Observation of the East-West Anisotropy of the Atmospheric Neutrino Flux

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The east-west anisotropy, caused by the deflection of primary cosmic rays in the Earth's magnetic field, is observed for the first time in the flux of atmospheric neutrinos. Using a 45 kt yr exposure of the Super-Kamiokande detector, 552 e-like and 633 μ-like horizontally going events are selected in the momentum range between 400 and 3000 MeV/c. The azimuthal distributions of e-like and μ-like events agree with the expectation from atmospheric neutrino flux calculations, verifying that the flux of atmospheric neutrinos in the GeV energy range is reasonably well modeled by calculations that account for the geomagnetic field. [S0031-9007(99)09471-5]

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The primary cosmic ray flux approaching the Earth is known to be almost isotropic [1]. However, since the Earth has a magnetic field and the primary cosmic rays are positively charged, an angular anisotropy is produced for those primaries which reach and interact in the atmosphere. This azimuthal anisotropy, called the east-west

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effect, was discovered in the 1930s as a deficit of secondary cosmic rays (muons) arriving from the easterly direction compared to a westerly direction [2]. In fact, this effect was used to infer that the primary cosmic rays are positively charged. The azimuthal anisotropy varies according to the position on the Earth and the momentum and charge of the primary cosmic ray. The anisotropy is largest for the lowest momenta particles. The anisotropy can be characterized by a cutoff momentum, the maximum momentum at which the incoming particle cannot reach the atmosphere. Since Super-Kamiokande is located close to the geomagnetic equator (25.8° N geomagnetic latitude), the cutoff momentum for horizontally arriving protons from the east is $\sim$50 GeV/c, considerably higher than the average over directions [3,4]. Figure 1 illustrates typical allowed and forbidden tracks of cosmic rays. This results in the depletion of primary cosmic ray interactions directed at Kamioka from the east. The flux of neutrinos produced in the atmosphere by these cosmic rays should likewise be depleted.

In this paper we report the first observation of the east-west anisotropy in the atmospheric neutrino flux. We observe a neutrino east-west effect which is in agreement with expectations based on detailed flux calculations [3,4] and a Monte Carlo simulation of neutrino interactions [5,6]. This confirms that the angular dependence of the atmospheric neutrino flux calculations in the GeV energy range is reasonable.

The Super-Kamiokande detector is a 50 kt water Cherenkov detector located at the Kamioka Observatory, ICRR, University of Tokyo. The center of the detector is at 36°25′33″ N, 137°18′37″ E, 371.8 m above the sea level. To reduce the rate of cosmic ray muons, it is placed at 2700 meters-water-equivalent below the peak of Mt. Ikenoyama. It is cylindrically shaped with a height of 41.4 m and a diameter of 39.3 m, and divided into the inner and outer detectors by a stainless steel support structure with a pair of opaque sheets. The inner detector is viewed by 11 146 photomultiplier tubes (PMTs) of 50 cm diameter, facing inward to detect the neutrino events. The outer detector, a layer of water of 2.6 to 2.75 m thick, has 1885 PMTs of 20 cm diameter used to veto entering events and to tag exiting events.

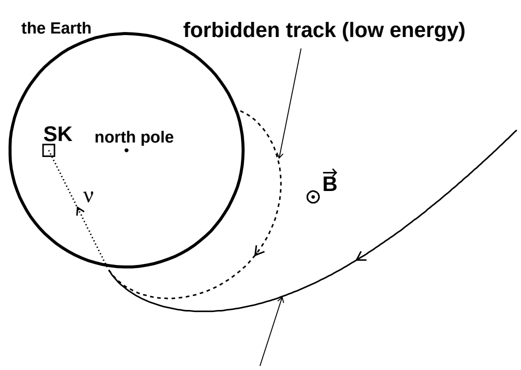

FIG. 1. Typical allowed and forbidden tracks of the incident cosmic rays. The curved line shows the allowed trajectory of the cosmic ray which has momentum larger than cutoff momentum, and the dotted curved line shows a forbidden trajectory. "SK" represents the Super-Kamiokande detector.

The energy and direction of a neutrino are measured from the momentum of the final state charged lepton which is produced in a charged current interaction of the neutrino on nucleus, $\nu + \mathrm{N} \rightarrow l + X$. The flavor of the final state lepton is used for tagging the flavor of the neutrino. With the 45 kt yr exposure of the Super-Kamiokande, a total of 4077 fully contained single-ring atmospheric neutrino events were observed with the following requirements: (1) total number of hits in outer detector less than 25, and no spatial cluster with more than 10 hits, (2) total charge collected in the inner detector more than 200 photoelectrons (pes), (3) the ratio (maximum pe in any single PMT)/(total pes) less than 0.5, (4) the time interval from a preceding event larger than 100 μs, (5) the vertex position should be inside the fiducial volume, 2 m inside from the inner detector wall, and (6) single-ring events with the momentum higher than 100 and 200 MeV/c for e-like and μ-like events, respectively. To determine the direction of neutrinos from the observed leptons, only single Cherenkov ring events were used. Then they were separated into e-like and μ-like events according to their showering or non-showering signature. The particle identification efficiency was estimated to be better than 99% [5].

