

Professor Koshiba and atmospheric neutrinos

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When Professor Masatoshi Koshiba proposed the Kamiokande experiment, the main motivation was the search for proton decays. However, it should be remembered that other physics topics were also considered. One of them was neutrino oscillation studies with atmospheric neutrinos. In this article, the atmospheric neutrino studies in Kamiokande and Super-Kamiokande are reviewed.
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1. Introduction

The idea of Grand Unified Theories (GUTs) of strong, weak, and electromagnetic interactions [1, 2] emerged in the 1970s. Subsequent analyses on the (non-SUSY) SU(5) GUT found that the nucleon lifetime should be about 10^{30} years with an uncertainty of about two orders of magnitude; see Ref. [3] for a review. For these proton lifetimes, it should be possible to observe proton decays with a 1000-ton class large-mass detector.

Professor Koshiba (simply referred to as Koshiba in most of this article) was asked to give a talk on a possible proton decay experiment at a workshop on “The Unified Theory and the Baryon Number in the Universe” held at KEK in 1979. He came up with the initial concept of Kamiokande [4], which was a water Cherenkov detector. In water, a highly relativistic charged particle with a velocity very close to the light velocity emits Cherenkov light in the direction of about 42 degrees from the direction of the particle motion. The Cherenkov light can be detected by photomultiplier tubes (PMTs).

Even before the start of the experiment, Koshiba had been thinking that the Kamiokande experiment should produce significant scientific results, even if proton decays were not observed. In fact, in the grant proposal for the Grant-in-Aid for Scientific Research of JSPS (Kakenhi) written in September 1981 [5], Koshiba and his team mentioned, in addition to the proton decay searches, studies of neutrino oscillations [6, 7], searches for heavy particles such as magnetic monopoles, and studies of cosmic rays underground including the detection of supernova neutrinos. The main part discussing the studies of neutrino oscillations in the proposal, translated from Japanese to English, was:

“ Δm^2 that can be studied with atmospheric neutrinos is approximately $10^{-3} eV^2$, which is close to the anticipated Δm^2 by SO(10) and the other GUTs. The experimental approach to study $\Delta m^2 \sim 10^{-3} eV^2$ should be as follows.

The event rate of neutrino interactions in a 1000 ton detector should be about 200/year. These include both ν_μ and ν_e interactions. In the absence of neutrino oscillation, the ratio of muon events to electron events should be

$$\frac{\nu + N \rightarrow e + X}{\nu + N \rightarrow \mu + X} = 0.40.$$

For neutrino oscillations whose oscillation length is much shorter than the radius of the Earth, and for neutrinos coming from underground, the ratio should be

$$\frac{\nu + N \rightarrow e + X}{\nu + N \rightarrow \mu + X} = 1.00 \text{ (for maximum mixing),}$$

where we assume that there are ν_μ and ν_e only, and the energy range is between 0.3 and 10 GeV.

For charged current interactions, ν_μ and ν_e events can be distinguished, and their energies and arrival directions can be measured. Specifically, the above ratio should be measured as a function of the neutrino flight length. It should be noted that, for neutrino flight lengths longer than 4000 km, the matter effect should be considered because it reduces the oscillation amplitude¹ and changes the oscillation lengths.

If the neutrino oscillation length is shorter than the diameter of the Earth, that is, if the neutrino mass range is between 0.01 and 1 eV, then we should be able to study neutrino oscillations.

To observe neutrino oscillations, one has to measure the direction of the secondary particles to determine the direction of neutrinos, as well as to discriminate electron and muon events. One must count the number of downward- and upward-going ones for both electrons and muons. For further studies, one should measure the above ratio for each zenith angle. Therefore, it will take at least five years to get some interesting results.”

2. Early atmospheric neutrino observations

Observations of atmospheric neutrinos began in the mid-1960s. Two experiments that were carried out in extremely deep mines in India [8] and South Africa [9] successfully observed muons produced by the atmospheric ν_μ interactions. In these experiments, only the muons that were produced by the atmospheric neutrino interactions in the rock surrounding the detectors were measured. In a subsequent publication in 1978 from the experiment in South Africa [10], the authors measured the flux of the atmospheric ν_μ . The ratio of the predicted flux over the observed one was 1.6 ± 0.4 . The uncertainty mainly arose from the flux and cross section. Due to the large uncertainty, the authors concluded that there was fair agreement between the observed and expected neutrino-induced muon fluxes. However, it should be noted that the observed flux was lower than expected.

