Low-energy atmospheric neutrinos

Haeshim Lee*
Department of Physics, University of Pennsylvania, Pennsylvania 19104

Sidney A. Bludman†
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 18 September 1987)

Results of a three-dimensional Monte Carlo calculation of the low-energy spectrum and angular distribution of atmospheric neutrinos are presented and compared with earlier one-dimensional calculations valid at higher neutrino energies. The three-dimensional results agree with the one-dimensional calculation above 200 MeV, but are up to a factor of 2 lower below 50 MeV. Geomagnetic-cutoff effects on primary cosmic rays significantly reduce the neutrino flux at low geomagnetic latitudes. Azimuthal angular dependence shows a strong north-south asymmetry for upward-going fluxes, whereas an east-west effect is apparent only at low geomagnetic latitudes.

I. INTRODUCTION

One-dimensional Monte Carlo calculations of cosmic-ray production of neutrinos in Earth's atmosphere, including geomagnetic and solar modulation effects, for $E_\nu > 200$ MeV have been reported,[1,2] and agree well with the flux and angular distribution of neutrinos observed in underground detectors.[2] At lower energies, the transverse-momentum distribution of hadron interaction and decay products requires a three-dimensional cascade calculation. Our preliminary three-dimensional Monte Carlo calculation[3] agrees with the one-dimensional calculation above 200 MeV, but shows the neutrino flux to be lower by a factor 2 than the result calculated one dimensionally at low energy (<50 MeV). We here present the details and results of the three-dimensional calculation, including zenith-angle dependence and geomagnetic effects at several underground detector sites.

Atmospheric neutrinos are produced by primary cosmic-ray protons and alphas interacting with air molecules to produce secondary mesons and nucleons. These secondaries interact again or decay to produce neutrinos and other decay products. The three-dimensional atmospheric neutrino flux is

$$dN_\nu(E_\nu,\theta_\nu,\phi_\nu)/dE_\nu = \int y_\nu \Omega(E_p,\theta_p,\phi_p,\lambda)(dN_p/dE_\nu)dE_p d\omega_p \ , \quad (1)$$

where $y_\nu(E_\nu,\theta_\nu,\phi_\nu,E_p,\theta_p)$ is the yield of neutrinos of energy E_ν, zenith angle θ_ν, and azimuth angle ϕ_ν by primary cosmic rays of energy E_p and zenith angle ϕ_p, dN_p/dE_p is the primary cosmic-ray spectrum, and $\Omega(E_p,\theta_p,\phi_p)$ is the geomagnetic cutoff. This geomagnetic cutoff depends on geomagnetic latitude λ and magnetic rigidity $R=pc/e$, where p is the primary-cosmic-ray momentum. Although concerned in this paper principally with low-energy neutrinos, our results (Figs. 4–8 below) include all neutrinos produced by primaries up to $E_p = 200$ GeV.

II. CALCULATION

The mesons produced by hadron-air interactions are relativistic in the laboratory frame even at threshold energy and the angular deviation between the incident hadron and the secondary meson is small. Nevertheless, because neutrinos with small angular deviation may escape without reaching Earth's surface, any small angular deviation becomes significant when the primary's incident angle is near the horizon. We therefore included the curvature of Earth in our calculations and modified the Gaisser-Protheroe-Stanev one-dimensional hadron interaction model[4] originally based on accelerator data and resonance phenomena at low energies, by assigning the formula

$$W(a,x_t)=(a+1)(a+2)x_t(1+x_t)^a \quad (2)$$

for the probability of transverse momentum p_t to the secondary hadron coming out of an incident hadron of momentum p (Ref. 3). Here $a=2p/\langle p_t\rangle+3$ for $p>1.5\langle p_t\rangle$, $a=0$ for $p<1.5\langle p_t\rangle$, $\langle p_t\rangle$ depends only on the type of secondary and $x_t \equiv p_t/p$. At low momenta $W \propto p_t/p$, at high p, $W \sim p_t \exp(-2p_t/\langle p_t\rangle)$. Our results are otherwise not sensitive to the choice of W.

