian Society for the Advancement of Science conference in Bari, Fermi argued again, as he had done in Paris, for laws different from those of ordinary quantum mechanics and advocated the view that "just as ordinary mechanics loses its validity in describing the behaviour of the electron when there is a change of scale from the ordinary to the atomic one, so the new change of scale from atomic to nuclear phenomena could necessitate a new modification whose features at the moment are unknown to us" (Fermi 1933a; for an English translation of this excerpt see Guerra & Robotti 2009). In Bari, Fermi acknowledged again the existence of Pauli's hypothesis of a new particle to explain the continuous beta decay. Differently than before, however, Fermi called it "*neutrino*" (an Italian term suggesting a small neutral object; SIPS 1933, p. CLVII) in order to avoid any confusion with Chadwick's "*neutron*" (suggesting a large neutral object).

The neutrino hypothesis was first presented for publication by his author a few days later, during the seventh Solvay Conference, held in Brussels on October 22 to 29, 1933. In the discussion section following Heisenberg's speech on the structure of the nucleus, Pauli negatively commented upon Bohr's hypothesis that the law of conservation of energy does not hold, and gave some details about the neutrino:

> This hypothesis does not seem to me either satisfying or even plausible. In the first place the electric charge is conserved in process, and I don't see why conservation of charge would be more fundamental than conservation of energy. (Pauli 1934, p. 324, as translated by Brown 1978, p. 28)

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where both Pauli's neutron and Chadwick's neutron are explicitly treated. According to the Berkeley physicists, if one assumed, as Pauli did, that the neutron "form a third element in the building of nuclei, in addition to the electrons and protons", has a mass not much greater than that of the electron, and its magnetic moment was small compared to the Bohr magneton, one could understand "the anomalous spin and statistics of certain nuclei, and the apparent failure of the conservation of energy in beta-particle disintegration". If, on the contrary, one assumed that the neutron "has a mass very close to that of the proton, and that such neutrons are substituted for pairs of electrons and protons in certain nuclei, instead of being added to them", such neutrons "would help explain the anomalous spin and statistics of nuclei, although they would throw no light on the beta-ray disintegrations" (Carlson & Oppenheimer 1932, p. 764). Both particles, Pauli's elementary one and Chadwick's composite one, might exist, and in fact, Carlson and Oppenheimer added, "there may very well be other types of neutral particles, which", as Chadwick's neutron, "are not elementary". In the meantime, Chadwick's neutron had started to change status, that is it began to be considered as an elementary particle through Heisenberg's 1932 nuclear theory under which nucleus was composed of protons and (Chadwick's) neutrons (Heisenberg 1932a, 1932b, 1932c).

Both at the Rome conference and at the Solvay conference (in the discussion section following Dirac' speech), Bohr had indeed argued for a primacy of the conservation of electric charges over the conservation of energy (Bohr 1932a, 1934). Pauli proposed instead the following interpretation:

> the emission of beta particles occurring together with the emission of a very penetrating radiation of neutral particles, which has not been observed yet. […] we first learn from atomic weights [of radioactive elements] that their mass cannot be much larger than that of electron. In order to distinguish them from the heavy neutrons, E. Fermi proposed the name "neutrino". (Pauli 1934, p. 325, as translated by Brown 1978, p. 28)

While at the Rome conference the neutrino hypothesis passed largely unnoticed, even if trace of it can be found in the proceedings, at the Solvay conference such an hypothesis prompted a brief discussion about the possible experimental methods to detect this elusive hypothetical particle. For example Chadwick, which was present at the conference, noted in this regard that "it is certain that the neutrino, if it does exist, it will be exceedingly difficult to detect". As matter of fact, however, the neutrino was almost neglected throughout the conference, and it was not seen by those who intervened on the problem of beta decay as one of the possible protagonists of the beta decay. With hindsight, we know that Fermi, who was the only Italian physicist who was invited to attend the Solvay conference, had quite a different approach. In a few weeks, he abandoned indeed his quest for new physical laws on the nuclear scale and showed how beta decay can be explained within the framework of ordinary quantum mechanics by resorting to the hypothesis of neutrino.

Between December 1933 and January 1934 Fermi published his theory of beta decay (Fermi 1933b, 1934a, 1934b), where he assumed, as Pauli had, that in beta decay both an electron and a neutrino are emitted, and that "the energy liberated during the process would be shared between the two particles, in such a way that the electron energy can take on all values from zero to some maximum". Furthermore, he arrived at the crucial conclusion that

> electrons do not exist as such in the nucleus before beta emission, but [together with neutrinos] acquire existence, so to speak, in the very moment they are emitted, in the same way as a light quantum, emitted by an atom during a quantum jump, cannot be considered in any way as pre-existing in the atom before the emission process. (Fermi 1933b/1962, p. 541)

It is important to emphasize that, as it is well known, the idea that a zero mass neutrino that "does not pre-exist in atomic nuclei," and that "it is created, like a photon is, at the time of emission" was also proposed in December 1933, independently of Fermi, by another participant to the Solvay conference, that is Frederic Perrin (1933).

