Discovery of Atmospheric Neutrino Oscillations

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1. INTRODUCTION

Neutrinos are a type of fundamental particles, like electrons and quarks. They have no electric charge and they come in three types (flavors), namely the electron neutrino (ν_e), the muon neutrino (ν_μ) and the tau neutrino (ν_τ). They are produced in various places such as in the Earth's atmosphere and in the center of the Sun. The interactions of neutrinos with matter are so weak that they easily penetrate through the Earth and even the Sun. They do interact with matter, however, but only very rarely. Because a charged current (CC) ν_e (ν_μ, ν_τ) interaction produces an electron (muon, tau), physicists can determine a neutrino's flavor by observing the lepton produced when it interacts.

The Standard Model of elementary particle interactions was established in the early 1970s and it describes the strong, weak and electromagnetic interactions very well. However, in the Standard Model these interactions are not unified and are treated as independent entities. Neutrinos are assumed to be massless within the Standard Model. However, physicists have wondered whether neutrinos really have no mass. If, on the other hand, neutrinos do have mass, they can change their type from one flavor to the other(s). This phenomenon is called "neutrino oscillations," and was theoretically predicted by Maki, Nakagawa and Sakata [1] and also by Pontecorvo [2]. For example, imagine that neutrino oscillations occur between ν_μ and ν_τ. Assuming that only these two

neutrinos oscillate, so-called two flavor oscillations, the oscillation probability can be written as,

$$P\left(v_{\mu} \to v_{\mu}\right) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \Delta m^2 \left(eV^2\right) L(km)}{E_v(GeV)}\right) \tag{1}$$

where $P(v_{\mu} \to v_{\mu})$ is the probability that a v_{μ} remains a v_{μ} after travelling a distance, L, with energy, E. Here θ is the neutrino mixing angle and Δm^2 is the difference in the square of the neutrino masses, $\left|m_3^2 - m_2^2\right|$. A v_{τ} is generated when the v_{μ} disappears so that the probability that the neutrino flavor being either v_{μ} or v_{τ} is one. As can be seen from Equation 1, the neutrino oscillation length is longer for smaller neutrino masses.

In the late 1970s new theories that unify the strong, weak and electromagnetic forces were proposed. These theories predicted that protons and neutrons, collectively known as nucleons, should decay with lifetimes between 10^{28} and 10^{32} years. To test these predictions, several proton decay experiments began in the early 1980s. These experiments had fiducial masses ranging from about 100 tons to several thousand tons in order to detect proton decays in the predicted lifetime range. One of these was the Kamioka Nucleon Decay Experiment, Kamiokande.

Kamiokande was a 3,000 ton water Cherenkov experiment with a fiducial mass of about 1,000 tons. It was located at a depth of 1,000 m underground in the Mozumi mine in Kamioka, Japan. When charged particles propagate through the detector's water at relativistic speeds, they emit Cherenkov photons. These photons are then detected by photomultiplier tubes installed on the inner surfaces of the Kamiokande water tank. Since the photons are emitted in a forward cone along the particle direction, they form a ring pattern (Cherenkov ring) on the detector walls.

2. ATMOSPHERIC NEUTRINO ANOMALY

The Kamiokande experiment began in July 1983. As a graduate student I was involved in the experiment from its early stages. In March 1986, I received a Ph.D. based on a search for proton decays into an anti-neutrino and meson final states using its data. No evidence for proton decay was observed.

At that time I felt that the analysis software was not good enough to select the proton decay signal most efficiently from its dominant background, atmospheric neutrino interactions. Therefore, as soon as I submitted my thesis I began to work on improving the software. One of the pieces of software was to identify

the type of particle seen in events with multiple Cherenkov rings. For each ring in these events, we wanted to estimate whether it was produced by an electron or by a muon. Since the rings are often overlapping it was a non-trivial task to identify the particle types that produced them. Typically one has to verify the performance of the software step-by-step, starting from the simplest cases to the most difficult ones.