At low energies, most muons decay at rest after energy loss by air ionization, so that for any primary direction, the angular deviation of the secondaries is appreciable. In such cases, the neutrino direction is nearly isotropic and half of the neutrinos escape without reaching Earth's surface. This factor-2 reduction in the surface flux at low energy is the main difference between the three-dimensional and one-dimensional calculations. For neutrinos above 200 MeV our three-dimensional results agree with those of one-dimensional calculations.[3,5]

While muons are produced polarized, their electromagnetic interaction with air molecules quickly degrades the polarization. The muon energy loss by air ionization is typically 2–3 MeV/(g/cm^2), so that a fraction of muons lose up to a few GeV energy in the atmosphere before they decay. This muon energy loss is significant not only for MeV neutrinos, but even for the production of GeV neutrinos.

In our computer program, analytic formulas are used for the energy distribution of decay particles.[3] For those energies, a microcanonical ensemble average is taken, conserving total energy in each individual decay. The secondary directions are, however, assigned according to a canonical ensemble, in which the total momentum is conserved on average, but not in individual decays. Hadron production by strong interactions is treated similarly. We use energy-dependent energy-loss rates for charged particles by air ionization in a nonisothermal atmosphere to determine the decay height and energy, and energy-dependent formulas for energy-loss rates to determine the interaction height and energy.

The geomagnetic-cutoff effect is significant for low-energy atmospheric neutrino fluxes even up to several GeV. This cutoff is approximately given by the Störmer formula

$$p_{\text{cutoff}}=\frac{59.6\cos^4\lambda}{R'^2(1+\sqrt{1-\cos^3\lambda\sin\theta\sin\phi})}\ \text{GeV}/c \qquad (3)$$

valid for charged particle orbits in an offset dipole geomagnetic field. Here p_{cutoff} is the primary's cutoff rigidity, λ is the offset dipole geomagnetic latitude, R' is the distance from the dipole center to the interaction height in units of the mean Earth radius, θ is the zenith angle, and ϕ is the azimuthal angle measured clockwise from geomagnetic north.

Downward neutrinos coming from above the horizon are produced near the detection site, so that, for practically all the primaries, λ is the value at the detector site. Upward neutrinos coming from below the horizon are, however, produced far away from the detector so that the relevant λ is not the value at the detector site.

III. RESULTS

Figure 1 shows the neutrino flux averaged over 4π solid angle without geomagnetic cutoff at solar minimum (1986–1987). The sharply decreasing primary-cosmic-ray flux and increasing neutrino field at $E_\nu < 50$ MeV as functions of primary energy provides peak production of 40-MeV neutrinos.

The total neutrino flux is strongly effected by the geomagnetic cutoff. Figures 2 and 3 show the calculated atmospheric neutrino flux, averaged over 4π solid angle at two detector sites at solar minimum. We take the cutoff at the primary's first interaction height. Cleveland has a high geomagnetic latitude ($\lambda=52.0°$N) so that the downward primary flux is practically unaffected by the cutoff: the small reduction of the neutrino flux is mainly due to the reduction of upward-coming neutrinos which are produced far away near the magnetic equator. The results at Homestake ($\lambda=52.2°$N) are practically undistinguishable from those at Cleveland. The significantly reduced neutrino flux at Kamioka ($\lambda=27.0°$N) is particularly important because Kamiokande

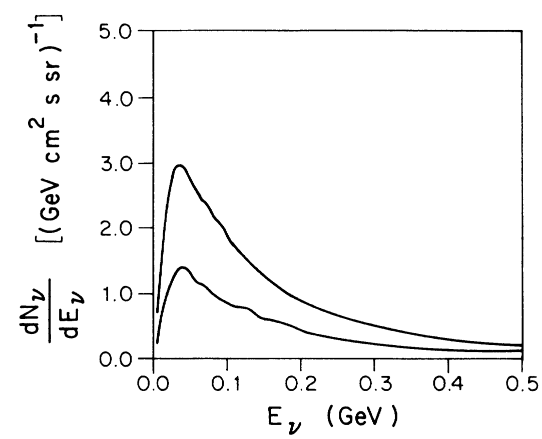

FIG. 2. Neutrino flux at Cleveland, averaged over 4π solid angle at solar minimum. The upper and lower curves refer to $\nu_\mu+\bar{\nu}_\mu$ and $\nu_e+\bar{\nu}_e$, respectively.

