FEATURE

Principal Investigator **Takaaki Kajita**
Research Area: Experimental Physics

Atmospheric Neutrinos and Neutrino Oscillations*

Introduction

About a hundred years ago, Victor Hess, aboard a balloon, measured the radiation levels at high altitudes and discovered cosmic rays. Later investigations revealed that the main components of the cosmic rays were protons and atomic nuclei, and their energy spectra extended to very high energies. The production sites and mechanisms of the cosmic ray acceleration are not fully understood up to now. Therefore, investigations are still made extensively in search of their origin.

Cosmic rays incident on the atmosphere interact with nitrogen and oxygen nuclei in the air, and pions are copiously produced in these interactions. Among them, positively or negatively charged pions decay into a muon and a muon antineutrino. Further, most of the muons produced in the upper atmosphere decay into an electron (or positron), a muon neutrino, and an electron neutrino (see Fig. 1), though the muon has a relatively long lifetime of 2 microseconds. It should be noted that for simplicity we do not distinguish between the positive and negative signs of the charges nor the particle and its antiparticle in this article. Therefore, it should be understood that a "neutrino" actually means either a neutrino or an antineutrino.

Neutrinos produced in this way are called *atmospheric neutrinos*. After the muon neutrino was discovered in an accelerator experiment in 1962, experiments to confirm the existence of atmospheric neutrinos were attempted deep underground in a mine in South Africa and in another mine in India. In these experiments, the atmospheric neutrinos were observed in 1965. In this article I will explain investigations of neutrino oscillations through observations of neutrinos produced by cosmic rays.

Atmospheric neutrino observations in Kamiokande

It was during the latter half of the 1980's that the atmospheric neutrinos attracted the attention of many researchers. Till then, the study of atmospheric neutrinos had not been developed as a widely recognized research area since their first observations in 1965. When several proton decay experiments started throughout the world in the 1980's, atmospheric neutrinos turned out to be the most disturbing background in the search of proton decay, and an understanding of this background was necessary. The Kamiokande experiment was among them. The Kamiokande detector, filled with pure water with an effective mass (usable for particle detection) of 1,000 tons, was located 1,000 m underground in a mine in Kamioka, Gifu prefecture. In this detector, Cherenkov light emitted by fast charged particles travelling in water with velocities faster than the light velocity in water was measured with 1,000 photomultiplier tubes of 50 cm in diameter.

Muons produced in the muon neutrino (ν_μ) interactions gradually lose their energy as they travel through water. On the other hand, electrons produced in the electron neutrino (ν_e) interactions

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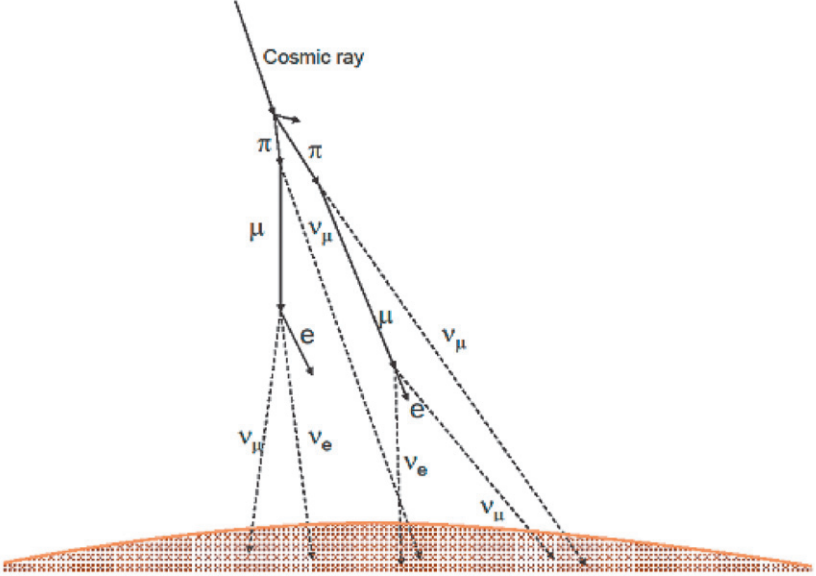
Figure 1. Production of atmospheric neutrinos.



