Atmospheric neutrinos: the anomaly becomes the discovery

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Large underground detectors that were operated in the 1980's to 90's observed the deficit of atmospheric neutrinos. However, the cause of the deficit was not known. In 1996, the Super-Kamiokande experiment began. This experiment observed many atmospheric neutrino events and discovered that the atmospheric neutrino deficit was due to neutrino oscillations.

1 Introduction

In the 1970's, Grand Unified Theories of strong, weak and electromagnetic interactions were proposed. These theories predicted that protons should decay with the lifetime of about 10^{30} years. Following these predictions, several proton decay experiments began in the early 1980's. Since atmospheric neutrinos have been the most serious background to the proton decay searches, these experiments studied atmospheric neutrinos. In 1988 the Kamiokande experiment [1] and subsequently in 1991 the IMB experiment [2], observed the deficit of atmospheric muon-neutrinos. The electron-neutrinos did not show any deficit. The Kamiokande [3] and IMB [4] experiments continued the analyses and confirmed the muon neutrino deficit with higher statistics data. For more details of these days, please refer P. Lipari [5] and J. Learned [6].

Subsequently, Kamiokande studies the zenith-angle dependence of the neutrino flux [7]. The data showed an indication of the zenith-angle dependent deficit of multi-GeV atmospheric muon-neutrinos. Unfortunately, due to the relatively small mass of the detector and therefore the relatively small statistics of events, it was not possible to draw any firm conclusion. A much larger detector was waited for.

2 Evidence for oscillation of atmospheric neutrinos

The Super-Kamiokande detector [8] is a large, cylindrical water Cherenkov detector; 41.4 meters high, 39.3 meters in diameter, and it contains 50,000 tons of pure water in the detector, located 1000 meters underground in Kamioka, Japan. Figure 1 shows the schematic of the Super-Kamiokande detector. 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 for the contained event analysis is 22,500 tons. The construction of the detector began in 1991. The experiment began on April 1, 1996.

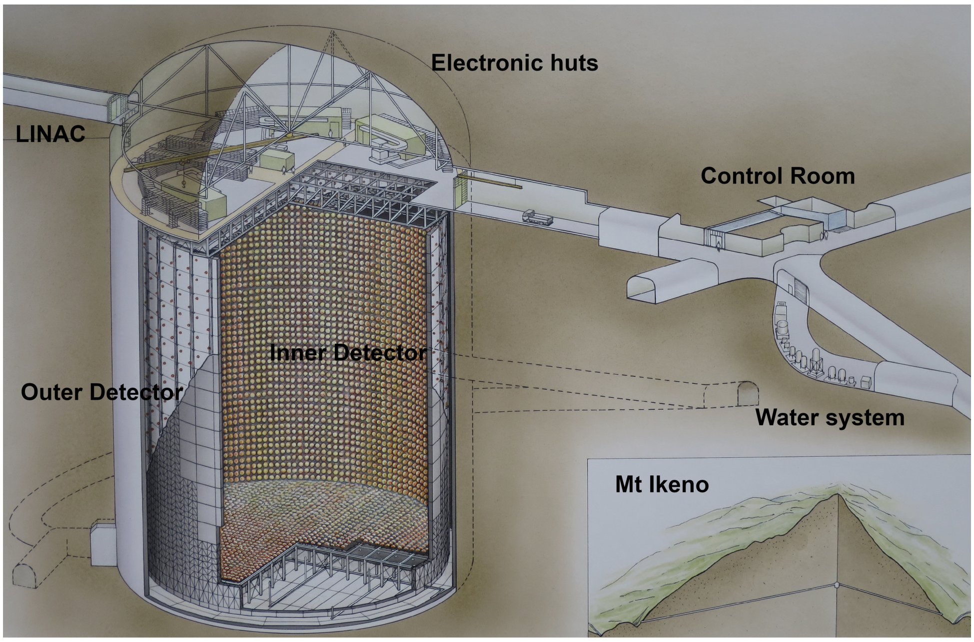


Figure 1 – Schematic of the Super-Kamiokande detector.

Many members of the Kamiokande and IMB collaborations joined in the Super-Kamiokande experiment. In the early stage of the experiment, the number of the collaborators was about 120. As of 2018, this number is about 170.

