

The Nobel Prize in Physics for the Year 2015

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Abstract

In the standard model (SM) of particle physics neutrinos are massless and chargeless spin $\frac{1}{2}$ particles. But from experiments it is found that neutrinos undergo flavour oscillations, violating lepton flavour conservation and implying that they have non-zero masses. The Nobel Prize in physics for 2015 has been awarded jointly to *Takaaki Kajita*, University of Tokyo, Kashiwa, Japan and *Arthur B. McDonald*, Queen's University, Kingston, Canada "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

1. Introduction

In 1914, while Sir James Chadwick was studying the decay of tritium into helium-3 plus an electron (${}^3\text{H} \rightarrow {}^3\text{He} + e^-$) he observed an interaction where a neutron changes to a proton and emits an electron which is known as beta (β) decay [1]. Chadwick and his colleagues found that in this radioactive beta decay experiment energy is not conserved. In December 1930 at a conference of radioactivity in Zurich, the Austrian physicist Wolfgang Pauli [2] proposed a solution that if an unobserved particle is also emitted in beta decay, then the law of energy conservation is possible. He called this particle the neutron. By introducing a third particle into the final state, the energy could be shared in a variety of ways between the three particles. Hence, one would observe a continuous energy spectrum in the beta decay. About two years later, Chadwick discovered the particle we now call a neutron with properties (other than charge) quite different from Pauli's proposed particle. In 1933, Enrico Fermi renamed Pauli's particle as the neutrino ("little neutral one" in Italian).

According to the standard model (also known as quark-lepton model [3,4] fundamental constituents of matter are of two types: quarks and leptons [4,5]. This model assumes three generations (or families) of quarks and three generations of leptons (Table 1). Quarks are called (up, down), (charm, strange), and (top, bottom). The leptons consist of three flavours of charged leptons, the electron e^- , muon μ^- and tau τ^- , together with three flavours of neutrinos – the electron neutrino ν_e , muon neutrino ν_μ and tau neutrino ν_τ [6–10]. All neutrinos are assumed to be massless and neutral.

At first the existence of only one type of neutrino was predicted in β -decay. Pauli's hypothesis was verified when F. Reines and C. L. Cowen [11] detected the anti-neutrino $\bar{\nu}_e$ emitted from a nuclear reactor at Savannah River in South Carolina, USA. The second neutrino flavour, muon-neutrino (ν_μ), was detected by its rescattering to produce a muon via $\nu_\mu \rightarrow \mu^- p (\bar{\nu}_\mu p \rightarrow \mu^+ n)$ by Danby *et al.* [12] at Brookhaven National Laboratory in New York in 1962. The third neutrino flavour, tau-neutrino (ν_τ), was discovered in 2000 by the DONUT experiment at Fermilab by observing the τ leptons produced via $\nu_\tau \eta \rightarrow \tau^- p (\bar{\nu}_\tau p \rightarrow \tau^+ \eta)$ in a nuclear experiment [13].

Neutrinos are the second most abundant particles in the universe (photons are first). Neutrinos are very elusive and hardly interact with matter. They do not undergo electromagnetic and strong interactions but take part only in the weak interactions. Neutrinos are copiously produced in the sun, in cosmic rays and even in laboratories. They are produced via the following processes:

(a) ($\nu_e, \bar{\nu}_e$): Beta decay (ν_e), Fission ($\bar{\nu}_e$) and

Fusion (ν_e) reactions.

(b) ($\nu_\mu, \bar{\nu}_\mu$): Pion decay ($\pi^+ \rightarrow \mu^+ + \nu_\mu$ or the charge conjugate process).

(c) ($\nu_\mu, \bar{\nu}_e, \nu_e, \bar{\nu}_\mu$): Muon decay ($\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$ or the charge conjugate process).

Solar neutrinos are produced through the process (a) while atmospheric (i.e. cosmic ray) neutrinos come from (b) and (c). Accelerator neutrinos rely on (b); reactor antineutrinos result from fission reactions (a). In the

Table 1: Three generations of Leptons and Quarks

First Generation	Second Generation	Third Generation
ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-
u	c	t
d	s	b