form electromagnetic showers in water. Therefore, muons and electrons behave very differently in water. In Kamiokande, electrons and muons are observed by detecting a ring-like pattern of emitted Cherenkov light. In water, the Cherenkov ring pattern of a muon is different from that of an electron as a result of their different behavior. By exploiting this fact, it is possible to identify muons and electrons. For reference, Fig. 2 shows the Cherenkov-ring pattern of an electron event and that of a muon event, both observed by Super-Kamiokande which will be mentioned later in this article. Based on this idea, it is possible to identify events which had a single electron-type Cherenkov ring and were therefore considered to be ν_e interactions and events which had a single muon-type Cherenkov ring and therefore were considered to be ν_μ interactions. As a result, from the counts of both types of events, it was found that the observed number of ν_e events was almost as expected, but that of the ν_μ events was about 60% of the expected number.

Here, the expected numbers of events were obtained by a Monte-Carlo simulation in which the numbers of neutrino interactions in the Kamiokande detector were obtained from neutrino interaction cross sections and calculated atmospheric neutrino fluxes, and the detection efficiencies, etc., were also taken into account. At around that time, it was thought that these expected numbers had about 20 – 30% errors which resulted from errors primarily in the observed cosmic-ray fluxes. As the ratio of the numbers of ν_e and ν_μ events was calculated with better accuracy, however, the error was estimated to be less than 5%. For these reasons, the above-mentioned Kamiokande results were considered not to be explained by the systematic errors in the calculations. On the other hand, it was possible to explain these results if oscillations between muon and tau neutrinos were postulated. This attracted much attention at that time.

Before going on, let me explain the neutrino oscillation. Here we consider two types of neutrinos for simplicity, muon neutrino ν_μ and tau neutrino ν_τ. If neutrinos have non-zero mass (in this case, neutrinos having definite masses are linear combinations of ν_μ and ν_τ), transmutation of neutrino in flight occurs in such a way that a neutrino which was initially ν_μ changes to ν_τ and then changes back to ν_μ. This phenomenon is called the neutrino oscillation. Conversely, if neutrino

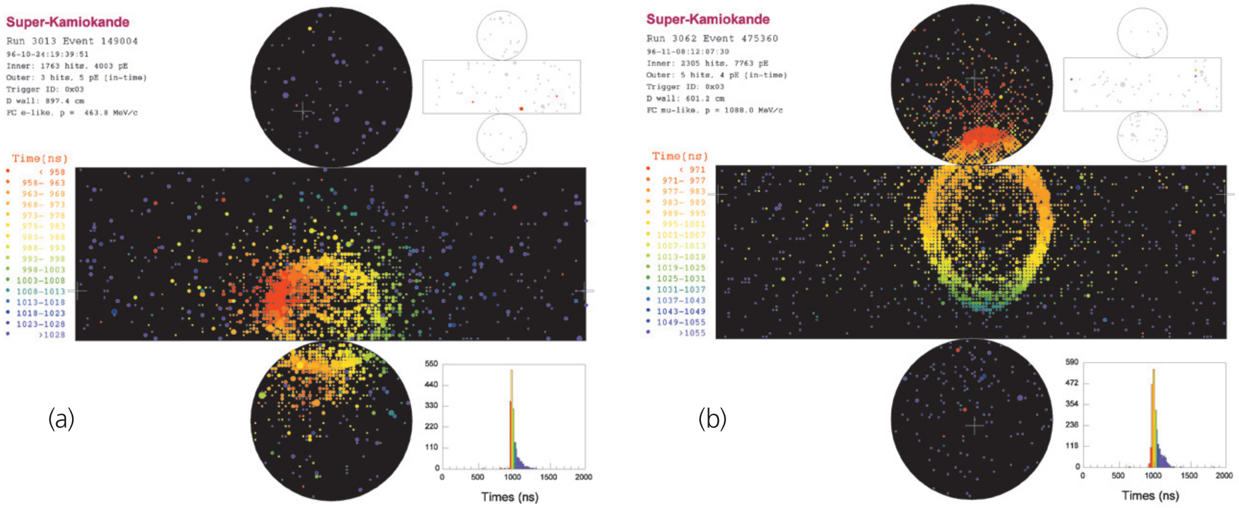


Figure 2. Examples of (a) electron neutrino and (b) muon neutrino events observed in Super-Kamiokande. The sizes of the circles in this figure show the observed light intensity. Also, the color of the circles shows the timing information of the observed light.