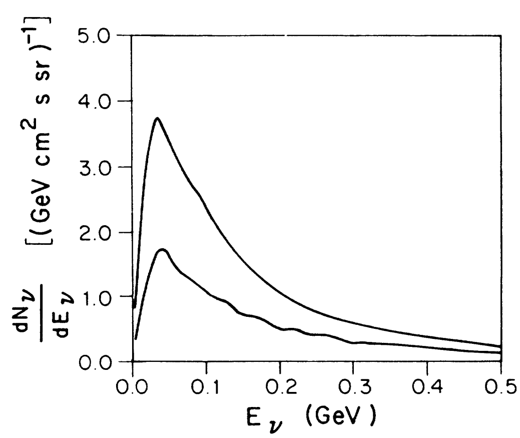

FIG. 1. Neutrino flux without geomagnetic cutoff, averaged over 4π solid angle at solar minimum. The upper and lower curves refer to $\nu_\mu+\bar{\nu}_\mu$ and $\nu_e+\bar{\nu}_e$, respectively.

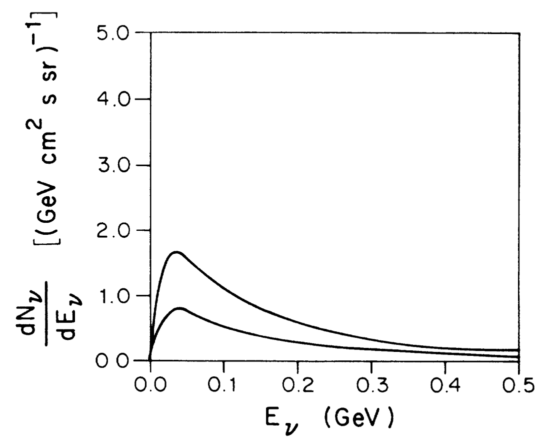

FIG. 3. Neutrino flux at Kamioka, averaged over 4π solid angle at solar minimum. The upper and lower curves refer to $\nu_\mu+\bar{\nu}_\mu$ and $\nu_e+\bar{\nu}_e$, respectively.

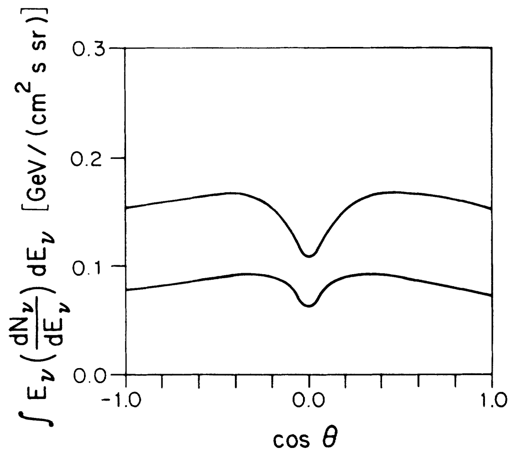

FIG. 4. Zenith-angle dependence of neutrino intensity, without geomagnetic cutoff, at solar minimum. Upper curve refers to $\nu_\mu+\bar{\nu}_\mu$, lower curve to $\nu_e+\bar{\nu}_e$.

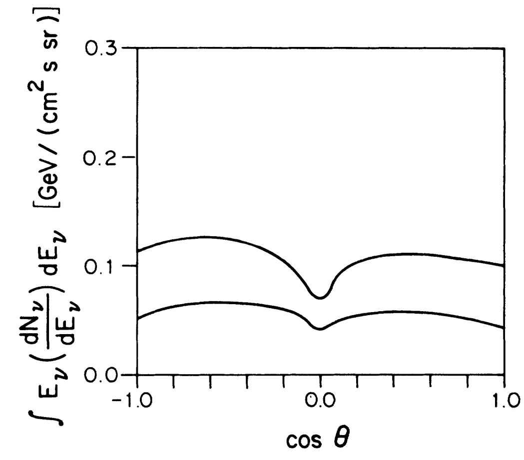

FIG. 6. Zenith-angle dependence of neutrino intensity at Kamioka. Upper curve refers to $\nu_\mu+\bar{\nu}_\mu$, lower curve to $\nu_e+\bar{\nu}_e$.

is observing low-energy astrophysical neutrinos.

