Part III
Teaching Specific Aspects of the Concept of Energy From Social, and Historical Perspectives

The Beta Decay and the Conservation of Energy: a Historical Case-Study to Overcome Learning Difficulties in the Upper Secondary School

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Abstract

This theoretical paper provides a case-study in the history of nuclear physics that could likely help overcoming a learning difficulty that upper secondary school students have in dealing with conservation of energy topics. As reported in the physics education literature, among the learning difficulties encountered by the students figures indeed limiting the validity of the principle of conservation of energy to mechanical and thermodynamic processes.

The historical case-study here proposed concerns Bohr-Pauli controversy in late 1920s to early 1930s about the continuous beta decay spectra. As it is well known, in order to explain this feature of the beta decay, Bohr suggested a violation of the principle of conservation in radioactive processes. On the contrary, Pauli defended the view that the unobserved portions of energy was carried off by one, or more, very light neutral particles, eventually named neutrinos.

Introduction

Over the years many researchers (e.g. Matthews 1994; Monk & Osborne 1997; Galili 2011) argued for the usefulness of History of science (HoS) in science and physics teaching. Among the main reasons reported for using HoS are its power to promote understanding the nature of science, to provide scientific clarification of the concepts to be taught, and to overcome conceptual difficulties of the students. This theoretical paper provides a case-study in the history of nuclear physics, that is the continuous spectrum of beta decay, that could help especially useful to overcome the learning difficulties that upper secondary school students have in dealing with conservation of energy topics.

The continuous spectrum of beta rays

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. 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.

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 as the mechanism of their expulsion in radioactive processes posed a number of serious theoretical problems concerning the confinement of the electron in the nucleus, the electron spin, and the continuous spectrum of beta rays (e.g. Stuewer 1983).

As regards the latest problem, that is the continuous spectrum of beta rays, two possibilities existed in order to explain the heterogeneity of electron energies. According to the first hypothesis, in each disintegration the nucleus emits an electron of a given characteristics energy through a process which is the same for each atom of a nuclide. If this is so, the continuous spectrum of these electrons is due to secondary effects. Under the second hypothesis, the process of electron emission is different for the different atoms of a nuclide, and therefore it might be argued that the continuous spectrum is due to the fact the energy of disintegration is not a constant characteristics of a nuclide.

In 1927, Charles D. Ellis and William A. Wooster, through a well known calorimetric experiment, demonstrated beyond doubt the correctness of the second hypothesis and that therefore the beta electrons are emitted by the nucleus with various energies (Ellis & Wooster 1927; Franklin 2004).

Niels Bohr's hypothesis

In order to explain the puzzle of the continuous energy spectrum of the electrons in beta decay, as early as July 1, 1929, Niels Bohr sent a note to Wolfgang Pauli discussing the possibility of energy conservation being violated 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 b-ray disintegrations" (Bohr 1986, [5]). Pauli's reply was very negative 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 b-ray disintegrations, and are even led to complications and difficulties in trying to do so" (Bohr 1932b), was written only in 1932. The first, full, open announcement of Bohr's idea on this matter occurred in October 1931 during the Rome international conference of nuclear physics, organized by Enrico Fermi among the others. In the section "problems of intra-nuclear electrons" of his paper *Atomic stability and conservation laws*, sent to Fermi for inclusion in the proceedings of the Rome conference, Bohr discussed the beta decay puzzle after having reported about how quantum mechanics can explain the nuclear disintegrations in which alpha particles are emitted (Bohr 1932a, pp. 129-130).

> Just like the a-ray products, all b-ray products have a well-defined rate of decay, but nevertheless for each product the energy of the emitted b-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.

Wolfgang Pauli's hypothesis

According to a radically different hypothesis, no less radical than Bohr's one, the continuous energy spectrum puzzle might be explained through a "ghostly particle" (Reines and Cowan 1956). On December 4, 1930, Pauli put forward just such an hypothesis when he wrote 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 the conservation of energy (and the statistics), 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 b-spectrum would then become understandable by the assumption that in b 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.