oscillation is discovered, it gives evidence for non-zero neutrino mass. Fig. 3 shows the probability for a neutrino, which was initially ν_μ, to remain ν_μ as a function of the flight distance. Here, the mass of the heavier neutrino state is assumed to be about $1/10^7$ of the electron mass. If neutrino mass is heavier than this value, the period of oscillation is shorter, and vice versa. Therefore, we can find the heavier neutrino mass from the measurement of the rate of neutrino's transmutation. In reference to Fig. 3, it should be noted that the "zero" survival probability is actually realized in a special case. Generally, the extent of ν_μ disappearance is somewhere between a tiny level and complete disappearance. The effect of neutrino oscillation is maximized in the case of "zero" survival probability in Fig. 3. This is the easiest case to observe the neutrino oscillation.

Let us now think about combining Fig. 3 and the atmospheric neutrino before returning to the real experiment. Roughly speaking, neutrino interactions at energies around 1GeV are most frequently observed in atmospheric neutrino experiments. Looking at Fig. 3, it is clear that if the heavier neutrino state has about $1/10^7$ of the electron mass, the ν_μ survival probability becomes 0 after a ν_μ traveled about 500 km, showing clear oscillation effects. If neutrinos produced in the upper atmosphere come from directly above, their distance of flight to the detector is about 15 km on the average, so that neutrinos do not yet oscillate. Neutrinos coming from the opposite side of the earth, however, reach the detector after several times of oscillations because the earth's diameter is about 12,800 km.

Though the Kamiokande results were very interesting, they were not necessarily accepted by many physicists. At that time, there were at least three detectors that could observe atmospheric neutrinos other than Kamiokande, but their observation results were not consistent. Because of this situation, we had to wait for the next generation neutrino detector, namely, Super-Kamiokande (SK) which would have overwhelming statistical accuracy.

Atmospheric neutrino observations in SK and neutrino oscillations

As soon as the Super-Kamiokande experiment was commissioned in 1996, the observed atmospheric neutrino data greatly increased since its effective mass for observation was about 20 times that of

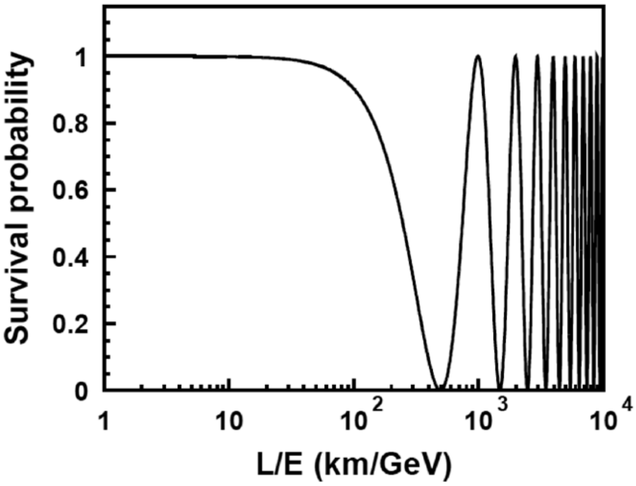


Figure 3. The survival probability of muon neutrinos is shown as a function of L/E, where L (km) is the distance and E (GeV) is the energy. The mass of the heavier neutrino state is assumed to be $1/10^7$ of the electron mass.

Kamiokande. Also, having accumulated more than 10 years of observational data already, and further continuing observation for longer than any other previous experiments, Super-Kamiokande makes it possible to investigate atmospheric neutrinos using far more observational data.

The most significant method to show neutrino oscillations of atmospheric neutrinos is to compare the numbers of neutrinos coming from above and below and to study if they are consistent with the expected numbers. Without neutrino oscillations, calculations show that these numbers are nearly the same. Therefore, if the number of events of the neutrinos coming from below is significantly smaller than that from above, then it must be compelling evidence for the neutrino oscillation. Furthermore, if neutrino oscillations are taking place between muon neutrinos and tau neutrinos, electron neutrinos do not take part in these oscillations. Therefore, an up-down asymmetry should be observed in muon neutrino events but not in electron neutrino events. Along these lines, the zenith-angle distributions of the atmospheric neutrino events have been precisely measured. The results with the Super-Kamiokande data up to 2008 are shown in Fig. 4, where a deficit of the upward-going neutrino events is clearly evident. Also, the zenith-angle distributions show that the effect of up-down asymmetry is more prominent at higher energies. This is because of the following reason. At low energies the angular correlation between the incoming neutrino and the electron or muon produced in the neutrino reaction is poor, and consequently the direction of the muon is not a good indicator of the up-down asymmetry. These results led to the discovery of neutrino oscillation in 1998.

