Special Contribution

Observation of Neutrinos at Super-Kamiokande Observatory

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1. Introduction

Neutrinos are one of the fundamental particles making up the universe. Elementary particles include particles that make up matter (such as quarks, electrons, and neutrinos), gauge bosons which propagate force, and Higgs bosons which are related to mass (**Figure 1**). Electrons and neutrinos are collectively called "leptons." Leptons include three types (flavors) of charged particles having properties similar to those of the electron, namely, the electron, muon (μ), and tau (τ). There are also three flavors of neutral leptons: the electron neutrino, muon neutrino, and tau neutrino. Thought for a long time to have a mass of zero, neutrinos interact with particles like quarks and electrons that make up matter only through "weak interaction." As a result, the probability of neutrino interaction with matter is extremely small, making them difficult to detect. Research with the aim of explaining this property continues to this day.

This paper describes the Super-Kamiokande neutrino detector, explains neutrino oscillation, and discusses the purposes and the current status of neutrino research. The Super-Kamiokande detector has been observing neutrinos from the sun and atmosphere, as well as from particle accelerators, and through these observations, it has been playing an important role in understanding the properties of neutrinos. In this paper, we take up, in particular, our research on atmospheric neutrinos in relationship to the 2015 Nobel Prize in Physics.

2. What is a neutrino?

In 1930, Wolfgang Pauli, who had been researching nuclear decay, predicted the existence of the neutrino. He hypothesized that the experimental finding that the energy of electrons emitted by beta decay—one type of nuclear decay—is not constant could be explained by the existence of an extremely light particle having no charge. However, it was difficult to actually observe this particle, and it was not until 1956 that Frederick Reines and Clyde L. Cowan successfully observed electron antineutrinos from a nuclear reactor.[1)] Then, in 1962, Leon Lederman, Melvin Schwartz, and Jack Steinberger discovered the existence of muon neutrinos, which differ from electron neutrinos, among the neutrinos created by a particle accelerator.[2)] The existence of a third type of neutrino (the tau neutrino) was predicted in the 1970s and actually observed in 2000.[3)]

From the birth of the universe up to the present time, a vast number of neutrinos have been generated by various sources. They are the most common type of particle in terms of quantity. It is thought that there are about 300 neutrinos per cubic centimeter throughout the universe. As a result of nuclear fusion, each star emits not only light but also a huge number of neutrinos. Estimated 66 billion neutrinos emitted by the Sun strike each square centimeter of the earth each second. Raymond Davis Jr. and his colleagues were the first to observe solar neutrinos, providing conclusive proof that the source of a star's heat is nuclear fusion.[4)]

A supernova explosion, which occurs at the end of a massive star's life, emits a variety of heavy elements and a huge amount of light, but neutrinos are

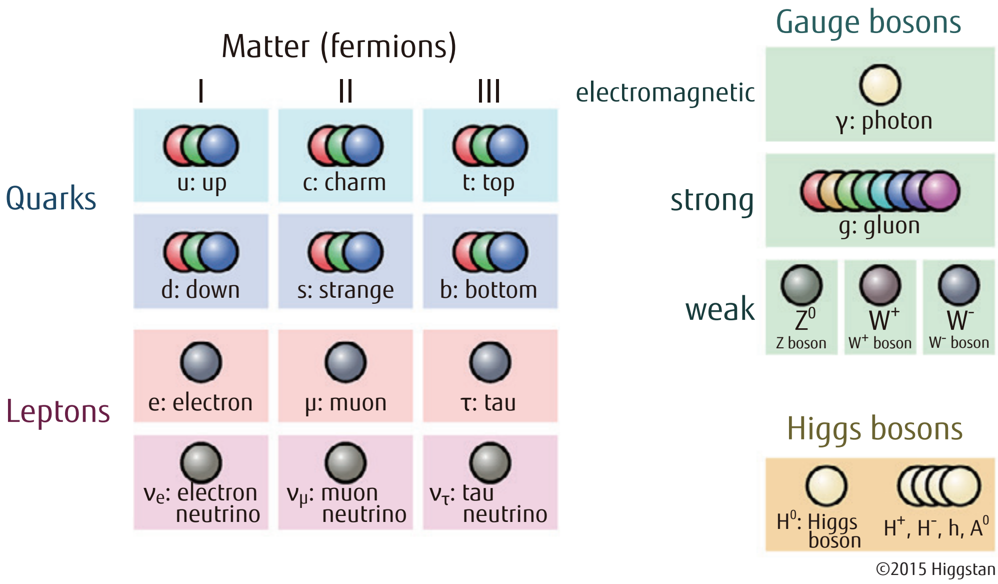

Figure 1
Elementary particles.

thought to carry approximately 99% of the energy from the explosion. In 1987, neutrinos from a supernova explosion were discovered for the first time using the Kamiokande detector,[5] an achievement that resulted in the awarding of the Nobel Prize in Physics to Professor Masatoshi Koshiba in 2002.