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 of what Pauli later recalled in a lecture delivered in Zurich in 1957 (Pauli 1964), at the time of Pasadena meeting, Pauli still considered his "neutron" to be a nuclear constituent and kept referring to them as "neutrons" (AAAS 1931).

Two months later, Samuel Goudsmit reported about Pauli's hypothesis in his paper (written in August 1931) for the Rome conference, where he pointed out that this hypothesis might explain why it seems that the law of conservation of energy is not fulfilled in beta decay (Goudsmit 1932, p. 41). "Pauli's neutron" did not immediately proved popular, nor was further discussed during the Rome conference. 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.

A few months after the Rome conference (February 1932), a new nuclear constituent was actually discovered at the Cavendish Laboratory in Cambridge through the study of 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 its discoverer, James Chadwick, as "*neutron*". Since the mass of Pauli's neutron was expected to be much smaller than the mass of Chadwick's neutron, Fermi proposed to call "*neutrino*" (that is "small neutron", in Italian language) Pauli's particle.

As Pauli's hypothetical neutron, Chadwick's neutron as well was the output of a strongly held belief in the validity of the principle of conservation of energy. The alternative g-like hypothesis advocated by Frederic Joliot and Irene Curie, as reported by Chadwick (1932), "can only be upheld if the conservation of energy […] be relinquished at some point".

Enrico Fermi's theory of beta decay

The neutrino hypothesis was first presented for publication by Pauli during the seventh Solvay Conference, held in Brussels on October 22 to 29, 1933. In the discussion section following Werner 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 (Pauli 1934; for an English translation see Brown 1978).

While at the Rome conference the neutrino hypothesis passed largely unnoticed, 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, that he had been carrying out for some time, and showed how beta decay can be explained within the framework of ordinary quantum mechanics by resorting to the hypothesis of neutrino and to another bold hypothesis, that is the transformation of a particle into another one.

Between December 1933 and January 1934 Fermi published his theory of beta decay (Fermi 1933; 1934a), 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". Under Fermi's theory, "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" (Fermi 1933; see also Perrin 1933).

While through Pauli's hypothesis we had a qualitative possibility to explain the experimental facts without abandoning the principle of energy conservation, by Fermi's theory we had a quantitative tool for explaining phenomena concerning nuclear electrons. In this theory, when a beta decay occurs, 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 [n]," according to the reaction

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

By the discovery of artificial radioactivity induced by alpha particles and neutrons, 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.

The 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 Werner Heisenberg had introduced in order explain the protons plus neutrons nuclear structure, and that one year later were revised by Majorana.

Concluding remarks

The confidence in the validity of the principle of energy conservation even within the nucleus domain, had in early 1930s important theoretical and experimental consequences.

In 1930, it led Pauli to propose the existence of a new particle, the neutrino, that, on the one hand allowed to smartly explain the phenomenon of the continuous spectrum of beta rays, but on the other hand worsened the theoretical problems posed by the nuclear electrons. Two years later, the confidence in the principle fostered Chadwick's experimental discovery of a new nuclear constituent, the neutron. Finally, in 1933 it led Fermi to accept the neutrino and to see it, as well as the beta electrons, as something different of a new nuclear constituent but, rather, as a particle acquiring existence in the very moment it is emitted, because of the transformation of a neutron into a proton.

The domain of validity of the principle of conservation of energy, besides being a crucial issue of the late 1920s – early 1930s nuclear physics, is a major point also in the modern physics education.

As reported in the physics education literature, among the learning difficulties encountered by the students figures indeed limiting the validity of the principle of conservation of energy to mechanical and thermodynamic processes. By structuring an activity where the students are asked to estimate the kinetic energy of an electron emitted during the beta decay of a given chemical element, and to explain the empirical fact that the electrons may assume whatever value within a range of energies, the students are made working on different explanatory hypotheses which can justify the principle of energy conservation. Previous experiences (e.g. Solbes & Tarìn 1998, 2004; Solbes et al 2009), suggest that this path is feasible and successful.

The use of this case-study in a classroom setting would therefore enable us to support or challenge the view (e.g. Monk & Osborne 1997; Galili 2011) that HoS is not only an object of teaching *per se* but is a means of acquiring an element of knowledge.

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