INSTITUTE FOR NUCLEAR STUDY
UNIVERSITY OF TOKYO
Tanashi, Tokyo 188
Japan

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M. HONDA and K. KASAHARA

Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188, Japan

K. HIDAKA

Department of Physics, Tokyo Gakugei University, Koganei, Tokyo 184, Japan

S. MIDORIKAWA

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Abstract

A detailed Monte Carlo simulation of neutrino fluxes of atmospheric origin is made taking into account the muon polarization effect on neutrinos from muon decay. We calculate the fluxes with energies above 3 MeV for future experiments. There still remains a significant discrepancy between the calculated $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu)$ ratio and that observed by the Kamiokande group. However, the ratio evaluated at the Frejus site shows a good agreement with the data.

The anomalously large $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu)$ ratio of atmospheric neutrinos recently observed at Kamiokande [1] is very interesting because it may shed new light on the properties of neutrinos. Attempts have been made to explain this anomaly in terms of neutrino oscillations [2] . However these analyses are based on neutrino fluxes calculated neglecting the muon polarization effect [3] . As is well known, muons from pion decay are completely polarized in the pion rest frame. The electron and muon neutrinos from muon decay tend to be emitted in the forward and backward directions with respect to the muon momentum, respectively. This effect decreases the energy of muon neutrinos and increases that of electron neutrinos compared with the unpolarized case. This in turn increases the ratio $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu)$ at a fixed neutrino energy [4] , since the fluxes are decreasing functions of energy. It is therefore necessary to make a quantitative estimate of the muon polarization effect [5] [6] .

In this letter we present a detailed Monte Carlo calculation of atmospheric neutrino fluxes at the Kamioka site. We have also calculated the fluxes with time variation at Baksan, Frejus, Gran Sasso, IMB, KGF, and Sudbury by taking into account the solar modulation. We have carried out the calculation of neutrino fluxes with energies above 3 MeV for future experiments [7] .

The primary cosmic ray particles arrive in the vicinity of the earth almost isotropically. In our calculation we take protons, helium nuclei, and CNO's as primary particles [8] , neglecting the other heavy primaries. The energy spectra of the primary particles are affected by two factors. One is solar activity and the other is the geomagnetic cutoff. The solar modulation is treated according to the prescription by Nagashima et al. [9] . The geomagnetic field is described by a series of Legendre functions up to the 5th order. A table of geomagnetic cutoff energy is made for each location of a detector as a function of incident cosmic ray direction by tracing the orbits of anti-protons which are ejected in given directions. As energy increases, the antiproton becomes able to escape from the geomagnetic field at a certain energy. We then fix the cut off energy at this value.

The atmospheric model used is the US standard atmosphere [10] the composition of which is taken to be 78% nitrogen, 21% oxygen and 1% argon in volume percentage.

In calculating atmospheric neutrino fluxes, we use a Monte Carlo code named COSMOS [11] which was originally developed by one of the present authors and others for the simulation of cosmic ray propagation in the atmosphere. For the interaction of hadrons with air-nuclei targets, we employ subroutine packages contained in the CPC program library. At total energy less than 5GeV/nucleon, we use NUCRIN [12] . At energy above 5GeV/nucleon we employ the LUND Monte Carlo program, FRITIOF version 1.6 [13] and JETSET version 6.3 [14] . For the interaction of nuclei with air nuclei targets, we sample nuclei which are to be the projectile fragments and interacting nucleons responsible for multiple production as described in ref.11. (As far as neutrino fluxes are concerned, this gives almost the same result as the superposition model.) The interacting nucleons are treated by the NUCRIN or LUND program. We modify FRITIOF so that it can accept K^0 and $\bar{K}^0$ as projectile particles. However, almost all mesons decay before collisions at our concerned energies. The inelastic nuclear interactions are considered above the kinetic energy of 200MeV. All non-rare

decay modes of pions and kaons are included in our calculation. Pions and kaons produce polarized muons, which propagate, lose their energies, and eventually decay. These effects are also included in our program.

We show in Fig. 1 our result of the differential energy spectra of the atmospheric neutrinos at the Kamioka site, the salient feature of which is a peak at $E_\nu \simeq 35$ MeV and a slight concavity at $E_\nu \simeq 50$ MeV, especially for electron neutrinos. This is a reflection of kinematics. Very low energy($E_{kin} \lesssim 100$ MeV) muons are copiously produced, and they tend to decay after stopping due to ionization loss. The mean energy of the neutrino from decay of a stopped muon is about $m_\mu/3$ and the maximum energy of the neutrino is $m_\mu/2$. The energy of the neutrino from decay of a pion at rest is 30 MeV. We also plot the result obtained by Barr et al. [15] including the muon polarization effect for comparison, and find that at $E_\nu < 0.5$ GeV our fluxes are systematically higher than theirs; the discrepancy grows as energy decreases. Our results contrast with those of Bugaev et al. [16] , which are systematically smaller than those of Barr et al. at $E_\nu < 1 \sim 2$ GeV.