For analysis of the east-west anisotropy, the following additional cuts were applied: (7) momentum was required to be between 400 and 3000 MeV/c for both e-like and μ-like events and (8) the cosine of the zenith angle of the leptons was required to be between -0.5 and 0.5. Criterion (7) selects the momentum region where the east-west anisotropy is expected to be most significant. The east-west anisotropy of the flux is expected to be larger for lower energy neutrinos because of the cutoff momentum. On the other hand, the lepton direction is more poorly correlated with the neutrino direction at low energy, which tends to wash out the flux anisotropy. The estimated mean scattering angle in the momentum region of criterion (7) is 36° for both ν_e and ν_μ charged current events. The contamination of neutral current events in these e-like and μ-like events was estimated to be 9.0% and 1.3%, respectively. Criterion (8) is to select neutrino events from near the horizon where the effect of the geomagnetic cutoff is maximum.

After these criteria, 552 e-like and 633 μ-like events remained. These data were compared with Monte Carlo simulations using two independent flux calculations [3,4]. These calculations represented the geomagnetic field map by a multipole expansion of the spherical harmonic function. Cutoffs were calculated for all zenith and azimuthal angles at the Super-Kamiokande detector site by backtracing antiprotons through the three dimensional map of the geomagnetic field. Figure 2 shows the azimuthal distributions for e-like and μ-like events. The number of Monte Carlo events (494.3 e-like and 820.7 μ-like based on the flux of Ref. [3], and 487.0 e-like and 790.5 μ-like based on the flux of Ref. [4]) was normalized to the number of data events to compare the azimuthal shape without regard to the 20% uncertainty in absolute flux and the deficit of μ-like events most likely due to neutrino oscillations [5,7,8]. The Monte Carlo events we used here assumed no neutrino oscillations. The lengths of the flight paths of the neutrinos vary with zenith angle but do not vary with the azimuthal angle. Therefore, neutrino flavor oscillations have little effect on east-west anisotropy. The estimated effect from neutrino oscillations is far below the statistical accuracy of the data.

The azimuthal angles are divided into eight bins, 45° each. Agreement between the data and the Monte Carlo is good: the χ^2 values were 5.1/7 DOF and 2.6/7 DOF for e-like and μ-like events, respectively.

A quantitative comparison between the data and Monte Carlo using the flux of Ref. [3] was performed using a Kuiper test [9,10] (similar results were obtained using the flux of Ref. [4]). This test calculates a binning and starting-point free probability that observed data are the result of an assumed distribution. The Kuiper statistic V is defined as

$$V = \max_{0<\phi<2\pi}[S_N(\phi) - P(\phi)] + \max_{0<\phi<2\pi}[P(\phi) - S_N(\phi)],$$

where ϕ is the azimuthal angle, $S_N(\phi)$ is a cumulative probability function from data, and $P(\phi)$ is the one from

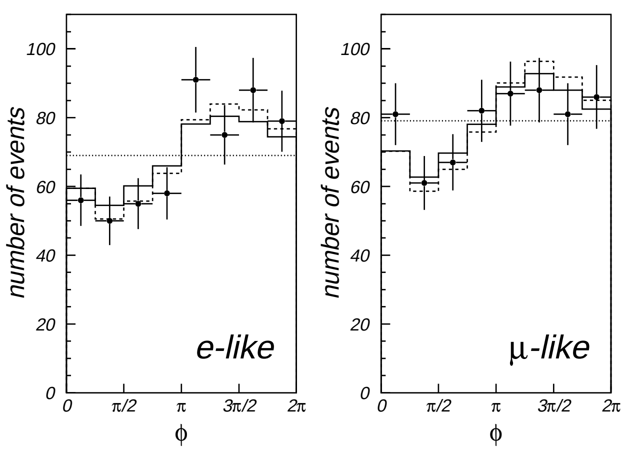

FIG. 2. Azimuthal angle distributions of e-like and μ-like events. The crosses represent the data points, and the histogram drawn by solid line (dashed line) shows the prediction of the Monte Carlo based on the flux of Ref. [3] ([4]). Data are shown with statistical errors. The Monte Carlo has 10 times more statistics than data. The Monte Carlo histogram is normalized to the total number of the real data. ϕ represents the azimuthal angle. $\phi = 0$, $\pi/2$, π, and $3\pi/2$ show particles going to north, west, south, and east, respectively.