In addition to neutrinos, very-high-energy protons (hydrogen nuclei) and helium nuclei are flying about in space. When such particles collide with the earth's atmosphere, they create neutrinos and other types of particles. The observation of these "atmospheric neutrinos" at the Super-Kamiokande observatory published in 1998 revealed that neutrinos change type during flight (oscillation phenomenon), thereby demonstrating that a neutrino has mass.[6] As a result of this achievement, Professor Takaaki Kajita was awarded the 2015 Nobel Prize in Physics. Another question still being investigated is where and how particles like protons are accelerated to such high energies.

A major source of heat in the earth's interior (geothermal heat) had long been thought to be nuclear fission, similar to the reaction in a nuclear reactor. The KamLAND (Kamioka Liquid-scintillator Anti-Neutrino Detector) Collaboration proved this conjecture by successfully observing for the first time geological antineutrinos originating in nuclear fission. Later observations, moreover, revealed that about half of this geothermal heat could be attributed to nuclear fission while the remaining portion appeared to be heat remaining from the time when the earth was formed.[7]

Neutrinos and antineutrinos can be also generated using a particle accelerator. Such artificially produced neutrinos are now being used in diverse experiments for exploring the properties of neutrinos.

3. Super-Kamiokande observatory

Constructed underground inside a mine in Kamioka-cho, Hida City, Gifu Prefecture, Japan, the Super-Kamiokande detector began observations in April 1996. It is being used to observe solar neutrinos, neutrinos from supernova explosions of relatively low energy, high-energy atmospheric neutrinos, and neutrinos from particle accelerators. It is also being used for various types of research in astrophysics and particle physics such as the search for proton decay.

The Super-Kamiokande detector consists of a cylindrical 50,000-ton pure-water tank approximately 40 m in diameter and depth and photomultiplier tubes (PMTs) serving as high-sensitivity optical sensors (**Figure 2**). This detector observes Cherenkov light emitted in small amounts when charged particles in the water move faster than the speed of light in water.

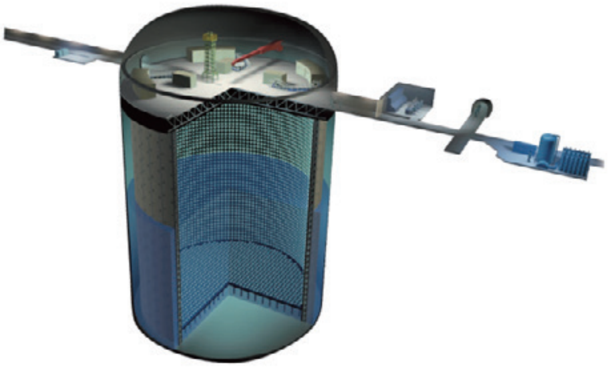

Figure 2
Super-Kamiokande detector.

A neutrino itself has no charge and emits no observable Cherenkov light, but it can interact with electrons in the water and impart energy to them. A neutrino can also interact with protons and neutrons in the water, creating electrons, muons, and other charged particles. Measuring the Cherenkov light produced by particles created by such reactions enables information on the original neutrino such as flavor, energy, and interacted position to be reconstructed.

Despite the scale of this detector, it can observe only about ten solar neutrinos and about eight atmospheric neutrinos per day. Furthermore, since the occurrence of phenomena such as supernova explosions and proton decay are impossible to predict, it is essential that the detector be in continuous operation.

The detector is set in a location surrounded by about 1,000 m of earth and rock in all directions. Since charged particles like muons shower the earth's surface at a rate of about 1 particle per 100 square centimeters per second, the detector is buried in this manner to reduce the penetration of such particles to approximately 1/100,000 that rate.

The water tank is optically separated into two regions by a wall that mounts the PMTs. The region on the inner side of the wall is called the inner detector, and that on the outer side is called the outer detector. The wall mounts 11,129 PMTs, each 50 cm in diameter, facing the inner detector, resulting in a PMT sensitive area covering about 40% of the wall's surface. The wall also mounts 1,185 PMTs, each 20 cm in diameter, facing the outer detector. The inner detector is used to observe particles created by neutrino reactions within the inner detector. The outer detector is used to observe particles that have penetrated the detector from the outside as well as particles created in the inner detector and flying to the outside.