Indeed, the software worked very well for the simplest case, namely for simulated atmospheric neutrino events with only a single Cherenkov ring. Muons (electrons) produced by simulated atmospheric ν_μ (ν_e) interactions were correctly identified approximately 98% of the time. With this knowledge, the flavor of atmospheric neutrino interactions observed in Kamiokande was checked. The result was strange. The number of ν_μ events was far fewer than predicted by the simulation. At the same time, no such discrepancy was seen in the number of ν_e events. At first I thought that I had made some serious mistake. In order to find where I had made the mistake, I decided to check the events in the data by eye. Immediately I realized that the analysis software was correctly identifying the particle types. Unfortunately, I thought that this meant that the problem must not be simple. It seemed very likely that there were mistakes somewhere deep in the simulation, data selection, or the event reconstruction software. Together Masato Takita and I embarked on various studies to try and find such mistakes late in 1986.

After studies for a year, we did not find any serious mistake and concluded that the ν_μ deficit could not be due to a major problem with the data analysis or the simulation. It should be mentioned that the ratio of the atmospheric ν_μ and ν_e fluxes can be accurately predicted independently of the absolute flux values due to the neutrino production mechanism. Atmospheric ν_μ and ν_e are generated in the decay chain of pions produced by cosmic ray interactions in the atmosphere. A pion decays into a muon and a ν_μ and the muon subsequently decays into an electron in conjunction with another ν_μ and a ν_e. These neutrinos have almost the same energy and therefore the ratio of the atmospheric ν_μ to ν_e fluxes is expected to be about two, regardless of the details of the cosmic ray flux. In fact, detailed calculations predicted that this flux ratio is approximately two for neutrino energies around 1 GeV. In 1988 we estimated the uncertainty of this ratio to be about 5%. However, the absolute flux was only predicted to a precision between 20% and 30%. These predictions indicated that the data from Kamiokande were very difficult to explain by uncertainties in the flux calculation.

A paper was written and published in 1988 [3]. The observed numbers of μ-like events (mostly due to ν_μ interactions), and e-like events (mostly due to ν_e interactions), were compared with the corresponding numbers from a simulation.

TABLE 1. Comparison of the number of observed events in Kamiokande with the expectation from simulations. The detector exposure was 2.87 kiloton years.

	Data	Prediction
e-like (mostly CC ν_e interactions)	93	88.5
μ-like (mostly CC ν_μ interactions)	85	144.0

The results of the comparison are summarized in Table 1. Note that though the simulation used the calculated atmospheric neutrino flux and assumed standard neutrino properties, it did not include the effect of neutrino oscillations.

From these considerations Kamiokande concluded in [3] that "We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccounted-for physics such as neutrino oscillations might explain the data." In fact, I was most excited by the possibility of neutrino oscillations with a large mixing angle. Namely, ν_μ seemed to be almost completely oscillating into some other neutrino type. At that time a large mixing angle was not expected. So this gave me strong motivation to continue the study of atmospheric neutrinos.

Subsequently, another large water Cherenkov experiment, IMB, published an observed deficit of ν_μ events [4], [5]. Kamiokande then published a second paper on the atmospheric neutrino deficit including a detailed evaluation of systematic errors in the ratio of μ-like to e-like events for both data and simulation as well as allowed regions for oscillation parameters assuming neutrinos oscillate [6]. The results suggested that the atmospheric neutrino data might indicate neutrino oscillations. However, neutrino oscillation was still only one of the possible explanations for the data. This was due partly to the fact that the observed effect was only a small ratio of μ-like to e-like events. Indeed, the deficit of μ-like events seen in Kamiokande and IMB at energies below about 1 GeV (sub-GeV) did not show a strong dependence on the angle of the event direction relative to the vertical axis of the detector (zenith angle) nor on the event momentum.

