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History

1.1 On the earlier and more recent history of the neutrino

WOLFGANG PAULI, 1957*

1 Problems concerning the interpretation of the continuous energy spectrum of beta rays

The continuous energy spectrum of beta rays discovered by J. Chadwick in 1914 [CHA 14] immediately posed difficult problems with respect to its theoretical interpretation. Was it directly due to the primary electrons emitted from the radioactive nucleus or was it to be attributed to secondary processes? The first hypothesis, which proved to be the correct one, was advocated by C. D. Ellis [ELL 22a], the second one by L. Meitner [MEI 22]. Meitner appealed to the fact that nuclei possess discrete energy states, as was known from alpha and gamma rays. She focused attention on the discrete energies of electrons, which had also been observed for many beta-radioactive nuclei. Ellis interpreted them as electrons being ejected from the outer shells by inner conversion of monochromatic nuclear gamma rays and assigned them to the observed X-ray lines. According to Meitner's theory, however, at least one of the electrons of discrete energy should be a genuine primary electron from the nucleus, which, in a secondary process, could then emit from the outer shells more electrons with smaller energies.[1] However, this postulated primary electron of discrete energy was never detected. Moreover, there are beta-radioactive nuclei, like RaE, that do not emit gamma rays and for which the electrons with discrete energies are missing altogether. In the polemic that arose between Ellis and Meitner, Ellis summarized [ELL 22b] his point of view in the following way:

> The theory of Miss Meitner is a very interesting attempt to provide a simple explanation of β-decay. The experimental facts, however, do not fit the framework of this theory and there is every indication that the simple analogy between α- and β-decay cannot be maintained. The β-decay is a considerably more complicated process and the general suggestions I made in this context appear to me to require the least constraint.

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* Translation by Gabriele Zacek (CERN, Geneva), of "Zur älteren und neueren Geschichte des Neutrinos," published in Wolfgang Pauli, *Physik und Erkenntnistheorie*, pp. 156–80; Friedr, Vieweg, & Sohn, Braunschweig/Wiesbaden, 1984.

[1] In a later work [MEI 25] Meitner has proven experimentally that the γ-rays, contrary to an earlier opinion of Ellis, were emitted by the nucleus, which is generated *after* the emission of the α- or β-particle.

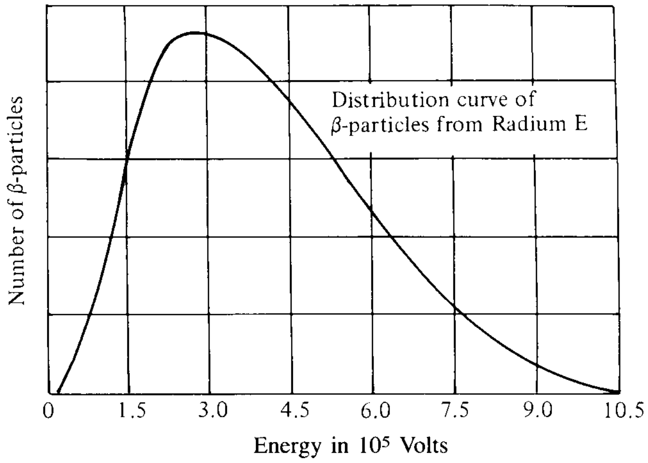

Fig. 1 Continuous beta spectrum of RaE.

This statement obviously did not bring researchers any closer to an answer to the question of how to interpret the continuous beta spectrum, and opinion remained divided on whether the spectrum was of primary origin (Ellis) or whether an initially discrete energy did broaden into a continuum by subsequent secondary processes (Meitner). This dispute finally came to an end in an experiment: the *measurement of the absolute heat in the absorption of beta electrons.* It was known from counting experiments that *one* electron is emitted from the nucleus per decay. In subsequent secondary processes, the heat measured in the calorimeter per decay should correspond to the upper limit of the beta spectrum; in the primary process, however, it should correspond to its mean energy. Ellis and W. A. Wooster [ELL 27] performed the measurement on RaE. The result for each decay, converted to Volts, was a heat of

$$344\,000 \text{ Volts} \pm 10\%$$

which corresponded well to the mean energy of the beta spectrum (Fig. 1). The upper boundary of the beta spectrum, however, would correspond to about 1 million Volts, which was completely excluded by the experiments. Ellis stressed that his experiment still left open the possibility of restoring the energy balance by a continuous gamma spectrum that would not have been absorbed in the calorimeter and would have escaped observation.

