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The history of neutrinos, 1930–1985. What have we learned about neutrinos? What have we learned using neutrinos?

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ABSTRACT

An attempt to remember some of the main events which highlight the evolution of our knowledge of the neutrinos and their properties, the “families” of particles, a few of the very interesting persons who contributed to this progress, as well as the contribution of neutrino beam experiments to the validation of the electro-weak and quantum-chromo-dynamic theories, and the structure of the nucleon.

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1. Early history. Continuous spectrum in β -decay, the Pauli letter, the Fermi interaction

In 1914, Chadwick showed that the electron spectrum in the β -decay of Radium B + C is a continuum [1]. The important implications of this were far from clear at the time (see Figs. 1 and 2).

16 years later, in 1930, 2 years before the same Chadwick discovered the neutron, Wolfgang Pauli wrote his famous letter to the Kongress der Radioaktiven. To conserve energy and angular momentum in β -decay, he proposed that together with the electron a new particle is emitted, neutral, with a magnetic dipole and with ionization power no greater than γ -rays. Pauli did not dare to publish this until 3 years later. For me the letter is the most interesting and fun document I know in this field, and I give here the German original, as well as an English translation (see Figs. 3–5).

The next leap forward in our understanding was the brilliant Fermi theory [2] for β -decay in the very early days of field theory. Fermi proposed a Lagrangian, which is the product of two Dirac “currents”, one transforming a neutron into a proton, the other an electron into a neutrino, the basis of the weak interaction until this day.

2. “Families” and the “universal fermi interaction”

For me, the history of “families” begins with the 1947 Physical Review Letter of Pontecorvo [3], in the wake of the 1946 cosmic ray experiment of Conversi et al. [4], which had shown that negative cosmic ray mesotrons (now muons), stopped in carbon, had a small probability to be captured by the nucleus, whereas if stopped in iron, the capture probability was most probable. It was immediately understood that the negative muon is captured in the atomic K -orbit in a time very short compared to the muon life time, and consequently recognized that this showed that the interaction strength of the muon and nucleon is much too small to be the “Yukawa particle” proposed by Yukawa to be responsible for nuclear forces, but, in addition, Pontecorvo saw that the interaction strength is comparable to the Fermi interaction strength in β -decay. Pontecorvo’s letter was the first suggestion that there is a parallel between electrons and muons, and therefore of what is now known as “families”. The proposal was totally rejected at the time by the physics community, including his friend and teacher Fermi, the father of weak interaction theory. The notion of a possible relationship of muon and electron was difficult to imagine at that time (see Fig. 6).

For the next step, I give credit to my thesis experiment of 1948 [5], which showed that the electron spectrum in muon decay is a continuum, and therefore two low mass neutral particles must accompany the electron. It was known that gamma rays are not emitted in muon decay, so the neutral particles were assumed to be neutrinos (see Fig. 7).

Although neither I nor my thesis advisor, Fermi, were clever enough to realize this, it was quickly noted, independently, by Lee et al. [6], who were fellow graduate students at Chicago, Tiomno and Wheeler [7], and Puppi [8], that given the muon lifetime, the three interactions, β -decay, muon capture and muon decay, can be understood by combining three Fermi currents, a neutron–proton current, a muon–neutrino current and an electron–neutrino current, in three different ways, with the same interaction strength, to describe the three different processes. This was the beginning of the “universal Fermi interaction”, which was immediately accepted by the community, including Fermi (see Fig. 8).

3. Demonstration of the neutrino

In 1956, three and a half decades after the Pauli letter, Reines and Cowan [9] were able to detect the reactions produced in a cadmium loaded liquid scintillator by the antineutrinos of a nuclear reactor. This was possible for them because of their access to a nuclear reactor of the Atomic Energy Agency, which produced tritium for nuclear weapons, and with considerably higher fluxes than non-military reactors for commercial energy production. In their detector, the antineutrino, reacting with a proton, produces an electron and a neutron, and they observed the coincidence of the electron pulse with the delayed pulse produced by the scattering of the neutron on cadmium (see Fig. 9).

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