The electronic signals output from the PMTs are converted into digital data by a custom board called QTC-Based Electronics with Ethernet (QBEE). A single QBEE board connects to 24 PMTs and transfers the converted data to a group of 20 readout computers by Fast Ethernet. Each computer reads about 720 PMTs' worth of data (about 480 PMTs' worth of data for the outer detector), rearranges that data in chronological order, and sends the data to 6 data-consolidation/event-triggering computers. These computers consolidate the data received from the readout computers, search for the physics events over the entire detector, and record event data at a rate of about 12 kHz. Event triggering in large-scale particle physics experiments had been done by hardware in the initial system while the system in use since 2008 performs event triggering entirely by software. This was the first system in the world for this kind of experiment to eliminate the hardware trigger system, and it was made possible by the faster processing speeds of computers and networks.

Triggered event data are recorded on large-capacity disk storage and tapes. A group of computers for analysis purposes is then used to perform "event reconstruction," which includes reaction position, number of particles, energy, flight direction, and particle type for each event in the tank. The output from this process is used in the research of neutrino oscillation and the search for proton decay.

4. Neutrino oscillation

Neutrinos are extremely light, and it is still not possible to make direct measurements of their mass. Additionally, as the Standard Model of particle physics, which had been constructed on the assumption that neutrinos were massless, had been repeatedly supported by almost all experimental results, the common belief was that a neutrino had no mass. For this reason, the discovery of neutrino oscillation in 1998 demonstrating that neutrinos did indeed have mass was a major shock, and it was this finding that led to the awarding of the 2015 Nobel Prize in Physics to Professor Kajita.

A neutrino is produced in one of three flavors:

electron, muon, and tau. When a neutrino weakly interacts with a quark and becomes a charged lepton, an electron neutrino becomes an electron, a muon neutrino becomes a muon, and a tau neutrino becomes a tau—no other combinations are allowed. However, while a neutrino may be an electron neutrino or muon neutrino at the time of its creation, it was observed that the subsequent creation of the expected charged lepton would be inhibited or the creation of an unexpected charged lepton would occur after that neutrino traveled a certain distance. This meant that a neutrino in flight would have to change into a different flavor of neutrino in a phenomenon called "neutrino oscillation." This phenomenon can be well explained by considering that neutrinos of three flavors each constitute a state mixed with neutrinos of three different masses (1, 2, and 3), as shown in **Figure 3**. In this regard, a neutrino propagates through space as a wave with a wavelength that differs in accordance with mass. For example, given a muon neutrino initially created by weak interaction, the neutrinos with different masses included in that neutrino propagate through space in different ways. As a result, the original muon neutrino enters a mixed state in flight consisting not only of a muon neutrino but also of an electron neutrino and a tau neutrino (**Figure 4**). This property can be used to investigate in detail how a neutrino flavor changes (oscillates), which makes it possible to learn about mass differences and mixing states in neutrinos despite their extreme lightness preventing direct measurement of their mass.

Neutrino oscillation is being studied at the Super-Kamiokande observatory using electron neutrinos created in the sun and muon neutrinos created in the atmosphere and by using particle accelerators.

5. Observation of atmospheric neutrino oscillation

At the time of an interaction between a neutrino and a neutron or proton, an electron neutrino creates an electron and a muon neutrino creates a muon, which means that neutrino flavor can be determined if the observed particle can be identified as an electron or a muon. In the Super-Kamiokande detector, a muon creates a ring with a clear contour while an electron creates a ring with a fuzzy contour (**Figure 5**). This difference can therefore be used to determine neutrino flavor. In addition, as the amount of observed light is correlated with particle energy and as the number of observed rings corresponds to the number of charged particles, this information can be used to analyze atmospheric neutrino oscillation.

Atmospheric neutrinos are created anywhere on earth and were therefore thought to have a nearly up/down symmetric distribution. Specifically, since an electron or a muon created by the reaction between a

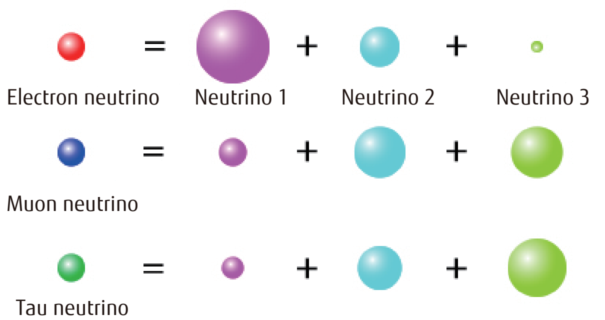

Figure 3
Neutrino mixing states.