It was already recognized in the late 1970s and early 1980s that atmospheric neutrino data could give information on neutrino oscillations, because of the long flight distance of neutrinos. See, e.g., Ref. [11] and references therein, and also Refs. [12–14].

In the early 1980s, several proton decay experiments, including Kamiokande, started, with detector masses ranging from about 100 to 3000 tons. These experiments did not observe any convincing signal of proton decays. The results from these experiments in the early 1980s can be found in Ref. [15]. However, these experiments observed hundreds of atmospheric neutrino interactions. These were called fully contained neutrino events because the neutrino interactions occurred in the detector and all the visible secondary particles stopped in the detector. The proton decay signal and the atmospheric neutrino background can only be separated by studying the details of the secondary particles. Because of this, these experiments studied details of these neutrino interactions. The early studies suggested that various distributions of the observed contained events were consistent with the expectations from atmospheric neu-

¹It seems that this description does not agree with the present knowledge on the matter effect for neutrinos (for the normal mass ordering case) or for anti-neutrinos (for the inverted mass ordering case). In any case, nowadays, we understand that the matter effect is the key to determine the neutrino mass ordering. The fact that the importance of the matter effect was already mentioned should not be forgotten.

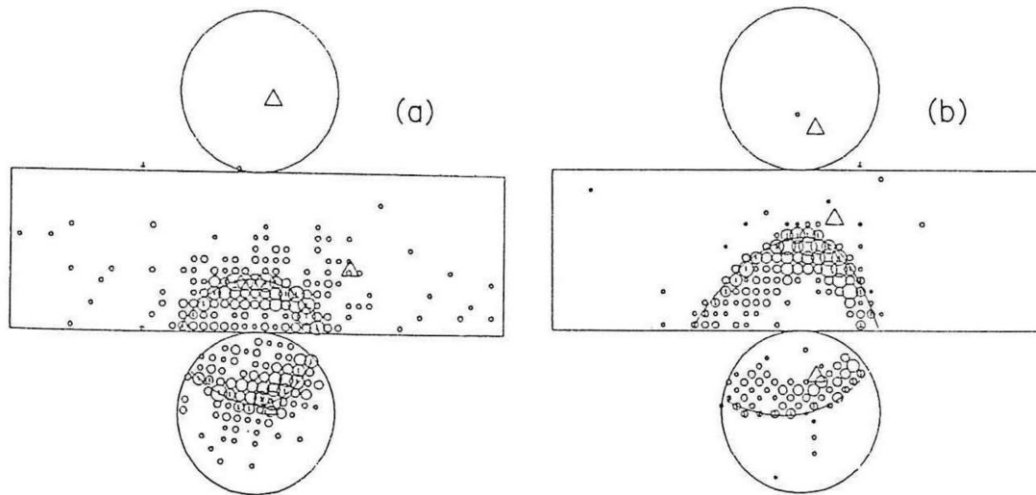


Fig. 1. Event pattern for (a) an e -like and (b) a μ -like event observed in Kamiokande. Each circle represents a PMT that detected Cherenkov photons; the area of the circle is proportional to the observed photoelectron number.

trino interactions [16, 17]. However, it should be noted that the IMB [16] and Kamiokande [17] experiments observed that the fraction of events with muon decay was smaller than expected.

3. Atmospheric neutrino studies in Kamiokande

Kamiokande had a fiducial mass of about 1000 tons, while the IMB experiment in the USA had a 3300-ton fiducial mass. To produce significant scientific results from Kamiokande as compared with those from IMB, Koshiba had the idea to develop 20-inch diameter photomultiplier tubes (PMTs) and use these PMTs in Kamiokande. Kamiokande had installed one of these large PMTs per 1 m^2 of the entire inner surface of the detector, while IMB had installed one 5-inch PMT per 1 m^2 . Consequently, as compared with IMB, Kamiokande had approximately 16 times higher photon detection efficiency. Koshiba thought that this high photon detection efficiency should be very important to observe various decay modes of protons, convincingly separating proton decay signals from the atmospheric neutrino events.