While Fermi and Perrin had the same basic idea, Fermi used the concept of Pauli's "ghostly particle" (Reines and Cowan 1956) to build a powerful, quantitative, theory, which "is in many ways still the standard theory" (Brown 1978). According to this theory, in beta decay a neutron in the nucleus is transformed into a proton, which would "necessarily be connected with the creation of an electron, observed as the beta particle, and of a neutrino [ν]," according to the reaction

$$n \rightarrow p + e^{-} + \nu$$

By the discovery of artificial radioactivity induced by alpha particles (Joliot & Curie 1934) and neutrons (Fermi 1934b), that is the induced positron and electron emission (Guerra et al. 2006, 2012), the natural beta decay was understood to be just one of the possible manifestations of weak interactions. Two years later, in 1936, Bohr himself remarked that no longer existed grounds for serious doubts as to the strict validity of the conservation laws in the problem of the emission of beta rays from atomic nuclei. This was the outcome of the "suggestive agreement between the rapidly increasing experimental evidence regarding beta-ray phenomena and the consequences of the neutrino hypothesis of Pauli so remarkably developed in Fermi's theory" (Bohr 1936).

This initial success of Fermi's theory much contributed to the acceptance of neutrino's hypothesis, as it is shown by the topic of exchange interactions in nuclear physics, that is the interactions that Heisenberg had introduced in order to explain the protons plus neutrons nuclear structure (Heisenberg 1932a, 1932b, 1932c), and that one year later were revised by Majorana (1933). By this approach, a remarkable unification between nuclear forces and forces responsible for the beta decay would have taken place. Soon after having heard about Fermi's theory, Heisenberg set off with this attempt of deriving the exchange forces from the β-decay theory, as it is shown by the intense exchange of correspondence between Fermi and Heisenberg in early 1934 (correspondence preserved in Heisenberg archives, formerly at the Max Planck Institut in Munich, now at the Max Planck Institut in Berlin) and by the contents of Scott lectures delivered in April 1934 in Cambridge, where Heisenberg established a detailed connection between Fermi's theory of beta decay and the force-law between neutrons and protons (Mehra 2001, p. 826).

In fact, as Franklin (2004) has demonstrated with abundant details, despite its initial success, since 1935 Fermi's theory of beta decay was no longer the accepted theory in the second half of the 1930s. This was mainly the outcome of the comparison with the available measurements that showed an excess of electrons, with respect to the theory, in the low energy region. This prompted E.J. Konopinski and G.E. Uhlenbeck to propose in 1935 to change Fermi's theory in order to shift the distribution towards higher neutrino, i.e. lower electron energies (Franklin 2004, p. 89-97; see also Amaldi 1982). In early 1940s, Fermi's theory was eventually accepted again after considerable work had shown that the excess of low energy electrons was an experimental artefact and that "the experiment-theory comparison was wrong" (Franklin 2004, p. 96).

6 Conclusion

As we have seen, the problems posed by the nuclear electrons, and particularly the continuous spectrum of the β-particles, led in late 1920s to early 1930s to two radically different approaches, whose only common denominator was their boldness. On the one hand, we had physicists like Bohr and Fermi who believed that just as classical mechanics loses its validity when there is a change of scale from the ordinary to the atomic one, so a new physics was expected to replace quantum mechanics when a new change of scale, from atomic to nuclear phenomena, occurs. In this respect, Bohr was even willing to depart from the conservation of energy in nuclear disintegrations. On the other hand, we had Pauli, who insisted in maintaining conservation laws even at the expense of introducing a new, almost undetectable, particle, the neutrino. By this hypothesis, besides having a new neutral constituent of the nucleus, we had a solution that formally preserved conservation of energy by assuming the unobservable particle to carry off the balance. The neutrino hypothesis, however, was not free from drawbacks. In some respect, it worsened the problems posed by the nuclear electrons since even the neutrino would had to be confined within the nucleus.

The way out of the puzzle was found by Fermi. In late 1933 he abandoned the search for a new physics, alternative to quantum mechanics in the nuclear scale, and developed a weak interaction theory. Though inspired by quantum mechanics, Fermi's theory surpasses it by removing electrons and neutrinos as nuclear constituents. These particles acquired existence in the very moment they were created in the interaction.

Once again energy conservation shows its heuristic power.

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