The atmospheric neutrino flux is predicted to be up-down symmetric due to the isotropic nature of the cosmic ray flux. Note that while this is not exactly true for sub-GeV atmospheric neutrinos due to the effects of the geomagnetic field on the cosmic ray flux, the flux of the multi-GeV neutrinos is nonetheless very nearly up-down symmetric. If neutrinos have very small masses, then their oscillation length could be 100 kilometers or even longer. If this is the case, vertically downward-going neutrinos, which typically travel tens of kilometers before reaching an underground detector, may not oscillate before they interact within it. On the other hand, vertically upward-going neutrinos, which can travel

up to about 12,800 kilometers, may have enough time to oscillate into another flavor. Observing a disappearance effect in the upward-going events but not in the downward-going events would therefore be a very strong indication of neutrino oscillations.

Soon after submitting the first paper on the atmospheric ν_μ deficit in 1988, we started to select and study atmospheric ν_μ events with energies larger than 1 GeV (multi-GeV) in the data. A multi-GeV ν_μ interaction typically produces a multi-GeV muon. However, multi-GeV muons produced in the detector will often penetrate through it and exit into the surrounding rock, called partially contained (PC) events. They were selected for analysis. The angular correlation between the muon and its parent neutrino gets substantially better with increasing neutrino energy and therefore the zenith angle distribution of multi-GeV muons should represent the neutrino zenith angle distribution fairly well. Consequently, we studied the zenith angle distribution for the multi-GeV events.

Since the flux of the atmospheric neutrinos decreases rapidly with increasing energy, the rate of multi-GeV ν_μ events was only about 20 events per year in Kamiokande and it therefore took several years to collect a statistically meaningful number of them. Finally, Kamiokande published a study of the multi-GeV atmospheric neutrino data in 1994 [7]. The μ-like data showed a deficit of events in the upward-going direction, while the downward-going events did not show any such deficit. On the other hand, the corresponding distribution from the e-like data did not show any evidence for a deficit of upward-going events (Fig. 1). The ratios of upward- to downward-going events (the up/down ratio) for the multi-GeV μ-like and e-like data were $0.58^{+0.13}_{-0.11}$ and $1.38^{+0.49}_{-0.30}$, respectively. The
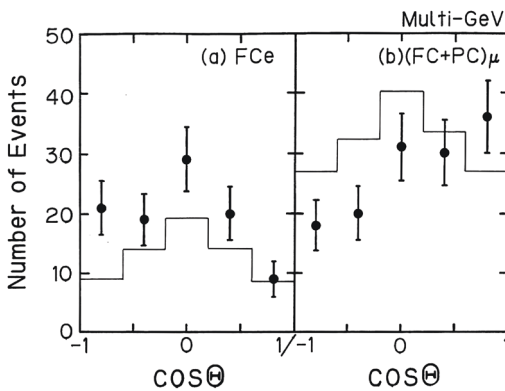

FIGURE 1. Zenith angle distributions for multi-GeV (a) e-like and (b) μ-like events observed in Kamiokande [7]. Solid histogram shows the predicted distributions without oscillations. Absolute normalization had an uncertainty of 20 to 30%.

statistical significance of the observed up-down asymmetry in the μ-like data was equivalent to 2.8 standard deviations. In other words, the probability that the observed result could be due to a statistical fluctuation was less than 1%. It was an interesting observation which showed for the first time that the ν_μ deficit depended on the neutrino flight length as predicted by neutrino oscillations. However, the statistical significance of the observation was not strong enough to be conclusive and this prompted the need for an even larger data set, namely an even larger detector.

3. DISCOVERY OF NEUTRINO OSCILLATIONS

The Super-Kamiokande detector is a large, cylindrical water Cherenkov detector; 41.4 meters high, 39.3 meters in diameter, and it has a total mass of 50,000 tons. Super-Kamiokande is divided into two parts, an inner detector that studies the details of neutrino interactions and an outer detector that identifies incoming and exiting charged particles. The fiducial mass of the detector is 22,500 tons, which is about 20 times larger than that of Kamiokande. Figure 2 shows a schematic of the Super-Kamiokande detector.

