The Nobel Prize in Physics for the Year 2015

S. SAHOO[1] and M. GOSWAMI[2]
[1]Department of Physics, National Institute of Technology,
Durgapur – 713209, West Bengal, India. E-mail: sukadevsahoo@yahoo.com
[2]Department of Physics, Regional Institute of Education (NCERT),
Bhubaneswar - 751022, Orissa

Abstract

In the standard model (SM) of particle physics neutrinos are massless and chargeless spin ½ 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 ($^3H \rightarrow {}^3He + e^-$) 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 -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 e^-	ν_μ μ^-	ν_τ τ^-
u d	c s	t b

future, neutrino factories are being planned. These will employ muon storage rings. The decay of the highly collimated muons – process (c) – in the ring will result in an intense beam of neutrinos. There are other neutrino sources, e.g., supernovae, which are also detectable. Physicists detected the neutrinos from a supernova in 1987 when a star collapsed some 150000 light-years away in the Large Magellanic Cloud, the galaxy nearest to the Milky Way.

2. Neutrino Puzzles and Neutrino Oscillation

In the 1960s, John Bahcall was trying to calculate what types of nuclear processes are occurring in solar fusion. He predicted that the reaction $H^{+}+H^{+}\rightarrow He^{2+}+\nu+$ (other) generates around 7×10^{10} neutrinos/(cm^2.s) on earth. Around 100 billion solar neutrinos are passing through our body every second. But they interact so weakly with other matter that remarkably little is known about them. The fusion reactions that take place in the sun only produce electron neutrinos. In order to detect these neutrinos he teamed up with experimentalist Ray Davis. Ray Davis and his team built a tank to hold 380,000 litres of perchloroethylene in the Homestake Gold Mine in South Dakota. But they detected the solar electron neutrino flux at earth is about 1/3 of the theoretical value. This is known as "*solar neutrino puzzle*". A similar discrepancy was also seen in atmospheric neutrinos. Atmospheric neutrinos are created as a consequence of cosmic ray protons from space hitting earth's atmosphere (which contains protons and neutrons). High energy proton/proton or proton/neutron collisions produce charged pions. These charged pions decay into muons and muon neutrinos. Then muons decay into an electron, an electron neutrino and a muon neutrino. Thus atmospheric neutrinos predict that for every electron neutrino there should be two muon neutrinos. But from Homestake experiment it was observed a ratio of one to one. This was "*atmospheric neutrino puzzle*".

In 1996, the SuperKamiokande detector was built in a zinc mine under 1,000 meters of solid rock in Japan. It was filled with 50,000 tons of ultra-pure water (not heavy water) and was designed to detect atmospheric neutrinos. These neutrinos interact with atomic nuclei in the water to produce electrons, muons or tau leptons. Atmospheric neutrinos are mostly muon neutrinos. In 1998 [14], SuperKamiokande collaboration discovered that muon neutrinos converted or oscillated to tau neutrinos as they passed through the earth. Neutrinos oscillate in flavour because they have mass [15,16]. In 1998, the SuperKamiokande collaboration announced the first evidence for neutrino mass. The SuperKamiokande was also used to study solar neutrinos. The fusion reactions that take place in the sun only produce electron neutrinos. But these neutrinos can subsequently oscillate into both muon neutrinos and tau neutrinos. Though the experiment was able to detect the solar neutrinos, it was unable to distinguish different neutrino types. Meanwhile, the Sudbury Neutrino Observatory (SNO) was constructed in a nickel mine under more than 2,000 meters of rock in Canada. Its tank was filled with 1,000 tons of heavy water. It was designed to study solar neutrinos. The SNO [17,18] could identify the electron neutrinos because it is filled with 'heavy water', which contains hydrogen nuclei with an extra neutron. The combined data from SuperKamiokande and SNO determined how many muon neutrinos or tau neutrinos were incident at the detector. The SNO results also provided further evidence for neutrino mass and confirmed that the total number of neutrinos from the sun agreed with theoretical calculations.

Takaaki Kajita was the team leader of the SuperKamiokande collaboration and Arthur B. McDonald directed the Sudbury Neutrino Observatory. On 6th October 2015, the Royal Swedish Academy of Sciences has announced to award the Nobel Prize in physics for 2015 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*". Their work has been published in an international reputed journal – Physical Review Letters [14,17,18]. Including this year, there are four neutrino related Nobel Prizes in the years 1988, 1995, 2002 and 2015.