What we are most concerned with is the muon polarization effect on flavor ratio $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu)$. We show in Fig. 2 the ratio with and without the polarization effect. The muon polarization effect increases the ν_e and $\bar{\nu}_e$ fluxes at $E_\nu \gtrsim m_\mu/3$ and decreases at $E_\nu \lesssim m_\mu/3$. The effect is reversed and is very small for ν_μ and $\bar{\nu}_\mu$ fluxes. The spectra of neutrinos in the muon rest frame are not affected by the muon polarization effect. This leads to a reverse of the effect on $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu)$ at energy $E_\nu \simeq m_\mu/3$, the mean energy of a neutrino from the decay of a stopped muon, since the total number of neutrinos is almost independent of the muon polarization effect. We also show the result of Barr et al. in Fig.2.

The major source of neutrino is pions. Thus the ratio $\bar{\nu}_e/\nu_e$ which is shown in Fig. 3 reflects the ratio $\mu^-/\mu^+ \sim \pi^-/\pi^+$. We find $\bar{\nu}_e/\nu_e \simeq 0.9$ for $E_\nu \lesssim 50$ MeV and $\bar{\nu}_e/\nu_e \simeq 0.8$ for $E_\nu \gtrsim 50$ MeV. It has a peak at $E_\nu \sim 30$ MeV. The larger ratio at lower energies is due to the following fact. As primary cosmic rays are almost all protons, whose flux has a peak at $E_{kin} \sim 1$GeV, the main processes of pion production around this energy are

$$p + A \to \pi^+ + n + \cdots$$
$$\downarrow$$
$$n + A \to \pi^- + p + \cdots .$$

Thus μ^+ are more energetic than μ^-, resulting in the portion of $\bar{\nu}_e$ from the decay of almost stopped μ^- being larger than that of ν_e from the decay of almost stopped μ^+. Since $\pi^+ \to \nu_\mu + \mu^+$ and $\mu^+ \to \bar{\nu}_\mu + \cdots$, one expects $\bar{\nu}_\mu/\nu_\mu = 1$ at low energy where all muons decay. The result in Fig.3 shows good agreement with the expectation. As the muon polarization effect is the same for neutrinos and antineutrinos, the ratios of $\bar{\nu}/\nu$ of the same flavor is little affected by the effect.

Now we compare our result with the recent Kamiokande data [17] . As in the previous paper [18] , we define

$$< \epsilon_\alpha \sigma_\alpha F_\beta > = \sum_{\nu,\bar{\nu}} \int \epsilon_\alpha(E_\alpha)\sigma_\alpha(E_\nu, E_\alpha)F_\beta(E_\nu, \theta_\nu)dE_\alpha dE_\nu d\theta_\nu,$$

where $\epsilon_\alpha(E_\alpha)$ is the detection efficiency for α-type charged lepton with energy E_α, σ_α is the differential cross section of ν_α, $F_\beta(E_\nu, \theta_\nu)$ is the incident ν_β flux

with energy E_ν and zenith angle θ_ν. Then, it is more convenient to use, instead of the number N_μ and N_e of the observed muon and electron events, the ratio $U_\mu = N_\mu/\kappa < \epsilon_\mu\sigma_\mu F_\mu >$ and $U_e = N_e/\kappa < \epsilon_e\sigma_e F_\mu >$, where $\kappa = (number\ of\ nucleons) \times (time)$. From the Kamiokande data with $\kappa = 3.43$ *kton yr*, we obtain

$$U_e = 0.352 \pm 0.100, \quad U_\mu = 0.493 \pm 0.141 \ \text{and} \ \frac{U_e}{U_\mu} = 0.713 \pm 0.0980 \quad (1)$$