Super-Kamiokande is an international collaboration. A collaborative agreement between research groups from the USA and Japan was signed in October 1992. Many members of the Kamiokande and IMB collaborations joined in the experiment. The Super-Kamiokande detector was designed based on the
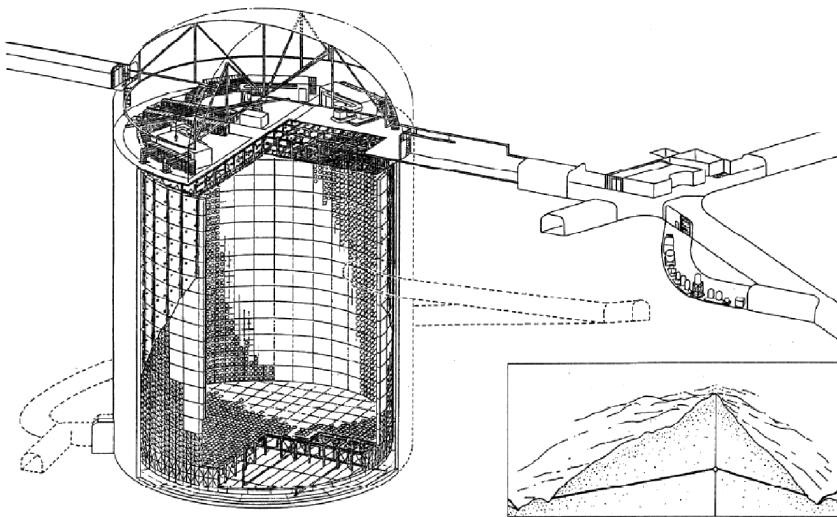

FIGURE 2. Schematic view of the Super-Kamiokande detector.

experience of these experiments and included various technological improvements. As of 2015, about 120 people from seven countries are members of the collaboration.

The Super-Kamiokande experiment started in the spring of 1996 after a five year period of detector construction. Due its larger fiducial mass, Super-Kamiokande accumulates neutrino events approximately 20 times faster than Kamiokande. Furthermore, Cherenkov rings are observed by 11,200 photomultiplier tubes making it possible to study the detailed properties of neutrino events. Methods for analyzing atmospheric neutrino interactions had been well established by studies performed in previous experiments. Therefore, from the very beginning of the experiment, Super-Kamiokande analyzed various types of atmospheric neutrino events, including fully contained events, which have no charged particle exiting the inner detector and partially contained events, which has at least one charged particle exiting the inner detector [8], [9]. In addition, upward-going muon events induced by neutrino interactions in the rock below the detector and that traverse it entirely [10] as well as those that stop within it [11] were analyzed. The topologies and features of these events types differ significantly from one another. Therefore the collaborative work of many researchers, especially young scientists, was essential for the analysis of the data. Super-Kamiokande developed simulations and analysis programs based on those from Kamiokande and IMB. For this reason Super-Kamiokande was able to produce reliable results relatively quickly after the start of the experiment.