By comparing the data and the expected distribution with neutrino oscillation, shown in Fig. 4, neutrino's basic physical quantities can be measured. First of all, the mass of the heavier neutrino state is estimated to be about $0.05 eV/c^2$. It is $1/10^7$ of the mass of the electron, the lightest particle other than the neutrinos. But, it may be that the heaviest neutrino mass should be compared with the heaviest quark (top quark) mass. In this case, the ratio is about $1/(4\times10^{12})$. The probability of muon neutrino disappearance due to neutrino oscillations is consistent with the theoretically allowed maximal value shown in Fig. 3. If the experiment had better accuracy, periodical decrease and increase of the

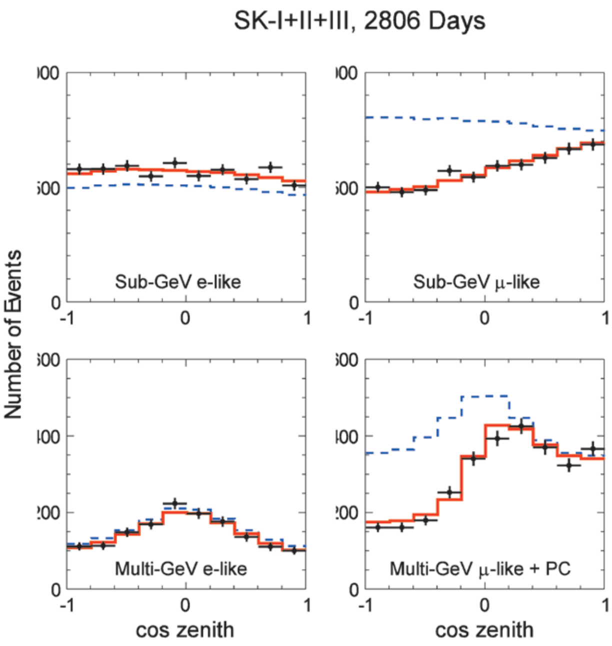


Figure 4. Zenith-angle distribution of the atmospheric neutrinos observed in Super-Kamiokande. cosθ = -1 corresponds to the upward-going direction and cosθ = 1 corresponds to the downward-going direction. The two panels on the left side show electron events (mostly electron neutrino events) and the two panels on the right side show muon events (mostly muon neutrino events). The events shown in the upper panels have visible energy of less than 1.3 GeV, and the events shown in the lower panels have that of greater than 1.3 GeV. The lower right panel (for muon events) also includes those events in which muons penetrate through the detector. The broken histograms show the expected distributions without neutrino oscillations, and the solid histograms show the expected distributions with neutrino oscillations, assumed between muon neutrinos and tau neutrinos.

survival probability of ν_μ would be seen. Such variation is averaged out, however, in the data shown in Fig. 4. That is to say, the survival probability of ν_μ maximally decreases and increases, but it is observed as the averaged value (a half). In any case, the effect of the neutrino oscillation seems to be maximal. Physicists call it as a *large mixing*. Although the tiny neutrino mass seems to be explained by a promising idea of the *seesaw mechanism*, it seems that fundamental understanding of the reason for the large mixing is yet to be obtained, requiring further consideration by theorists. Further accurate measurements will be needed experimentally as well.