Koshiba thought that Kamiokande should be very efficient in distinguishing the Cherenkov rings generated by electrons and muons. He told his younger collaborators that the images of Cherenkov rings contain a lot of information that makes it possible to separate electron and muon rings efficiently, and that the software for distinguishing between the electron and muon rings should use all the available information in the ring image. The number of photoelectrons to be observed in Kamiokande for a $1 \text{ GeV}/c$ electron and muon was about 3000, which was indeed large enough for the efficient separation of the electron and muon Cherenkov rings.

The ring image of the Cherenkov radiation due initially to an electron (or a positron) is a summation of the ring images of many electrons and positrons in an electromagnetic shower and shows a fuzzy ring pattern. On the other hand, a muon propagates in water almost straight, slowly losing energy without producing an electromagnetic shower. Consequently, the ring image due to a muon shows a sharp ring edge. Figure 1 shows e -like and μ -like events observed in Kamiokande. Therefore, it should be possible to separate Cherenkov rings due to an electron (e -like or showering type) and a muon (μ -like or non-showering type).

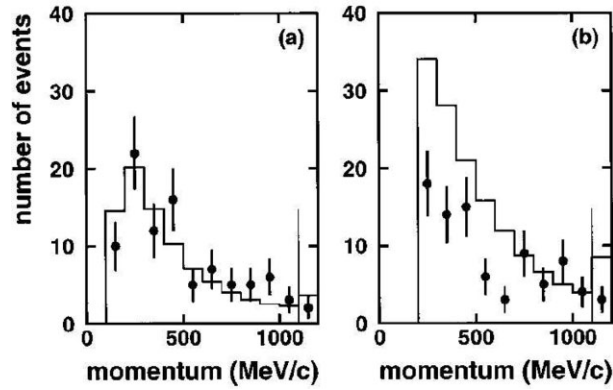


Fig. 2. Momentum distributions for (a) e -like and (b) μ -like events [18]. The histograms show the Monte Carlo predictions.

The Kamiokande experiment started in July 1983. In the summer and autumn of 1983, much time was spent examining the detector performance and developing analysis programs for events such as proton decays and atmospheric neutrinos. Several nucleon decay candidates were observed. However, the possibilities of the atmospheric neutrino interactions were not negligibly small.

In 1984, work began on a large-scale upgrade of Kamiokande to Kamiokande-II for the detection of solar neutrinos. The upgrade work continued for a few years. Even during this work, the search for proton decay continued. Furthermore, the upgrade work also motivated systematic improvements of the reconstruction programs for contained events in the GeV energy range, proton decays, and atmospheric neutrino interactions. The improvements included the particle identification (e -like and μ -like particle separation).

A dedicated program to separate the electron and muon Cherenkov rings was developed in late 1986. The particle identification program utilized the maximum likelihood method, implementing Koshiba's idea to use all the available information. For each PMT, the observed number of photoelectrons was compared with the expectations assuming either an electron or a muon for the reconstructed vertex position, particle direction, and the total number of photoelectrons. The Cherenkov rings were separated into " e -like" and " μ -like" ones. The estimated probability of the correct particle type identification was 98%.

In late 1986, immediately after the development of the new particle identification program, a hint of a deficit of the μ -like events relative to the Monte Carlo prediction of the atmospheric neutrino interactions was observed. One possibility recognized immediately was a deficit of the ν_μ flux due to some unknown physics such as neutrino oscillations, since more than 90% of the μ -like events were predicted to be due to ν_μ interactions. However, it was possible that some unrecognized problem with the detector or the data analysis was the cause of the deficit. Therefore, various studies on the deficit of the μ -like events started immediately after the initial recognition of the deficit. It took about a year to complete the studies. These studies, however, did not find any serious problem.