By the spring of 1998 Super-Kamiokande had analyzed 535 days of data, which is equivalent to a 33 kiloton · year exposure of the detector. In total there were 5,400 atmospheric neutrino events, which was already several times larger than the data sets of previous experiments. At the 18th International Conference on Neutrino Physics and Astrophysics (Neutrino '98), Super-Kamiokande announced evidence for atmospheric neutrino oscillations [12], [13]. The zenith angle distributions shown at Neutrino '98 have been reproduced in Fig. 3. The top and bottom panels of the figure show the zenith angle distributions of multi-GeV e-like and multi-GeV μ-like (fully contained and partially contained events have been combined) data, respectively. While the e-like data did not show any statistically significant up-down asymmetry, a clear deficit of upward-going μ-like events was observed. The statistical significance of the effect was more than six standard deviations, implying that the deficit was not due to a statistical fluctuation. Figure 4 shows the summary of the oscillation analyses from Super-Kamiokande and Kamiokande that were presented at the Neutrino '98 conference. The allowed regions for the neutrino oscillation parameters obtained from the two experiments overlapped, indicating that the data could be consistently
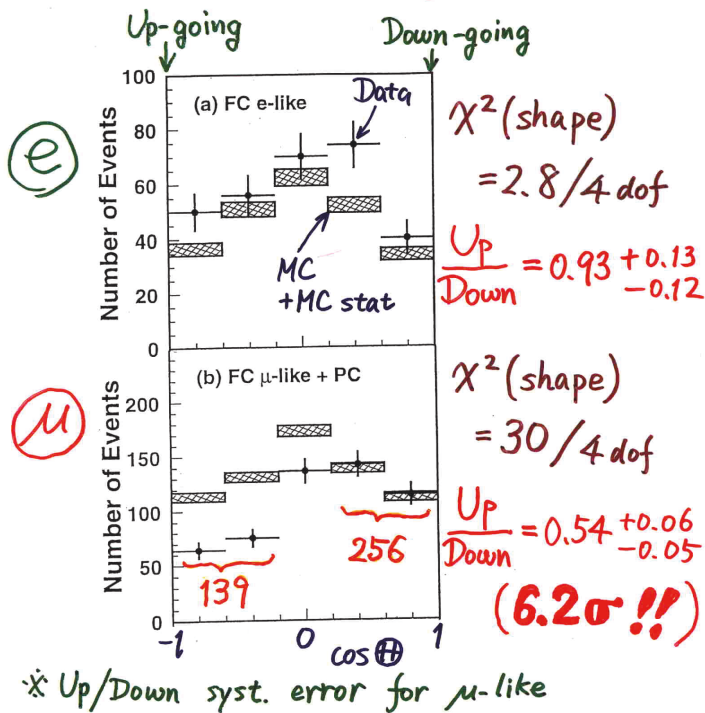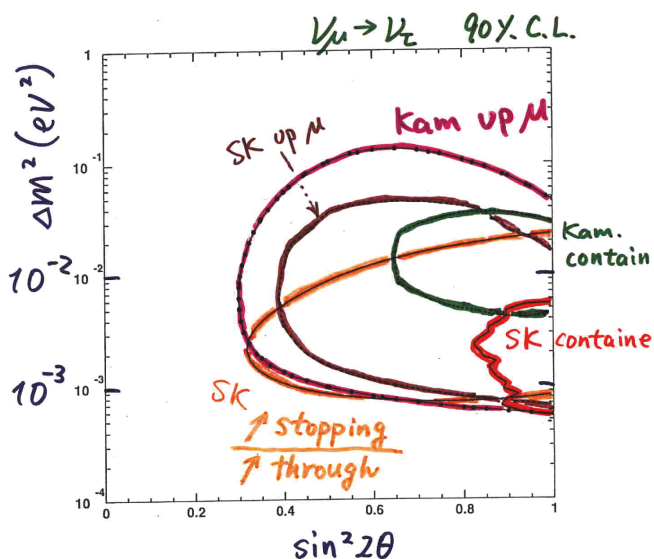
FIGURE 3. Zenith angle distributions for multi-GeV atmospheric neutrino events presented at the 18th International Conference on Neutrino Physics and Astrophysics (Neutrino '98) by the Super-Kamiokande collaboration [12].

explained by neutrino oscillations. Super-Kamiokande concluded from the analysis of these data that muon neutrinos oscillate into other types of neutrinos, most likely into tau neutrinos.

There were two other experiments, Soudan-2 and MACRO, which were observing atmospheric neutrinos at that time. Soudan-2 was a 1 kiloton iron tracking calorimeter detector which had been gathering data since 1989. This

FIGURE 4. The final slide (summary slide) of the presentation by the Super-Kamiokande collaboration at Neutrino '98 [12].