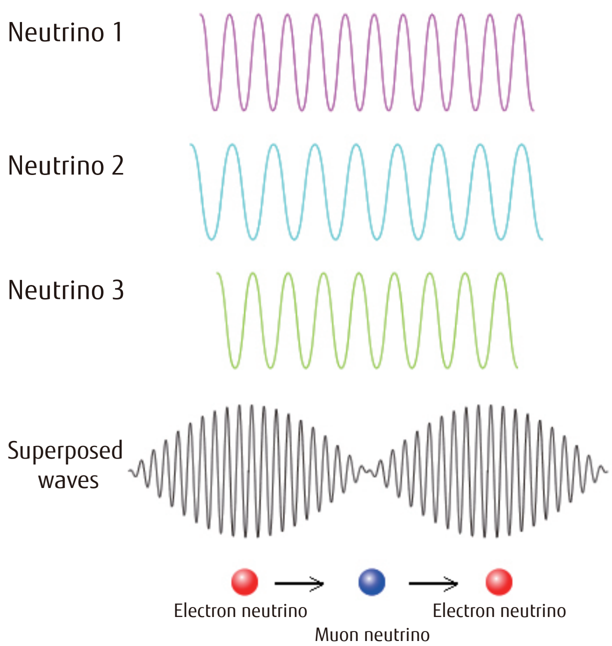

Figure 4
Neutrino propagation and oscillation.

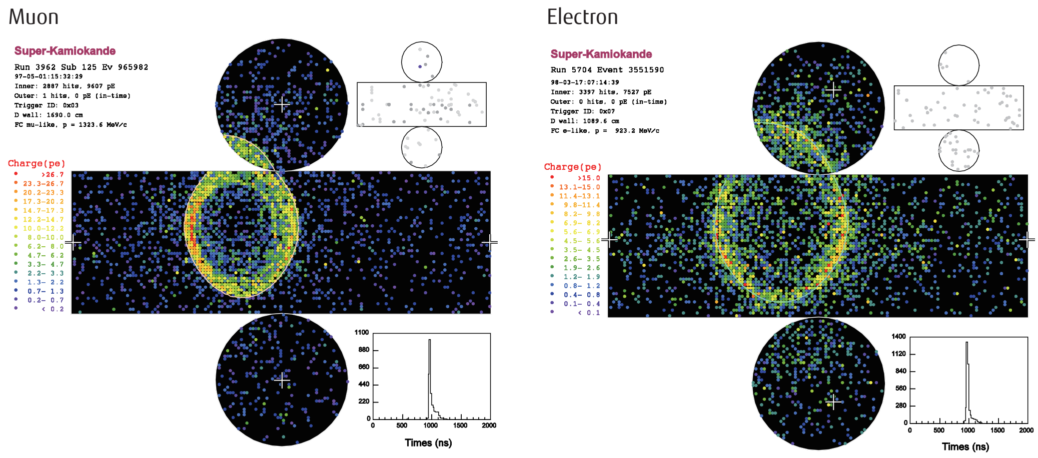

Figure 5
Differences in observing electrons and muons.

neutrino with sufficiently high energy and a nucleon (proton or neutron) is emitted at an angle near the direction of neutrino movement, the distribution of observed electrons or muons was likewise expected to be nearly up/down symmetric. However, actual observations at the Super-Kamiokande observatory revealed that muons flying in the upward direction, that is, muon neutrinos flying into the detector from the backside of the earth, were fewer in number than muon neutrinos flying downward into the detector from the sky (**Figure 6**). In this regard, a tau neutrino having sufficient energy can give rise to a reaction that creates a tau particle, but most atmospheric tau neutrinos are low in energy and cannot create tau particles, which explains why the latter are not observed. The above observations concerning muons could therefore be explained if muon neutrinos traveling a long distance were to oscillate into tau neutrinos. This was the discovery of the neutrino oscillation phenomenon in 1998. Since then, continuous observations have resulted in an accumulation of data that researchers have been analyzing in detail to obtain a deeper and more accurate understanding of neutrino properties.

