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Observation of atmospheric neutrinos in Super-Kamiokande and the neutrino oscillation parameters

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Abstract

The atmospheric neutrino data of a 45kton·yr (F.C.) and a 42kton·yr (P.C.) exposure of the Super-Kamiokande detector exhibit a zenith angle dependent deficit of muon neutrinos. The data are in good agreement with a two-flavor $\nu_\mu - \nu_\tau$ oscillation hypothesis, while uncertainties in the flux prediction, neutrino interaction cross sections, and experimental biases are ruled out as the explanation of the observation.

1 Atmospheric neutrinos

Atmospheric neutrinos detected by large underground detectors provide a good probe to test the neutrino properties. These neutrinos are produced by the decay chain of mesons, which are generated by the collisions of the primary protons and nucleus at the top of the atmosphere. Neutrinos travel downward for the distance of the depth of atmosphere ($\sim 10km$) and upward for the diameter of the earth ($\sim 10^4 km$). The observed zenith angle is directly related to the neutrino path length. Therefore they can be utilized to test the neutrino oscillation hypothesis from $\Delta m^2 = 10^0$ to 10^{-4}eV^2. Kamiokande (Hirata et al.1988) and IMB (Casper et al. 1991) reported the deficit of the μ-like data. Recently, Super-Kamiokande (Fukuda et al. 1998) and Soudan-II (Allison et al. 1997) confirmed this anomaly.

The Super-Kamiokande is a 50 kton Water Cherenkov detector at the Kamioka observatory in Japan. The detector consists of a cylindrical tank to store 50 kton water, viewed by 11,146 of 50cm diameter PMTs distributed at wall of the inner detector and 1885 of 20cm diameter PMTs in the outer detector. The fiducial volume of the atmospheric neutrino and the proton-decay analysis is defined as 22.5 kton. The Super-Kamiokande experiment started its operation in April, 1996. Using a 45kton·yr (Fully contained event, F.C.) and a 42kton·yr (Partially contained event, P.C.) exposure of the Super-Kamiokande detector, total of 6085 F.C. events and 374 P.C. events were selected in the fiducial volume. Each single ring F.C. event was identified as e-like or μ-like according to its Cherenkov ring pattern (showering or non-showering) with the misidentification probability of less than 1%, and used for the atmospheric neutrino analysis. Table 1 shows the summary of each data sample. The absolute values predicted by Monte Carlo (M.C.) has large uncertainty, coming from the large uncertainty in the flux calculation and neutrino interaction cross sections. Therefore, the double ratio, $R = (\mu/e)_{data}/(\mu/e)_{M.C.}$ is used to cancel the absolute uncertainty. Super-Kamiokande obtained the R for Sub-GeV ($E_{vis} < 1.3GeV$) as

$$\frac{(\mu/e)_{data}}{(\mu/e)_{M.C.}} = 0.668^{+0.024}_{-0.023}(stat.) \pm 0.052(syst.),$$

and for Multi-GeV ($E_{vis} > 1.3GeV$) + P.C. as

$$\frac{(\mu/e)_{data}}{(\mu/e)_{M.C.}} = 0.663^{+0.044}_{-0.041}(stat.) \pm 0.079(syst.).$$

Sub-GeV	Data	M.C.
1 ring	3224	3765.3
e-like	1607	1502.7
μ-like	1617	2262.6
Multi-GeV		
F.C. 1 ring	687	771.0
e-like	386	351.9
μ-like	301	419.1
P.C.	374	508.9

Table 1: Summary of each data sample. Expected numbers are based on 20yr M.C. in Honda's flux calculation.

Super-Kamiokande confirmed the small Rs value for Sub-GeV and Multi-GeV data samples with much more statistics than the KAMIOKANDE and other experiments.

The absolute normalization of the expectation has a large uncertainty. However, the shape of the zenith angle distribution has much smaller uncertainty for high energy neutrinos. Especially, most of the systematic uncertainties and biases are canceled if the up/down asymmetry is considered. Figure 1 shows the zenith angle distributions of Sub-GeV e-like (a), μ-like (b), Multi-GeV e-like (c) and μ-like+P.C. (d) events obtained by Super-Kamiokande. These distributions clearly show that the upward-going μ-like events are smaller than the expectation while the downward-going μ-like events are consistent with the expectation. The distributions of e-like events agree with the expectation well. The up/down asymmetry defined as $A = (\mathrm{up} - \mathrm{down})/(\mathrm{up} + \mathrm{down})$ for the Multi-GeV+P.C. data is $A = -0.31 \pm 0.04(stat.) \pm 0.01(syst.)$. No systematic biases can explain this large up/down asymmetry. These distributions strongly suggest that some of muon neutrinos have disappeared while traveling a distance of $10^3 \sim 10^4$km.