In 1988, Kamiokande reported a result on the studies of the atmospheric neutrino events [18]. Figure 2 shows the momentum distributions for the e -like and μ -like events observed in Kamiokande. When the paper was prepared, Koshiba had already retired from the University of Tokyo (in March 1987) and was in Europe. Therefore, Koshiba sent us his comments on

the draft paper. Looking at the draft paper and some other data on the atmospheric neutrinos from Kamiokande, Koshiba commented that the data seemed to indicate ν_μ to ν_τ oscillations. In addition, as an experimental physicist, he suggested that his younger colleagues make sure that the Monte Carlo simulation did not have any serious mistakes. People working on the paper were encouraged by his comments.

Subsequently, Kamiokande published the second paper in 1992 on this topic with the increased data statistics, including the results on the neutrino oscillation analysis [19]. Before the second publication, the IMB experiment published a paper on the atmospheric ν_μ deficit in 1991 [20]. This paper was important, because, in 1989 and 1990, the other underground experiments [21, 22] reported that there were no atmospheric ν_μ deficits in their data. The results from IMB were the first that were consistent with those from Kamiokande. Soon after knowing the results from the IMB experiment, Koshiba proposed to publish the second paper from Kamiokande on the atmospheric neutrinos. This proposal was critically important. The author believes that, without his suggestion, the second atmospheric neutrino paper might not have been published, at least in a timely manner. The author recalls visiting Koshiba's house several times to discuss the content of the paper.

In the paper, Kamiokande discussed that $[(\mu\text{-like}/e\text{-like})_{\text{data}}/(\mu\text{-like}/e\text{-like})_{\text{MC}}]$ was essentially independent of the choice of the flux models, and therefore that the systematic uncertainty of this double ratio is relatively small. Both $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillations were tested and concluded to be allowed, because the small $\mu\text{-like}/e\text{-like}$ ratio can occur for both oscillation channels, independent of the absolute neutrino flux, which had an uncertainty of 20% or larger. At that time, it was already recognized that the solar neutrino problem could be due to $\nu_e \rightarrow \nu_x$, where ν_x was ν_μ and/or ν_τ (the MSW mechanism [23, 24]). Therefore, it was concluded that only $\nu_\mu \rightarrow \nu_\tau$ oscillations might account for the atmospheric neutrino data based on the combined information of the atmospheric and solar neutrino data.

The observation of the deficit of the μ -like events suggested neutrino oscillation as a possibility. However, at that stage, neutrino oscillation was only one of the possibilities. We thought that other evidence that strengthened the earlier results and gave critical information on identifying the underlying physics was required. If the observed ν_μ deficit was due to neutrino oscillations, the deficit should depend on the neutrino flight length, and therefore depend on the zenith angle. However, in the sub-GeV energy range discussed in the 1988 and 1992 papers, the correlation between the neutrino direction and the muon direction is rather poor. The zenith-angle dependence in the neutrino direction is largely washed out in the muon zenith-angle distribution in this energy range. The angular correlation between neutrinos and charged leptons improves significantly as the neutrino energy increases, and the zenith-angle distribution for muons should represent the neutrino zenith-angle distribution well for multi-GeV neutrino events. If the neutrino oscillation length is about 1000 km for the neutrinos considered here, one expects that the ν_μ deficit should be observed in the upward-going directions, since the neutrino flight length is much shorter than 1000 km and much longer than 1000 km for downward-going and upward-going neutrinos, respectively. This was thought to be a critical measurement, since only neutrino oscillations can generate such up-down asymmetry. In 1994, Kamiokande reported the multi-GeV atmospheric neutrino data [25]. The μ -like data showed a deficit of events in the upward-going direction, while the downward-going μ -like events did not show such deficit. Furthermore, the corresponding distribution for e -like events did not show any evidence for a deficit of upward-going events. Figure 3 shows the observed zenith-angle