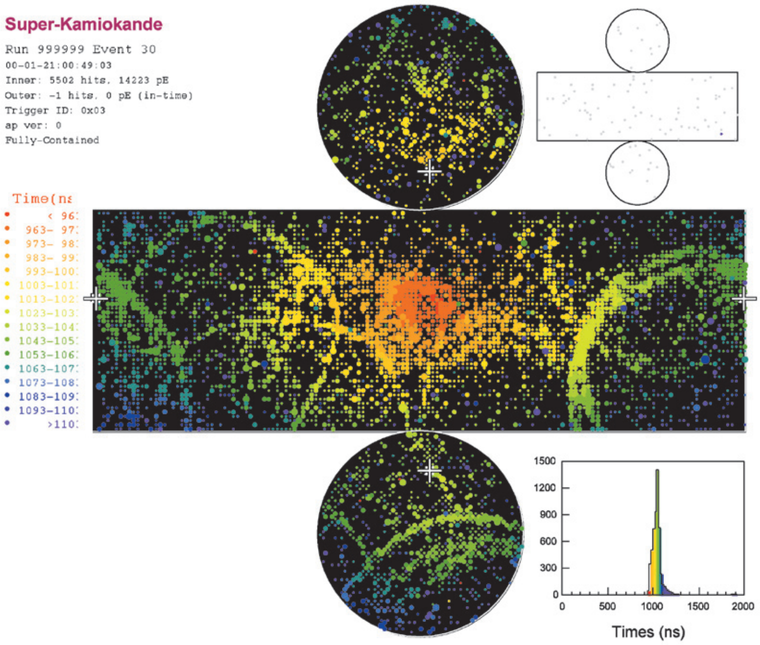
Detection of tau neutrinos

Thus far we have seen that neutrinos oscillate between muon neutrinos and tau neutrinos. To be precise, however, our arguments are the following. Namely, muon neutrinos transmute into other neutrinos due to the neutrino oscillation, and because the other neutrinos are not electron neutrinos, they should be tau neutrinos. It would therefore be decisive evidence if we can confirm the transmutation to tau neutrinos by detecting them.

For this reason, evidence has been sought after for tau neutrino production due to the neutrino oscillation in the atmospheric neutrino observation in Super-Kamiokande. Unfortunately, this search is not easy for the following reasons. First of all, the interaction rate is low because the threshold of the tau neutrino interaction is relatively high (about 3.5 GeV) due to the heavy tau mass and the atmospheric neutrino flux rapidly decreases with increasing energy. Furthermore, tau neutrino interactions are not clearly distinguished from the background events called *neutral-current* events, because the produced tau particles immediately decay, and, in particular, only hadrons such as pions exist (other than neutrinos) in the final state in 65% of the tau decay. A typical Monte-Carlo simulated tau neutrino event is shown in Fig. 5. Analysis of such an event seems difficult because of many overlapping Cherenkov rings.

On the other hand, there is an advantage characteristic to atmospheric neutrinos. Consider studying the zenith-angle distribution by selecting *tau neutrino-like* events. Tau neutrino events should

Figure 5. An example of a Monte-Carlo simulated tau neutrino event.



be all upward-going events because they are produced by neutrino oscillations. Background events other than muon neutrino events, on the other hand, should exhibit up-down symmetry. Therefore, if we can show an excess of upward-going events by studying the zenith-angle distribution of the tau neutrino-like events, we will be able to statistically show the existence of the tau neutrino events.

Based on this idea, the existence of the tau neutrinos produced by neutrino oscillations has been studied. The results of this study, though statistically not decisive yet, showed that the data were consistent with the production of tau neutrinos by neutrino oscillations. We hope that more significant conclusions can be obtained with increasing data in the near future. Also, searches for tau neutrinos are performed in accelerator experiments. It is expected that tau neutrinos produced by neutrino oscillations will be decisively observed in the near future.

Conclusions

As has been explained in this article, neutrino oscillation was discovered by the studies of atmospheric neutrinos, and details of neutrino oscillation phenomena have been studied in the high-statistics observations by Super-Kamiokande. Thus far, mainly neutrino oscillations between muon neutrinos and tau neutrinos have been studied. As there are three kinds of neutrinos, however, we have to study neutrino oscillations between three kinds of neutrinos. We already know from solar neutrino and reactor neutrino observations that electron neutrinos also oscillate. Furthermore, the recent data obtained in the T2K accelerator neutrino oscillation experiment and in other experiments suggest that muon neutrinos oscillate into electron neutrinos, though the oscillation probability is not very high. If atmospheric neutrinos are observed with very high statistical accuracy, we will be able to observe all these neutrino oscillations. Moreover, it is considered possible to measure the order of masses of the three neutrino states with definite mass, exploiting the unique characteristics of atmospheric neutrinos that travel through the earth. Therefore, studies of atmospheric neutrinos will keep contributing to neutrino physics for many years to come.