experiment confirmed the zenith angle dependent ν_μ deficit [14]. Similarly, MACRO was a large underground detector which was able to measure upward-going muons as well as partially contained neutrino events. This experiment also observed a zenith angle dependent deficit of both upward-going muons [15] and partially-contained ν_μ events [16]. The results from these experiments were completely consistent with those from Super-Kamiokande and consequently, neutrino oscillations were quickly accepted by the neutrino physics community.
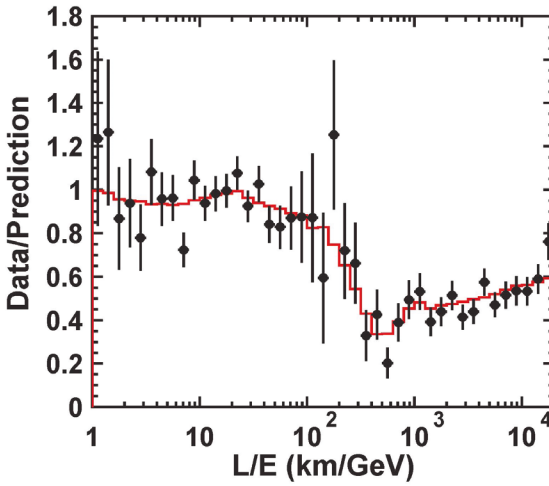
FIGURE 5. Data/Prediction as a function of L/E_ν from Super-Kamiokande [17].

4. RECENT RESULTS AND THE FUTURE

Super-Kamiokande's data showed that approximately 50% of muon-neutrinos disappear after traveling long distances, an effect which was commonly interpreted as neutrino oscillations. However, there were still several unanswered questions, such as "what are the values of the neutrino mass squared difference (Δm^2) and the neutrino mixing angle (θ)?", "does the ν_μ disappearance probability really oscillate as predicted by the theory of neutrino oscillation?", and "is it possible to confirm $\nu_\mu \to \nu_\tau$ oscillations by detecting ν_τ interactions?" These questions have been answered experimentally.

4.1. Observing "oscillation"

According to the neutrino oscillation formula shown in Equation 1, the neutrino survival probability should be sinusoidal. Specifically, at a given energy the probability should be smallest at a certain value of L/E_ν then come back to unity if twice the distance is traversed, and then continue oscillating back and forth in this way over longer distances. In Fig. 3 atmospheric neutrino events with a variety of L/E_ν values were included in each zenith angle bin so only an averaged survival probability could be observed.

Super-Kamiokande carried out a dedicated analysis that used only events whose L/E_ν value could be determined with good precision. In short, in this analysis Super-Kamiokande did not use neutrino events whose direction was

near the horizon, since the estimated neutrino flight length changes significantly for even small changes in the estimated arrival direction in this regime. Similarly, the analysis did not use low energy neutrino events because the scattering angle at these energies is large, and consequently, the uncertainty in the estimated neutrino flight length becomes large. Using only the high L/E_ν resolution events, Super-Kamiokande showed that the measured ν_μ survival probability has a dip corresponding to the first minimum of the theoretical survival probability near $L/E_\nu = 500$ km/GeV [17] as shown in Fig. 5. This was the first evidence that the ν_μ survival probability obeys the sinusoidal function predicted by neutrino oscillations.

4.2. Detecting tau neutrinos

If the oscillations of atmospheric neutrino are indeed between ν_μ and ν_τ, it should be possible to observe the charged current interactions of ν_τ generated by these oscillations. A charged current ν_τ interaction typically produces a tau lepton accompanied by several hadrons, most of which are pions. Due to the heavy tau mass (1.78 GeV/c^2), the threshold for this interaction is about 3.5 GeV. Since this threshold is rather high and the atmospheric neutrino flux at these energies is rather low, the expected event rate is only about one per kiloton per year. The rate of the charged current ν_τ interactions is therefore only about 0.5% of the total atmospheric neutrino interaction rate. It should be noted that the lifetime of the tau lepton is only 2.9×10^{-13} sec, hence, any tau lepton produced in an atmospheric neutrino interaction decays almost immediately into several hadrons and a neutrino. Therefore, a typical ν_τ interaction has many hadrons in the final state. However, high energy neutral current interactions also produce many hadrons. Searching for ν_τ events in a water Cherenkov detector is therefore complicated due to these backgrounds.