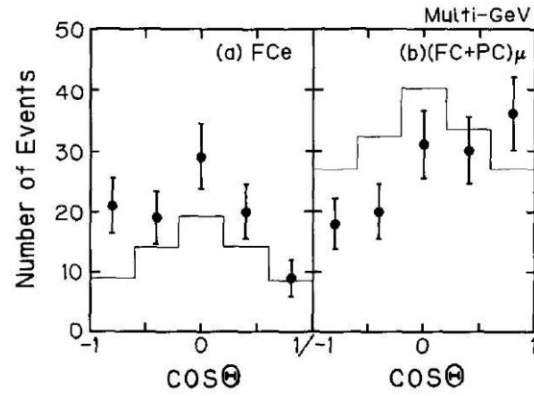


Fig. 3. Zenith-angle distributions for multi-GeV (a) e -like and (b) μ -like events in Kamiokande [25]. In panel (b), fully contained, multi-GeV, single-ring μ -like events and partially contained μ -like events are combined.

distributions for multi-GeV neutrino events in Kamiokande. The statistical significance of the observed up–down asymmetry in the μ -like events was 2.8 standard deviations. This 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 was not strong enough to be conclusive. Experimental data with much higher statistics were awaited.

4. Discovery of neutrino oscillations in Super-Kamiokande

As a future major experiment at Kamioka, a large water Cherenkov detector with a fiducial mass of 22 000 tons was proposed by Koshiba and presented for the first time at the “Workshop on Grand Unified Theories and Cosmology”, which was held at KEK in December 1983 [26]. In the autumn of 1983, when Koshiba proposed the ^8B solar neutrino detection with Kamiokande, he thought that the event rate would be too low for Kamiokande to carry out detailed studies of solar neutrinos. Koshiba thought that a detector with a much higher event rate, and therefore a much larger detector, than Kamiokande should be required to really open a new field of neutrino astrophysics. The name of Super-Kamiokande was given to this detector in the following year (1984) [15]. The Super-Kamiokande project was approved by the Japanese government in 1991. The detector construction took five years. The Super-Kamiokande experiment started on 1 April 1996.

By the spring of 1998, Super-Kamiokande had analyzed 535 days of atmospheric neutrino data. The total number of atmospheric neutrino events was 5400, which was about four times higher than that in Kamiokande.

At the 18th International Conference on Neutrino Physics and Astrophysics (Neutrino’98), Super-Kamiokande made an announcement of the evidence for atmospheric neutrino oscillations [27,28]. The evidence for neutrino oscillations was obtained by several different measurements. Among them, the strongest evidence for oscillations came from the zenith-angle distributions. The zenith-angle distributions shown at Neutrino’98 are shown in Fig. 4. The left panel of Fig. 4 shows the zenith-angle distribution for multi-GeV (namely, where the visible energy of an event must be larger than 1.33 GeV) e -like events, while the right panel shows that for fully contained multi-GeV μ -like plus partially contained neutrino events. It was clear that the deficit of the upward-going events was observed in the μ -like data sample. The statistical

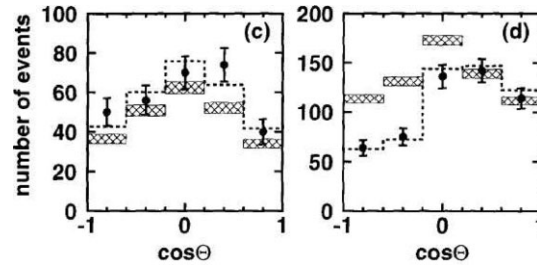


Fig. 4. The zenith-angle distributions shown at Neutrino'98 [27]. The left panel shows the zenith-angle distribution for multi-GeV (namely, where the visible energy of an event must be larger than 1.33 GeV) e -like events, while the right panel shows that for fully contained multi-GeV μ -like plus partially contained neutrino events.

significance was more than six standard deviations, implying that the deficit could not be due to a statistical fluctuation. On the other hand, the zenith-angle distribution for e -like events did not show any statistically significant up–down asymmetry. The atmospheric neutrino problem that Koshihba was very interested in was concluded to be due to neutrino oscillations.

5. Conclusion

The atmospheric ν_μ deficit was discovered and studied in Kamiokande. This problem was concluded to be due to $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillations by detailed studies of atmospheric neutrino events in Super-Kamiokande. Since then, Super-Kamiokande has continued studying atmospheric neutrinos and neutrino oscillations. Professor Koshihba was very much interested in the atmospheric ν_μ deficit and played very important roles in these studies. These accomplishments would not have been possible without his insight.

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