EXPERIMENTAL STUDY OF THE ATMOSPHERIC NEUTRINO FLUX

KAMIOKANDE II COLLABORATION

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Abstract

A total of 277 fully-contained events have been observed in the KAMIOKANDE detector, during an effective exposure time of 2.87 kton·yr. The number of electron-like single prong events is in good agreement with the predictions of a Monte Carlo calculation based on atmospheric neutrino interactions in the detector. On the other hand, the number of muon-like single prong events is 59±7% (statistical error) of the predicted number of the Monte Carlo calculation. It is very difficult to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes calculated so far.

Introduction

Atmospheric neutrinos are decay product of secondary mesons produced by primary cosmic rays striking the atmosphere. The KAMIOKANDE detector has observed 277 fully-contained events induced by atmospheric neutrinos, during an effective exposure time of 2.87kton·yr from July 1983 to November 1987. The KAMIOKANDE experiment is divided into 2 phases; KAM I and KAM II. The details on the detector[1),2)] and analysis[3)] will be found elsewhere.

Analysis

Out of the 277 fully-contained events, 190 events have single prong and 87 events have multi prongs. Single prong events are further classified as electron-like($e^{\pm}$,γ) or muon-like($\mu^{\pm}$,$\pi^{\pm}$) events with an average particle misidentification probability of 2%. The $\pi^{\pm}$ contamination to the muon-like events is estimated to be 5.4$\pm$0.8% by our Monte Carlo simulation[4)]. Gamma rays from π^0 production contribute to electron-like events by 6.7$\pm$1.2%. These contributions are correctly taken into account to evaluate the expected event rates. Table 1 summarizes the data together with the Monte Carlo predictions(21.8kton·yr equivalent). In this analysis, multi-prong events are omitted from further discussion, as the lepton identification in them is rather difficult and their event rate is more ambiguous than that of single prong events by $\sim \pm 20\%$ due to nuclear effects in ^{16}O nucleus. The energy interval for single prong events in this analysis is set at 30$\sim$1330 MeV/c for electrons and at 205$\sim$1500 MeV/c for muons. The ratio of the observed number to the expected number by the Monte Carlo simulation (DATA/M.C.) is 93/88.5=1.05$\pm$0.11 for electron-like single prong events with momentum p_e>100 MeV/c (electron-like events with $p_e \leq$100MeV/c are mostly of ν_μ origin as is explained[5)] in the footnote of Table 1), but is 85/144.0=0.59$\pm$0.07 for muon-like events. The data is consistent with the Monte Carlo evaluation for electron-like single prong events, but a big(40%) deficit is observed for muon-like single prong events. Another observation for the smaller number of muon-like events comes from the number of events followed by μ-decay electrons. The ratio DATA/M.C. is 60/110.3=0.54$\pm$0.07 for the total single prong events. On the other hand, the fraction of of events accompanied by μ-decay electrons is consistent with the Monte Carlo prediction for both electron-like and muon-like events, as is shown in Table 1. It should be noted that the detection efficiency of μ-decay electrons is estimated from cosmic-ray stopping muons, and therefore reliable. The μ-e decay detection efficiencies are shown in the footnote of Table 1. Fig.-1 shows the momentum distributions for the electron-like and muon-like events with the Monte Carlo prediction. Fig.-2 shows the cosΘ distributions for the electron-like and muon-like events with the Monte Carlo prediction, where Θ is the zenith angle. One also finds that the distributions for electron-like events are in good agreement with the expectation. On the other hand, the distributions for muon-like events deviate from the expectation.

Discussion

We have investigated a number of possible sources of errors or uncertainties in our data analysis and event assignments. Among them are; (i) the electron-like events are not of neutrino but of gamma ray or neutron origin from sources outside of the detector, while at the same time the detection efficiency and/or the atmospheric neutrino fluxes are much lower than estimated; however, the vertex positions for both the electron-like and muon-like events are distributed uniformly in the detector, and show no accumulation near the edges of the fiducial volume; (ii) possible systematic effects which might produce the deficit of muon-like events such as trigger bias, event reduction, event scanning, event fitting, absolute energy calibration uncertainty ($\pm$5%)[1] , and the Monte Carlo itself. We have as yet found no effect that reproduces the deficit of muon-like events relative to the total of electron-like events.

Another possibility of ambiguities in the analysis is that the calculation of the atmospheric neutrino fluxes may not be correct. The absolute values of those fluxes are expected to be accurate to about $\pm$20%[6]. This might account for part or all of the ~20% discrepancy between the total number of observed and Monte Carlo predicted events in Table 1. However, it is expected that the error in the ν_e/ν_μ ratio should be much smaller than 20%. The calculated ν_e/ν_μ ratio is 0.44[6] averaged between E_ν=0.2GeV and 2 GeV. The main uncertainty in the ν_e/ν_μ ratio comes from the uncertainty of the

K/π production ratio in the atmosphere($\pm 3 \sim 5\%$). The contributions of π, K and μ to the ν_μ and ν_e fluxes are given in Tables 1 and 2 of Ref.-7). From those tables we can estimate the change in the ν_e/ν_μ ratio as a function of the K/π ratio. We find that the quoted uncertainty in the K/π ratio by appreciably less than 5% for $E_\nu \sim$1GeV. Comparison[6),7),8)] of various calculations so far available on the atmospheric neutrino fluxes show that each calculation agrees within ~20% for the total fluxes and within 5% for the ν_e/ν_μ ratio down to 300MeV.