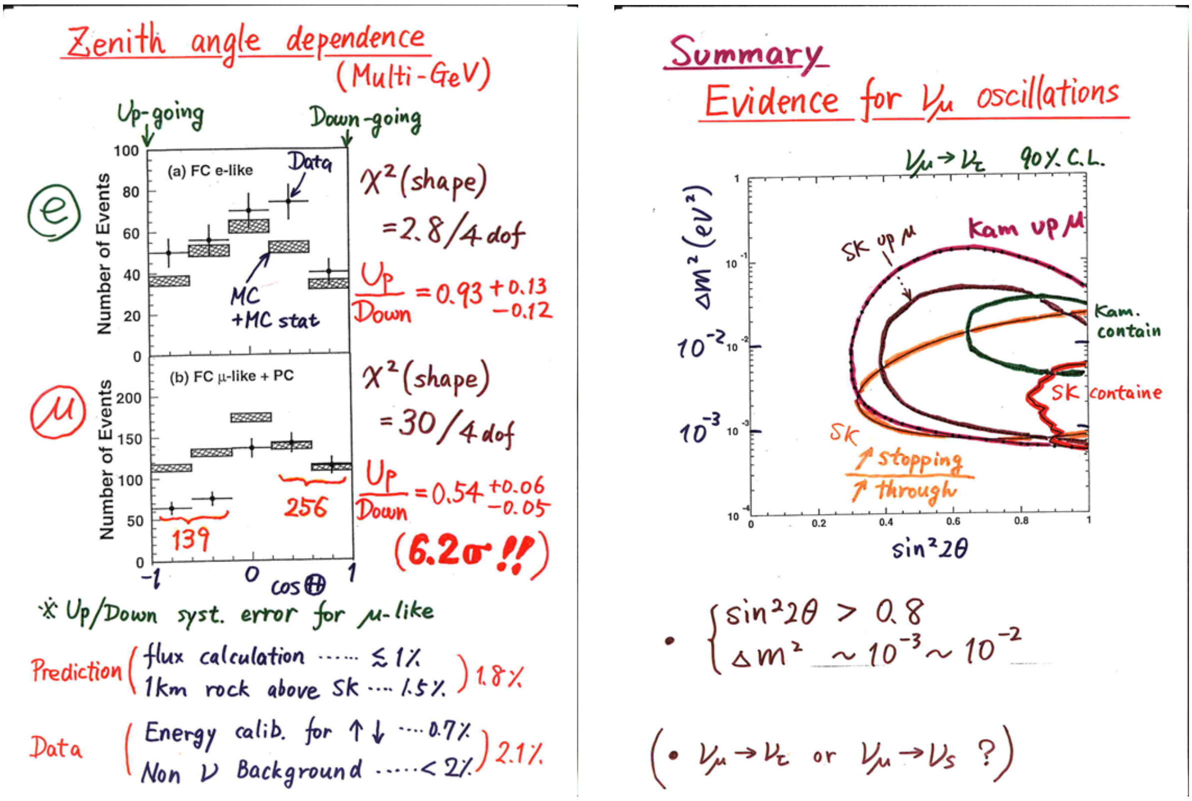
Due its larger fiducial mass, Super-Kamiokande accumulates neutrino events approximately 20 times faster than Kamiokande. Furthermore, Cherenkov rings are observed by 11,200 photomultiplier tubes making it possible to study the detailed properties of neutrino events. Methods for analyzing atmospheric neutrino interactions had been well established by studies performed in the previous experiments. However, in the previous experiments, the algorithm for identify the Cherenkov rings did not exist. Therefore, for example, in Kamiokande, physicists had to scan each event and identify the number of Cherenkov rings and the location of the rings on the detector wall. Therefore, Super-Kamiokande developed new software to identify the Cherenkov rings automatically. Automatic analysis was indeed necessary for the high-quality data analysis.

From the beginning of the experiment, Super-Kamiokande tried to confirm that the deficit of atmospheric neutrinos was due to neutrino oscillations [9,10]. Therefore, Super-Kamiokande analyzed various types of atmospheric neutrino events, including fully contained (FC) events and partially contained (PC) events [11,12]. In addition, upward-going muon events produced by neutrino interactions in the rock below the detector and that traverse it entirely [13] as well as those that stop within it [14] were analyzed. The topologies and features of these events types differ significantly from one another. Therefore, the collaborative work of the collaborators was essential for the analysis of these data.