Meitner was not yet convinced by this experiment and immediately decided to repeat it with an improved apparatus. W. Orthmann, a collaborator of Nernst, designed a special differential calorimeter for this purpose. This calorimeter made it possible to repeat the heat measurement of the beta electrons from RaE with increased precision. The outcome,

$$337\,000 \text{ Volts} \pm 6\%$$

confirmed the result from Ellis and Wooster.

Moreover, in special experiments using ionization tubes, Meitner [MEI 30] proved that the continuous gamma spectrum postulated by Ellis was not present. Following these experimental results, there remained only two theoretical possibilities for the *interpretation of the continuous beta spectrum*:

1 The conservation of energy holds only statistically in this particular interaction, which gives rise to beta radioactivity.
2 The conservation of energy holds strictly in each primary process; however, an additional, very penetrating radiation is emitted together with the electrons, which consists of *new*, *neutral particles*.

The first possibility was supported by Bohr, the second one by myself. Before treating the history of these further questions, which was finally settled in favor of the second possibility, we must explain how our ideas about nuclear structure developed.

2 Neutrino and nuclear structure

Following Rutherford's first experiments on artificially induced transformations of nuclei, it was generally accepted that nuclei consist of protons and electrons. Rutherford himself discussed nuclear structure in this way in his famous Bakerian Lecture [RUT 20]. Among other things, the lecture presented the hypothesis of the existence of a nucleus with charge 0 and its eventual properties. Soon it became known (compare, e.g., [CLA 21]) that Rutherford had proposed the name *neutron* for these new hypothetical particles. He thought of them as a combination of protons and electrons of nuclear dimensions. Consequently, he urged his laboratory to perform experiments looking for these neutrons in hydrogen discharges, which of course had to remain fruitless.

The idea that the nuclei were made up of protons and electrons was eventually dismissed, albeit reluctantly. The decisive blow came from the quantum and wave mechanics theory advanced in 1927. According to this theory, there are two sorts of particles, the antisymmetric fermions and the symmetric bosons. Composite particles are fermions or bosons with the number of their constitutive fermions odd or even. An equivalent argument also holds for the spin, with fermions always possessing half a unit and bosons always an entire unit of spin. Since it was soon found that electrons and protons are fermions, the idea that they alone were the building blocks of all nuclei led to the conclusion that the parity of the charge number should determine the symmetry character of the nuclei. This conclusion was not confirmed by experience. The first counterexample was the "nitrogen anomaly," as we called it then. Using the band spectra, R. Kronig [KRO 28] and W. Heitler and G. Herzberg [HEI 29] showed that nitrogen with a charge number 7 and mass number 14 has spin 1 and Bose statistics. Similar cases followed, such as Li 6 (charge 3, mass 6) and the deuteron (charge 1, mass 2); both also had spin 1 and Bose statistics. Thus it was shown that the symmetry character of the nuclei was determined by the parity of the mass number and not by the parity of the charge number.

Using the idea of a new particle, I tried to combine this problem of the spin and statistics of nuclei with the problem of the continuous beta spectrum, without abandoning the conservation of energy. In December 1930, when the heavy neutron had not yet been discovered experimentally, I sent a letter on this topic to a meeting of physicists in Tübingen, where Geiger and Meitner in particular were present.[2]

> Public letter to the group of the Radioactives at the district society meeting in Tübingen:
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> Physikalisches Institut   Zürich, 4. Dec. 1930
> der Eidg. Technischen Hochschule   Gloriastr.
>
> Zürich
>
> Dear Radioactive Ladies and Gentlemen,
>
> As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem"[3] of statistics and the law of 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 $\frac{1}{2}$ and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. – The continuous β-spectrum would then become understandable by the assumption that in β-decay, a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and electron is constant. Now the question that has to be dealt with is which forces act on the neutrons? The most likely model for the neutron seems to me, because of wave mechanical reasons (the details are known by the bearer of these lines), that the neutron at rest is a magnetic dipole of a certain moment μ. The experiments seem to require that the effect of the ionization of such a neutron cannot be larger than that of a γ-ray and then μ should not be larger than $e * 10^{-3}$ cm.

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[2] I am indebted to Mrs. Meitner for keeping a copy of this letter and for leaving it to me.

[3] This reads: exclusion principle (Fermi statistics) and half-integer spin for an odd number of particles; Bose statistics and integer spin for an even number of particles.