Investigating neutrino mass differences and mixing states using observed data involves the generation of simulation data corresponding to the observation of several thousand years' worth of observations. With this data, researchers can vary the parameters governing neutrino mass differences and mixing states and

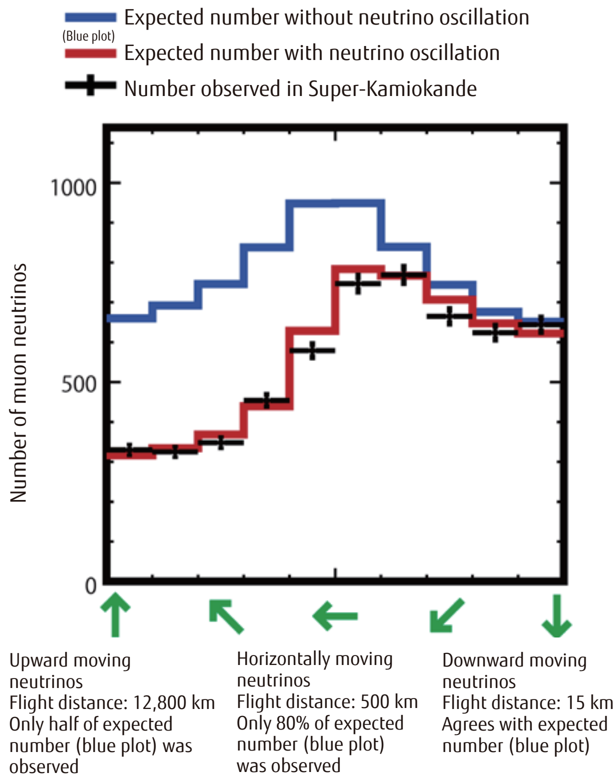

Figure 6
Distribution of observed muons.

calculate the distributions of expected observations to search for the parameters that produce the distribution closest to the observed data. Such analysis requires a considerable amount of software including programs for simulating neutrino/nucleon reactions, the propagation of particles created by those reactions in the detector, and the emission of Cherenkov light, programs for reconstructing events, and programs for varying neutrino oscillation parameters and calculating changes in distributions. Most of these programs have been developed within the experimental group. A specialized large-scale computer system has been introduced to enable these programs to be constantly improved and to generate new simulation data, enhance event reconstruction, etc. as needed.

6. Significance of neutrino research and future outlook

Extensive knowledge about neutrinos and their properties has been obtained over these last 20 years, but there are still things that are not understood. For example, which of neutrinos 1 and 3 in **Figure 3** is heavier is not known. In addition, it is still not known whether neutrinos and antineutrinos oscillate in exactly the same way. Furthermore, the universe at present consists mostly of matter—there is practically very little antimatter. For such a universe to exist, there must be a difference between matter and antimatter (charge parity [CP] asymmetry). However, the difference between quarks and antiquarks is exceedingly small, so this explanation is not entirely sufficient. A theory that would explain a large difference—if it exists—between neutrinos and antineutrinos has been formulated, and experiments focusing on this difference are being performed at the Super-Kamiokande observatory and other research institutions around the world. The Tokai to Kamioka (T2K) long baseline neutrino oscillation experiment using Japan's J-PARC particle accelerator and the Super-Kamiokande detector has begun to produce data showing signs of such a failure in CP symmetry. Future results are eagerly awaited.

It is thought that elements heavier than iron in the universe were created from supernova explosions. Such explosions for which neutrinos can be observed in great number have not occurred for 30 years, but observation of supernova neutrinos at the Super-Kamiokande observatory some day in the future would not only enable a more accurate understanding of the final stages of a star's life but also provide much information on the origin of the universe. Moreover, with the aim of efficiently observing neutrinos that should be ubiquitous in the universe from past supernova explosions, plans are progressing on upgrading the existing Super-Kamiokande detector.

Proton decay as well has yet to be observed. It has been shown from Super-Kamiokande observations that protons have a lifetime of more than 10^{34} years. If proton decay does become observable, it should be possible to solve the riddle as to why quarks and leptons like neutrinos both come in three generations.

It is expected that the ongoing collection and analysis of data at the Super-Kamiokande observatory will contribute to a deeper understanding of elementary particles and the universe, but a significant increase in the number of observable events in the short term is not foreseen. For this reason, a plan is being made to construct a Hyper-Kamiokande detector with an effective volume about 20 times greater than that of the Super-Kamiokande detector. Efforts to this end have begun.

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