for momentum cutoff $p_e > 100$ MeV/c and $p_\mu > 205$ MeV/c. Here we take into account the detection efficiency of the detector [19] , the uncertainty in the caluculated neutrino fluxes of ±25% mainly due to primary cosmic fluxes and interaction models, and the experimental error in the neutrino cross sections of ±10%. For the neutral current effect, we follow the analysis of the Kamiokande [19], which estimates that the contribution of neutral currents to both electron and muon like events is about 3% for each type of event. On the other hand, the expected value of U_e/U_μ is 0.472, which deviates by 2.46σ from the data. For U_μ the deviation is 3.60σ. We find that the total observed number of events $N_e + N_\mu$ is only 41% of the expected value, which has large uncertainties as mentioned above. However, the ratio $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu)$ of neutrino fluxes and hence the ratio N_e/N_μ of Monte Carlo calculation are insensitive to these uncertainties and have an error of $\sim 5\%$ at most. We note that our expected number of events N_e and N_μ are larger than those with fluxes of Barr et al. [15] but that the predicted ratio N_e/N_μ *of ours is very close to that with use of their fluxes.*

We study the possibility of explaining this anomaly by neutrino oscillations. Recent measurements of the Z^0 width at LEP [20] show that the number of light neutrino flavors is three We therefore consider three neutrino oscillations. The allowed regions in the (U_e, U_μ) plane by neutrino oscillations are determined by the parameter f which is given by $f \simeq \frac{<\epsilon_\mu \sigma_\mu F_e>}{<\epsilon_\mu \sigma_\mu F_\mu>} \simeq \frac{<\epsilon_e \sigma_e F_e>}{<\epsilon_e \sigma_e F_\mu>}$. Using $f = 0.472$ obtained from our neutrino fluxes, we derive the region in two typical cases: Case I where three neutrino flavors have executed many oscillations before being detected and Case II where only one oscillation mode dominates neutrino oscillations [18]. The allowed regions are depicted in Fig. 4 . We show the region corresponding to eq.(1) in Fig.4. From this figure we find that it is rather possible to explain the Kamiokande data by three neutrino oscillations. The line $U_e + U_\mu = 1 + f = 1.472$ corresponds to the two neutrino oscillations $\nu_e \leftrightarrow \nu_\mu$. From the data we obtain $U_e + U_\mu = 0.845 \pm 0.235$. The $\nu_e \leftrightarrow \nu_\mu$ oscillations are excluded at a very high CL.

Finally we apply our results to recent Frejus experimental data [21] . Using our fluxes, we caluculate the number of charged current muon and electron events ($CC\mu$ and CCe) to find that $CC\mu = 123.3$ and $CCe = 66.6$ for all events with 1.56 $kton\ yr$, where neutral current events are estimated to be 10.2% of all events. It is appropriate to compare the predicted $CCe/CC\mu$ ratio with the experimental value since the ratio is insensitive to the overall large systematic errors. From the above values, we obtain $CCe/CC\mu = 0.54$, which is in good agreement with the experimental value $(CCe/CC\mu)_{exp} = 0.56 \pm 0.06$. Our results are almost the same as those of ref. 21 based on the fluxes of Barr et al. [15], since their trigger efficiency is sizable only for neutrinos with $E_\nu \gtrsim 500$ MeV.

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Figure Captions

1. Differential energy spectra of the atmospheric neutrinos (averaged over all directions) at the Kamioka site. Spectra of $\bar{\nu}_\mu, \nu_e$, and $\bar{\nu}_e$ are multiplied by a factor of $10^{-1}, 10^{-2}$, and 10^{-3}, respectively. The top of each band is for solar minimum and the bottom for solar maximum. The histograms show the spectra calculated by Barr et al. [15] for solar maximum.

2. Flux ratio $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu)$ as a function of neutrino energy at the Kamioka site. The solid line includes the muon polarization effect, while the dashed line neglects the effect. The variations of the ratio due to solar activities are negligibly small. The histogram shows the result obtained by Barr et al. [15] including the muon polarization effect for solar maximum.

3. Ratios of antineutrinos to neutrinos. The error bars include not only statistical errors from simulation, but also variations of the ratios with the solar cycle. The histograms show the result of Barr et al. [15] for solar maximum.

4. Plots of U_μ vs. U_e. The value f is taken to be $f = 0.472$. The point A corresponds to no neutrino oscillations. The line AB corresponds to $\nu_e \leftrightarrow \nu_\mu$ mixing. The region ABCD (solid line) corresponds to three flavor mixing (Case I). The region ABCD (dashed line) corresponds to three flavor mixing (Case II). The region allowed by eq.(1) is represented by the hatched area.