2 Neutrino oscillation analysis

Super-Kamiokande observed the small R in the Sub-GeV and Multi-GeV+P.C. data samples, and a large up/down asymmetry in the Multi-GeV+P.C. sample. And, observed zenith angle distributions strongly suggest a $\nu_\mu - \nu_\tau$ oscillation, because zenith angle distributions of e-like data are consistent with the expectation. Thus, a $\nu_\mu - \nu_\tau$ oscillation analysis were performed by using the following χ^2 (Fukuda et al. 1998);

$$\chi^2(\sin^2 2\theta, \Delta m^2) = \sum \frac{(N_{data} - N_{fit})^2}{\sigma^2} + \sum \frac{\alpha_i^2}{\sigma_{\alpha_i}^2}, \tag{1}$$

where N_{data} is the observed number of events in each zenith angle and momentum bin, N_{fit} is the fitted expected number of events, calculated by using parameters, α_i, for each oscillation parameters ($\sin^2 2\theta$, Δm^2), and σ_{α_i} is the systematic uncertainty. The χ^2 value was minimized by varying parameters α_i within errors for each oscillation parameter. The minimum χ^2 value was obtained at ($\sin^2 2\theta$, Δm^2) = (1.0, 3.5×10^{-3}eV^2) with 62.1/67dof in the physical region. The dashed histograms in Fig.1 show the fitted expected zenith angle distribution at the χ^2_{min} point, and it reproduces the data well. Figure 2 shows the 90% confidence level allowed region for $\sin^2 2\theta$ and Δm^2 obtained by this oscillation analysis. If we assume no neutrino oscillation, χ^2 value is 175/69 dof and the probability is 5×10^{-9}. The no oscillation hypothesis is completely ruled out. If we assume a $\nu_e - \nu_\mu$ oscillation hypothesis, χ^2_{min} value is 110/67 dof (probability=8×10^{-4}. The $\nu_e - \nu_\mu$ oscillation hypothesis is not