The error in the absolute neutrino cross sections at low energies is about ±10%[9)]. This might also account for part of the discrepancy in the total number of events between data and the Monte Carlo prediction. However, uncertainties in the cross sections are too small to account for the (electron-like events)/(muon-like events) discrepancy in Table 1. The probability that the ratio of (electron-like events with p_e>100MeV/c)/(muon-like events) in the data relative to the corresponding ratio in the Monte Carlo could be due to a statistical fluctuation is 10^{-4}. This number is obtained by a Monte Carlo method as a probability of observing 93 or more electron-like events from 178 total events assuming the (electron-like events)/(muon-like events) ratio(0.61) easily calculated from Table 1.

In summary, we are unable to explain the data as the result of systematic detector effects or uncertainties in the available calculations of the atmospheric neutrino fluxes, still less as a statistical fluctuation. Some unexpected physics might be needed to explain the result. Neutrino oscillations might be one of the possibilities which could account for the data. The final results of other experiments should be compared with ours.

Acknowledgement

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9) Low energy neutrino data from experiments at ANL, BNL and CERN are used. For the individual references see Ref.-4)

Table 1. Comparison between the data and the expected neutrino events. The detector exposure is 2.87 kton·yr while the Monte Carlo event generation is 21.8 kton·yr exposure equivalent.

	DATA		NEUTRINO M.C.	
	total	μ-decay	total	μ-decay 1)
SINGLE PRONG	190(178) 2)	60	250.3(232.5)	110.3
muon-like	85	52	144.0	103.8
electron-like	105(93)	8	106.2(88.5)	6.5 3)
MULTI PRONG	87	34	86.2	37.1
TOTAL NUMBER	277(265)	94	336.5(318.7)	147.4

1) The detection efficiency of μ-decay electrons for μ^+ is 76% in KAM-I and 89% in KAM-II and for μ^- is 59% in KAM-I and 69% in KAM-II. These numbers are estimated from cosmic-ray stopping muons observed in the detector.
2) Numbers in the parentheses are for p_e>100MeV/c. Most of the electron-like events below 100MeV/c are due to decay electrons of neutrino induced muons which have momentum below Čerenkov threshold and are invisible.
3) Electron-like events with μ-decay electrons are mainly due to charged current single-pion(π^+) production by ν_e with pions invisible(mainly because of their low momenta). The fraction of electron-like events due to charged current single-pion production by ν_e is estimated to be 18% of the total electron-like events.

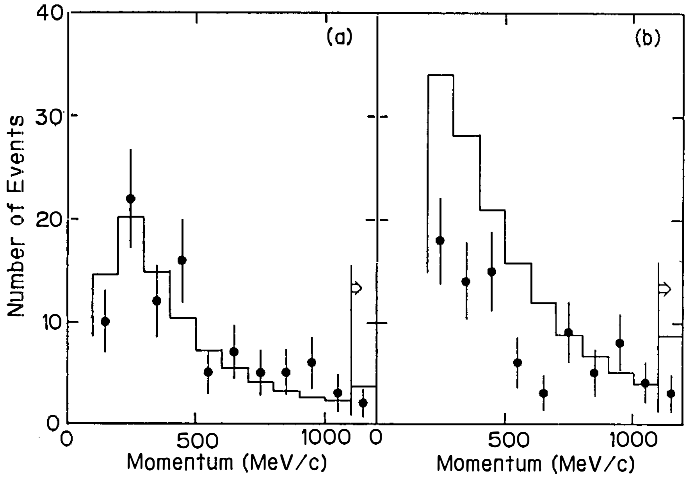

Fig.-1. Momentum distributions for; (a)electron-like events and (b)muon-like events. The last bin sums up all the events with their momenta larger than 1100MeV/c. The histograms show the distributions expected from atmospheric neutrino interactions.

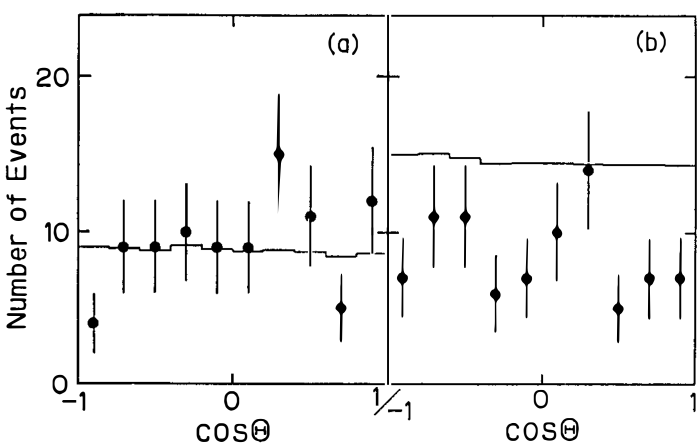

Fig.-2. Zenith angle distributions for; (a)electron-like events and (b)muon-like events. cosΘ=1 corresponds to downward-going events. The histograms show the distributions expected from atmospheric neutrino interactions.