Monte Carlo. The significance is obtained from the statistic $V^* = V(\sqrt{n} + 0.155 + 0.24/\sqrt{n})$, and defined as

$$\text{Prob} = 2\sum_{j=1}^{\infty}(4j^2V^{*2} - 1)\exp(-2j^2V^{*2}),$$

where n is the number of events.

From this test, the probability that the azimuthal distribution of the data originated from a flat parent distribution was 0.0008% (20%) for e-like (μ-like) events. The difference in probability can be traced to the run of 4 low bins in e-like data compared to only 2 low bins in μ-like data. The probability that the data matches the Monte Carlo in shape with the flux of Ref. [3] was 42% for e-like events and 92% for μ-like events. For a Monte Carlo with neutrino oscillations with $(\Delta m^2, \sin^2 2\theta) = (2.2 \times 10^{-3}\ \text{eV}^2, 1.0)$ [8], the probabilities were the same within 1% for both e-like and μ-like events. As expected, the probabilities did not change much with the addition of neutrino oscillations.

With current data, the deficit of the westward-going neutrinos is more significant in the e-like data sample than in the μ-like data sample. We define an east-west asymmetry by $(N_E - N_W)/(N_E + N_W)$, where $N_E(N_W)$ represents the number of eastward(westward)-going events. Here the azimuthal distribution was divided into two bins, and the same zenith angle cut (8) was used. The observed asymmetry in μ-like data, 0.08 ± 0.04, is smaller than in e-like data, 0.21 ± 0.04. However, both are consistent with expectation: 0.11 for μ-like and 0.13 for e-like based on the flux of Ref. [3]; 0.15 for μ-like and 0.17 for e-like based on the flux of Ref. [4].

The study of the east-west anisotropy as a function of lepton momentum is important for our understanding of the neutrino-lepton angular correlation and the geomagnetic field effect on the production of atmospheric neutrinos. Figure 3 shows the east-west asymmetry as a function of lepton momentum. The data and the Monte Carlo agreed well; the χ^2 value was 5.9/6 DOF (5.8/5 DOF) for e-like (μ-like) events. The χ^2 value of a comparison of the data and a straight line at $(N_E - N_W)/(N_E + N_W) = 0$ was 26.5/6 DOF (10.5/5 DOF) for e-like (μ-like) events. As expected from the large neutrino-lepton scattering angle, the measured east-west asymmetry was small below 400 MeV/c. Above 3 GeV/c, the neutrinos originate from primary cosmic rays that are minimally affected by the geomagnetic field, so the flux is symmetric from the east and west.

In summary, we have observed for the first time clear evidence for the east-west anisotropy in the atmospheric neutrinos, based on the data from 45 kt yr of exposure of the Super-Kamiokande detector. A deficit of westward-going e-like events was seen at more than 99% confidence level, while for μ-like events, it was statistically less significant. However, the azimuthal distributions of these events and the momentum dependence of the east-west anisotropy for both e-like and μ-like agreed well with

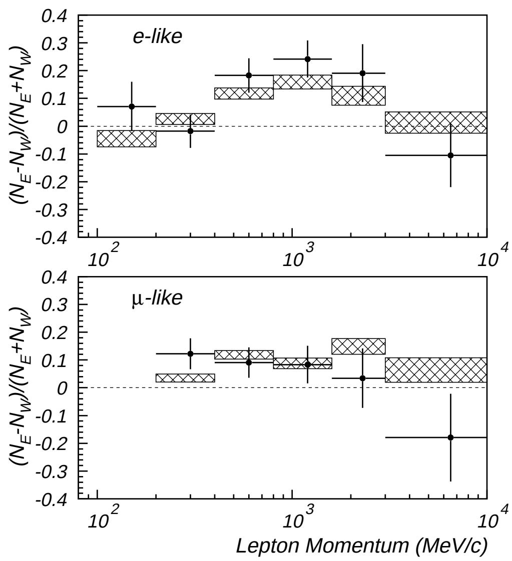

FIG. 3. East-west asymmetry $(N_E - N_W)/(N_E + N_W)$ as a function of lepton momentum for e-like and μ-like events, where N_E and N_W represent the number of eastward and westward-going events, respectively (see the text for the definition). The crosses with error bars represent the data and the hatched region represents the prediction based on the flux of Ref. [3]; error bars are statistical.

the prediction based on detailed neutrino flux calculations. This observation suggests that the geomagnetic field effects in the production of atmospheric neutrinos in the GeV energy range are reasonably well modeled.

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