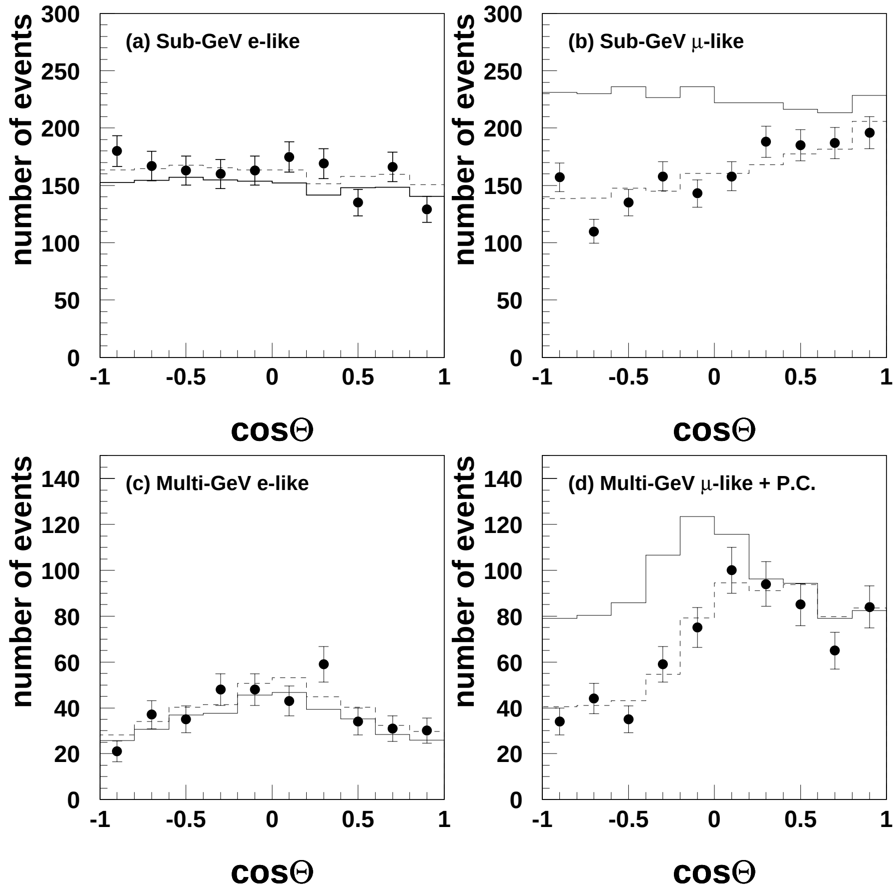

Figure 1: Zenith angle distribution observed by Super-Kamiokande. (a) Sub-GeV e-like events of data (closed circle), the expectation without oscillation (solid histogram) and with oscillation with $(\sin^2 2\theta, \Delta m^2) = (1.0, 3.5 \times 10^{-3})$ (dashed histogram). (b) same as (a) for Sub-GeV μ-like events. (c) same as (a) for Multi-GeV e-like events. (d) same as (a) for Multi-GeV μ-like + P.C. events.

favored by this analysis.

3 Conclusion

The total of 45kton·yr (F.C.) and 42kton·yr (P.C.) exposure of the atmospheric neutrino data in Super-Kamiokande were analyzed. These data confirmed the small Rs value for Sub-GeV and Multi-GeV samples. The μ-like data exhibit a zenith angle dependent deficit. The number of upward-going μ-like events were about half of that of downward-going events for the Multi-GeV data. No systematic uncertainties and biases can explain this anomaly. The data are in good agreement with two-flavor $\nu_\mu - \nu_\tau$ oscillations with $\sin^2 2\theta > 0.82$ and $1 \times 10^{-3} < \Delta m^2 < 8 \times 10^{-3}\mathrm{eV}^2$ at 90% confidence level.

References

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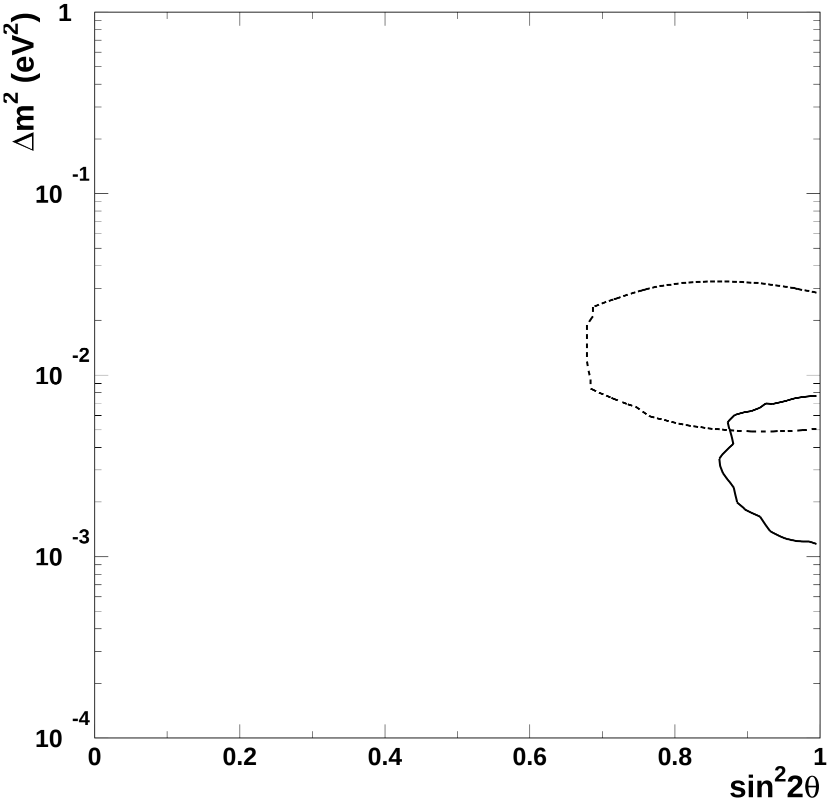

Figure 2: The 90% confidence level allowed region in $\sin^2 2\theta$-Δm^2 plane for $\nu_\mu - \nu_\tau$ two-flavor neutrino oscillation hypothesis (solid line). The dashed line shows that obtained by the KAMIOKANDE.

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