Nonetheless Super-Kamiokande searched for charged current ν_τ interactions in the detector. The search was carried out using various kinematic variables and advanced statistical methods [18], including an artificial neural network. Figure 6 shows the zenith angle distribution for candidate ν_τ events [19]. Even with these advanced methods many background events remain in the final sample. However, there is an excess of upward-going events that cannot be explained with the background events alone. The significance of the excess after taking various systematic uncertainties into account is 3.8 standard deviations [19]. These data are indeed consistent with the appearance of tau neutrinos due to atmospheric $\nu_\mu \rightarrow \nu_\tau$ oscillations.
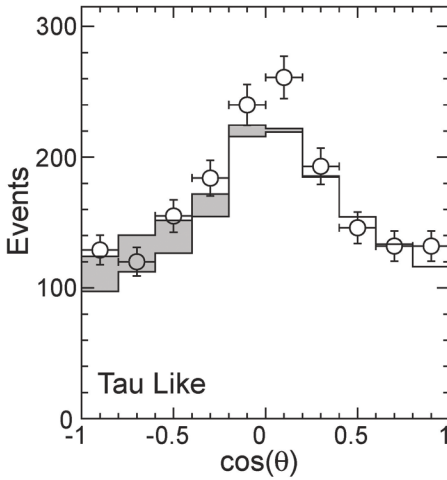
FIGURE 6. Zenith angle distributions for the τ-like events selected from the data observed in Super-Kamiokande [19]. Circles with error bars show the data. Solid histograms show the Monte Carlo prediction with $v_\mu \rightarrow v_\tau$ oscillations but without the charged current v_τ interactions. The gray histograms show the fit result including the v_τ interactions.

4.3. Data updates, neutrino masses and mixing angles

As of 2015 Super-Kamiokande has been taking data for about 5,000 days, which implies that approximately a factor of 10 larger data set than that in 1998 has already been obtained. Figure 7 shows the zenith angle distribution of these events. It is clear that the statistical error on the data sample has improved significantly relative to the 1998 data set (shown in Fig. 3). Neutrino oscillation parameters have been measured using these events and the data indicate that the
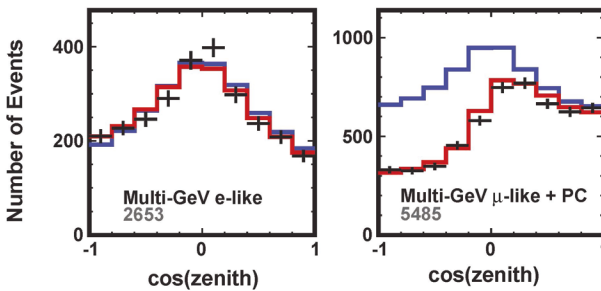
FIGURE 7. Zenith angle distribution for multi-GeV e-like (left) and μ-like (right) atmospheric neutrino events observed in Super-Kamiokande (2015).

neutrino mass squared difference (Δm^2) is approximately 0.0024 eV^2. Assuming that the neutrino masses are not degenerate, the heaviest neutrino mass is approximately 0.05 eV, which is 10 million times smaller than the electron mass (or more than one trillion times smaller than the top quark mass), suggesting that neutrino masses are extremely small compared to the masses of other elementary particles. These extremely small neutrino masses are naturally explained by the seesaw mechanism [20], [21], [22], implying that the small neutrino masses are related to the physics at an extremely high energy scale.

The measured mixing angle is consistent with maximal mixing, $\sin^2 2\theta = 1.0$. Compared to the measurements made in 1998, these parameters have been determined much more precisely. Note that the neutrino mixing angles are very different from the quark mixing angles. For instance, $\sin^2 2\theta \sim 1$ corresponds to $\theta \sim 45$ degrees, while the analogous quark mixing angle is only about 2.4 degrees. Before the discovery of neutrino oscillations this difference was not expected. Indeed, the difference in these sets of mixing angles may give us a hint to understand the profound relationship between quarks and leptons.