By the spring of 1998, the collaboration had analyzed 535 days of Super-Kamiokande data, which was equivalent to a 33 kiloton-year exposure of the detector for the contained neutrino events. In total, there were 5,400 atmospheric neutrino events, which were already several times larger than the data sets of the previous experiments. At the 18th International Conference on Neutrino Physics and Astrophysics (Neutrino'98) held in Takayama, Japan in June 1998, Super-Kamiokande announced evidence for atmospheric neutrino oscillations [15,16]. The zenith angle distributions shown at Neutrino'98 have been copied in Fig. 1 (left). The top and bottom panels of the figure show the zenith-angle distributions of multi-GeV e-like and multi-GeV μ-like

(FC and PC 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 6 standard deviations, implying that the deficit was not due to a statistical fluctuation. Furthermore, the other data, namely the small ν_μ/ν_e flux ratio in the sub- and multi-GeV energy ranges, the zenith-angle distribution for the upward through going muons and the stop/through ratio for upward going muons were consistent with neutrino oscillations.

Figure 2 (right) shows the summary of the oscillation analyses from Super-Kamiokande together with those from 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 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.



Zenith angle dependence
(Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ !!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲1% / 1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7% / Non ν Background …. < 2%) 2.1%

Summary

Evidence for ν_μ oscillations

$\nu_\mu \to \nu_\tau$ 90% C.L.

- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

Figure 2 – Left: 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. Right: The final slide (summary slide) of the presentation by the Super-Kamiokande collaboration at Neutrino'98 [15].

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 taking data since 1989. This experiment confirmed the deficit of muon-neutrinos [17], and later the zenith angle dependence of it [18]. 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 and partially-contained muon-neutrino events [19,20,21,22]. The results from these experiments were consistent with those from Super-Kamiokande, and consequently, neutrino oscillations were quickly accepted by the neutrino community.

3 Further confirmation of muon-neutrino to tau-neutrino oscillations

Super-Kamiokande's data showed that approximately 50 % of muon-neutrinos disappear after traveling long distances, an effect which was commonly interpreted as neutrinos 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?", "are the oscillations between muon-neutrinos and tau-neutrinos (i.e., not between muon-neutrinos and sterile-neutrinos), and if so "is it possible to confirm muon neutrino → tau-neutrino oscillations by detecting charged-current tau-neutrino interactions?" Super-Kamiokande carried out various analyses to answer to these questions as described below.

3.1 *Observing "oscillation"*

According to the neutrino oscillation formula, 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, where L is the neutrino flight length in km and E_ν is the neutrino energy in GeV. Then the probability come back to unity if twice the distance is traversed, and then continue oscillating back and forth in this way over longer distances. In Figure 2, 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. In 2004, 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 $L/E_\nu = 500\,\mathrm{km/GeV}$ [23] as shown in Figure 3. The L/E_ν distribution for ν_e events was essentially flat. This was the first evidence that the neutrino survival probability obeys the sinusoidal function predicted by neutrino oscillations.

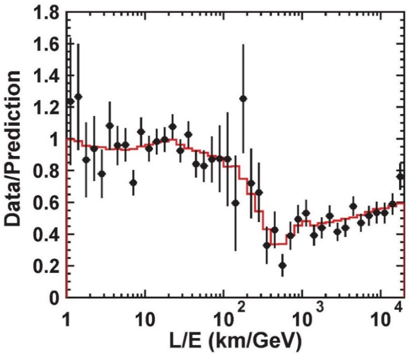


Figure 3 – Data/Prediction as a function of L/E_ν from Super-Kamiokande [23].

3.2 $\nu_\mu \to \nu_\tau$ *or* $\nu_\mu \to \nu_{sterile}$*?*

According to the early neutrino oscillation analysis, oscillations between muon-neutrinos and tau-neutrinos and those between muon-neutrinos and sterile-neutrinos were almost equally allowed.