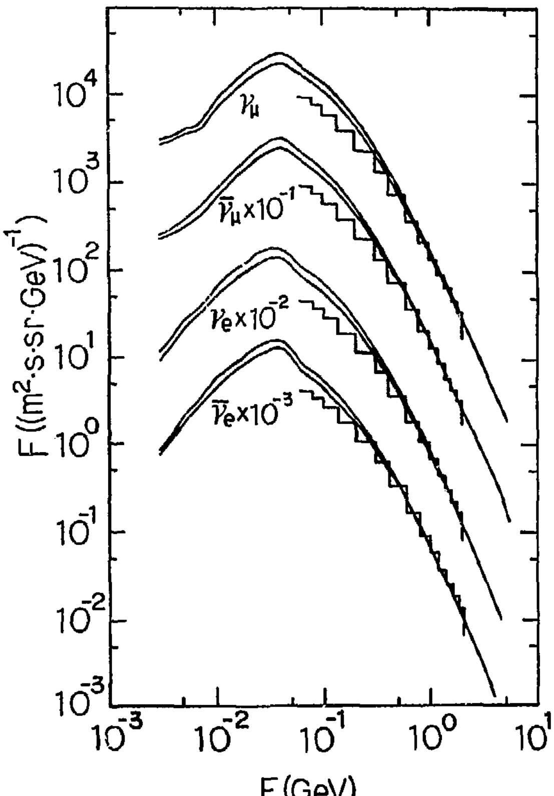

Fig.1

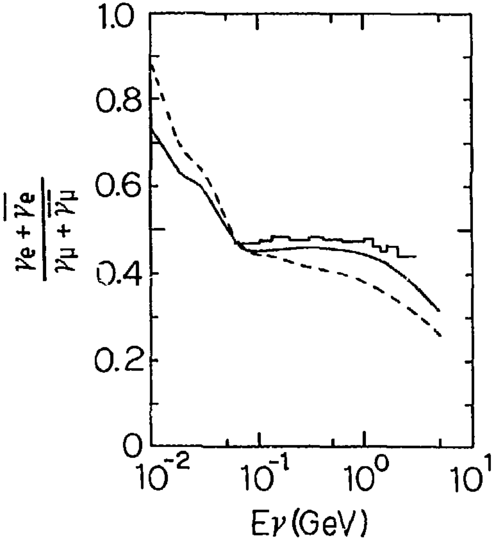
$\frac{\nu_e + \overline{\nu_e}}{\nu_\mu + \overline{\nu_\mu}}$
1.0
0.8
0.6
0.4
0.2
0
10^{-2}
10^{-1}
10^{0}
10^{1}
Eν (GeV)

Fig.2

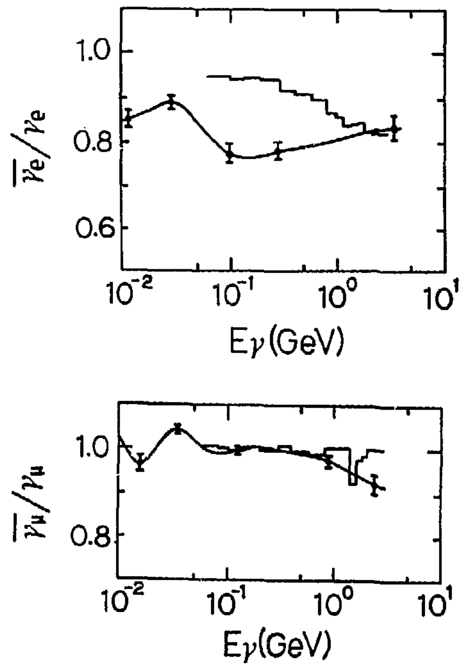
$\overline{\nu_e}/\nu_e$
1.0
0.8
0.6
10^{-2}
10^{-1}
10^{0}
10^{1}
Eν (GeV)
$\overline{\nu_\mu}/\nu_\mu$
1.0
0.8
10^{-2}
10^{-1}
10^{0}
10^{1}
Eν (GeV)

Fig.3

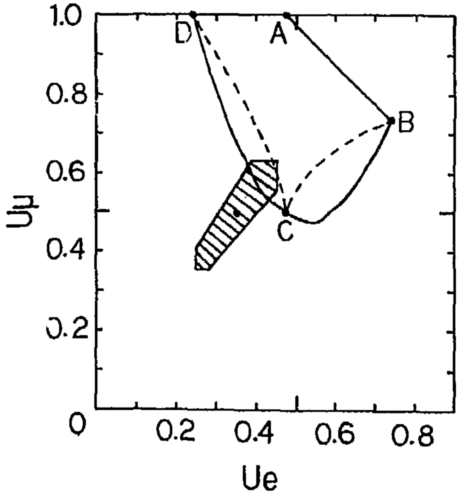

Fig.4