4.4. Neutrino oscillation experiments: past, present and future

As discussed above, the deficit of ν_μ events in early data from atmospheric neutrino experiments circa 1990 were confirmed to be the effect of neutrino oscillations in 1998 by the subsequent generation of experiments. Note that the atmospheric neutrino flux has a wide energy spectrum and also provides neutrinos with a wide range of path lengths. These features made it possible to probe neutrino oscillations over an equally large range of Δm^2 values and in fact led to the discovery of neutrino oscillations.

Early atmospheric neutrino data and the discovery of neutrino oscillations motivated accelerator based long-baseline neutrino oscillation experiments. In a long-baseline neutrino oscillation experiment the neutrino flight length is fixed to a single value since the neutrino beam is produced by an accelerator and observed in a detector located a fixed distance away. It should also be noted that the beam in such experiments has a high ν_μ (or anti-ν_μ) purity, while the atmospheric neutrino flux is a mixture of ν_μ, anti-ν_e, ν_μ and anti-ν_μ. For these reasons long-baseline experiments are well suited to carry out precision measurements.

The first generation long-baseline experiments were carried out in the 2000s. K2K and MINOS are the experiments of this generation and confirmed the neutrino oscillation phenomenon, independently measuring the neutrino oscillation parameters [23], [24]. OPERA was also a long-baseline experiment of this

generation and observed tau leptons produced by the interactions v_τ's generated by neutrino oscillations [25].

Oscillations between v_μ and v_τ have been well studied by both long-baseline and atmospheric neutrino experiments. Therefore, the next stage of oscillation studies is focused on three flavor oscillation effects. The first step towards realizing this goal was the establishment of the mixing angle, θ_{13}. Several reactor neutrino experiments (Daya Bay, RENO, and Double-Chooz) and long-baseline experiments (T2K and NOvA) have been carried out to search for evidence of this parameter. These experiments discovered and measured θ_{13} [26], [27], [28], [29], [30].

Including measurements by solar neutrino experiments [31] and a long-baseline reactor experiment (KamLAND) [32], all mixing angles (θ_{12}, θ_{23}, and θ_{13}) and the absolute values of the neutrino mass squared differences (Δm_{12}^2 and $\Delta m_{23(13)}^2$) within the three flavor neutrino oscillation framework have been measured. It is clear that our understanding of neutrino oscillations has improved tremendously since 1998. However, there are still unmeasured, but important parameters to be probed by future neutrino oscillation experiments. Notably the measurement of the neutrino mass ordering and the potential establishment of CP violation in neutrino oscillations are measurements being targeted by upcoming experiments. The order of the neutrino masses is usually assumed to be $m_{v1} < m_{v2} < m_{v3}$. In fact we know through measurements of solar neutrinos that $m_{v1} < m_{v2}$. However, we do not yet know if v_3 is the heaviest neutrino mass state. This must be measured. If CP is violated in the neutrino sector, the probabilities of oscillating from v_μ to v_e and from anti-v_μ to anti-v_e will not be identical. Discovering CP violation in the neutrino sector could have a profound impact on our understanding of the baryon asymmetry of the Universe [33]. Consequently, several long-baseline [34], [35], atmospheric [36], [37], [38] and reactor [39], [40] neutrino experiments are currently planned or are under construction in order to measure these properties. I expect that neutrino oscillation experiments will continue producing results of fundamental importance to our deeper understanding of the elementary particles and the Universe itself.

SUMMARY

An unexpected muon neutrino deficit was observed in the atmospheric neutrino flux by Kamiokande in 1988. At that time neutrino oscillation was considered as a possible explanation for the data. Subsequently, in 1998, through the studies of atmospheric neutrinos, Super-Kamiokande discovered neutrino oscillations,

establishing that neutrinos have mass. I feel that I have been extremely lucky, because I have been involved in the excitement of this discovery from its very beginning.

The discovery of non-zero neutrino masses has opened a window to study physics beyond the Standard Model of elementary particle physics, notably physics at a very high energy scale such as the Grand Unification of elementary particle interactions. At the same time, there are still many things to be observed in neutrinos themselves. Further studies of neutrinos might give us information of fundamental importance for our understanding of nature, such as the origin of the matter in the Universe.

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