Sterile-neutrino is a hypothetical neutrino-like particle which does not interact with matter by either charged current (CC) or neutral current (NC) weak interactions. If the oscillation is between muon-neutrinos and sterile-neutrinos, there will be a huge impact on particle physics implying the existence of new particle. Therefore, Super-Kamiokande carried out a dedicated analysis to know if a muon-neutrino oscillate to a tau-neutrino or to a sterile-neutrino ($\nu_{sterile}$).

There are several ways to discriminate between the two possibilities. One possibility was to use the matter effect[24] for upward going neutrino events. For $\nu_\mu \to \nu_\tau$ oscillations, the matter effect does not change the oscillation probability from those in the vacuum. On the other hand, for $\nu_\mu \to \nu_{sterile}$ oscillations, the matter effect changes the oscillation probability significantly, in particular for high energy (>10 GeV) atmospheric neutrinos traveling through the Earth. In addition, the zenith-angle distribution of a NC enriched event sample was useful to discriminate between the two possibilities, because the NC events should be affected only for $\nu_\mu \to \nu_{sterile}$ oscillations.

In 2000, Super-Kamiokande published an analysis using neutral-current enriched multi-ring events, high-energy PC events with the visible energy larger than 5 GeV, and upward through-going muon events. All these data confirmed that the favored oscillation was $\nu_\mu \to \nu_\tau$[25].

3.3 Detecting tau-neutrinos

If the oscillations of atmospheric neutrino are indeed between muon-neutrinos and tau-neutrinos, it should be possible to observe the charged current interactions of tau-neutrinos generated by these oscillations. A charged current ν_τ interaction typically produces a tau lepton accompanied by several hadrons, many 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. 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, and therefore, are serious backgrounds to the tau-neutrino search. (High energy charged-current interactions of electron- and muon-neutrinos are also the backgrounds, if the energy carried by the charged lepton is small.) Searching for tau-neutrino 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, such as artificial neural network. Super-Kamiokande began these analyses around 2000. However, due to the difficulty of the analyses, it took many years for Super-Kamiokande to publish the results. Super-Kamiokande has published the results from the tau-neutrino analysis in 2006[26], 2013[27] and 2018[28]. The statistical significance has been improving with time. Figure 4 shows the most updated zenith-angle distribution for candidate ν_τ events[28]. 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 4.6 standard deviations. These data are indeed consistent with the appearance of tau neutrinos due to $\nu_\mu \to \nu_\tau$ oscillations.

4 Summary

An unexpected muon neutrino deficit was observed in the atmospheric neutrino flux by water Cherenkov detectors in the late 1980's and early 1990's. Subsequently, in 1998, through the

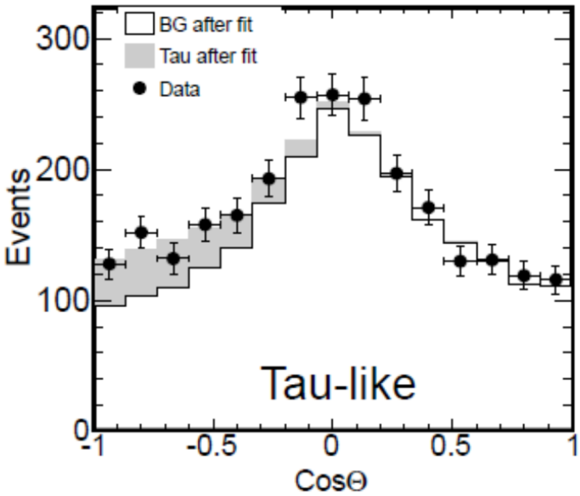


Figure 4 – Zenith angle distributions for the τ -like events selected from the data observed in Super-Kamiokande[28]. Circles with error bars show the data. Solid histograms show the Monte Carlo prediction with $\nu_\mu \to \nu_\tau$ oscillations but without the charged current ν_τ interactions. The gray histograms show the fit result including the ν_τ interactions.

studies of atmospheric neutrinos, Super-Kamiokande discovered neutrino oscillations, establishing that neutrinos have mass. After the discovery, atmospheric neutrinos have been used to study oscillations, and contributed substantially to establish the $\nu_\mu \to \nu_\tau$ oscillations generated by neutrino masses and mixing angles.

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