Year 1988

1. Leon M. Lederman (USA)
2. Melvin Schwartz (USA)
3. Jack Steinberger (USA)

Neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of muon-neutrino.

Year 1995

1. Martin L. Perl (USA)
2. Frederick Reines (USA)

Experimental contributions to lepton physics, specifically for the detection of the neutrino.

Year 2002

1. Ray Davis Jr. (USA)
2. Masatoshi Koshiba (JAPAN)
3. Riccardo Giacconi (USA)

1 & 2. Detection of Cosmic neutrinos.
3. Discovery of cosmic X-ray sources.

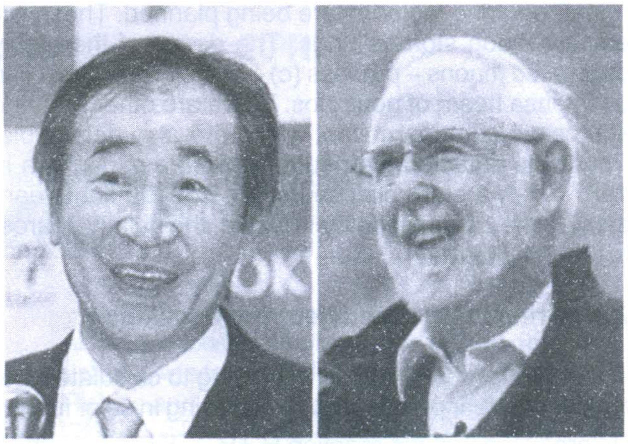
Year 2015

1. Takaaki Kajita (JAPAN)
2. Arthur B. McDonald (CANADA)

For the discovery of neutrino oscillations, which show that neutrinos have mass.

From the above discussion we came to know that neutrinos have non-zero mass, howsoever small it may be [19–23]. Then question arises: What happens if neutrinos do possess some mass? Astronomers and cosmologists, after several decades of observations, find that the bulk of the mass in the universe is unseen and this has been given the name – *dark matter* [24–27]. Neutrinos with mass may be one of the candidates for the dark matter. Small neutrino masses are sensitive to new physics at scales ranging from a TeV up to grand unification and superstring scales. The very smallness of neutrino mass leads many theorists to believe that they provide a window on physics at much higher energies than our accelerator can reach. Neutrinos are important for the study of the sun, stars, core-collapse supernovae, the origins of the cosmic rays, the large-scale structure of the universe, big bang nucleo-synthesis, and possibly baryogenesis. These tiny neutrino masses are of great interest because they might arise from some fundamentally different mechanism to the way the masses of other particles are generated i.e. the Higgs mechanism. Although the SM is very successful to explain many low as well as high energy phenomena in particle physics but within the framework of this model it is not possible to realize the massive neutrinos. The existence of neutrino mass is one of the signatures of new physics beyond the SM [28–30].

Further, we must mention that even the fundamental nature of the neutrino is still not known, namely whether neutrino is its own antiparticle or not (Majorana or Dirac particle). This question can be answered by the "neutrino-less double beta decay". Neutrino-less double beta decay is the only experiment that can probe the Majorana nature of the neutrino [31–34]. The values of the neutrino mass-squared differences are known, but the absolute values of neutrino masses are elusive. The observation of neutrino-less double beta decay would not only reveal the neutrinos are Majorana fermions, but would also provide information regarding the absolute values of the neutrino masses. There is possible evidence of neutrino-less double beta decay in the Heidelberg-Moscow experiment [31]. But so far, neutrino-less double beta decay experiments have not yielded definite results and hence more experiments are being planned. The aim of these experiments is to study the neutrino oscillations, search for neutrino-less double beta decay, measurement of absolute neutrino mass and the nature of neutrinos. Neutrinos have and will continue to provide important information on structure formation in the early universe, earth, solar and supernova physics, nuclear properties, and rare decays of charged leptons and hadrons [35]. The study of neutrino physics and the implications of the results connect many disciplines together, from particle physics to nuclear physics to astrophysics to cosmology. Thus, neutrino physics continues to be a very exciting field and may also bring us new surprises in this 21st century.



Takaaki Kajita and Arthur B. McDonald

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