The dependence of neutrino intensity on zenith angle, without geomagnetic cutoff, is shown in Fig. 4. As θ increases, the longer slant depth allows more high-energy muons to decay, increasing the neutrino flux. For primary directions nearly horizontal, however, the small angular deviation of the neutrino direction from the primary allows neutrinos to escape Earth even at high energies. This appears as a dip near $\cos\theta=0$ in the figure. We consider neutrinos produced by primaries with $E_p<200$ GeV.

The zenith-angle dependence of the neutrino flux at Cleveland at solar minimum is shown in Fig. 5. Here the downward neutrinos are practically unaffected by the geomagnetic cutoff, but the upward flux is strongly reduced because most of these neutrinos come from magnetic equatorial regions. Kamioka has a low geomagnetic latitude so that the downward neutrinos are suppressed more than the upward neutrinos (Fig. 6). These up-down asymmetries, produced by geometric cutoff of the primary cosmic rays, can simulate neutrino oscillations. There is so far no evidence for real neutrino oscillations over terrestrial diameters.[6] Only after such evidence appears, would an improved theoretical calculation, using a more realistic description of Earth's magnetic field, be necessary.

At low geomagnetic latitudes, the geomagnetic cutoff on primary cosmic rays produces a strong azimuthal dependence of the secondary neutrino intensities for nearly horizontal neutrinos. For downward-going neu-

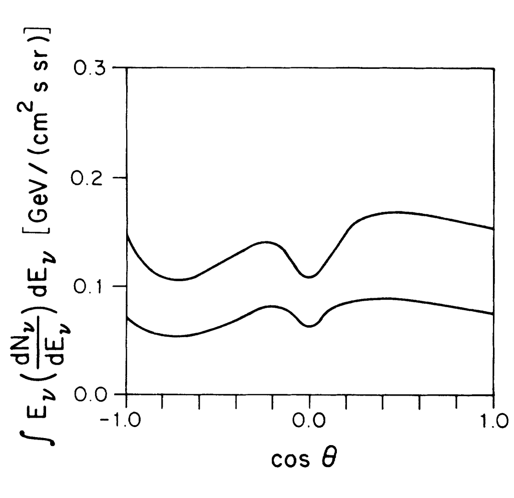

FIG. 5. Zenith-angle dependence of neutrino intensity at Cleveland. Upper curve refers to $\nu_\mu+\bar{\nu}_\mu$, lower curve to $\nu_e+\bar{\nu}_e$.

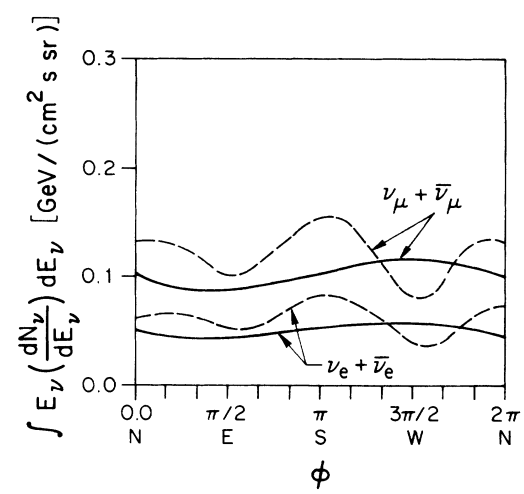

FIG. 7. Azimuthal-angle dependence of neutrino intensity at Cleveland. Solid curves show intensities averaged over zenith angle $60°<\theta<90°$, dashed curves, intensities averaged over zenith angle $90°<\theta<120°$. Upper curves refer to $\nu_\mu+\bar{\nu}_\mu$, lower curves to $\nu_e+\bar{\nu}_e$.

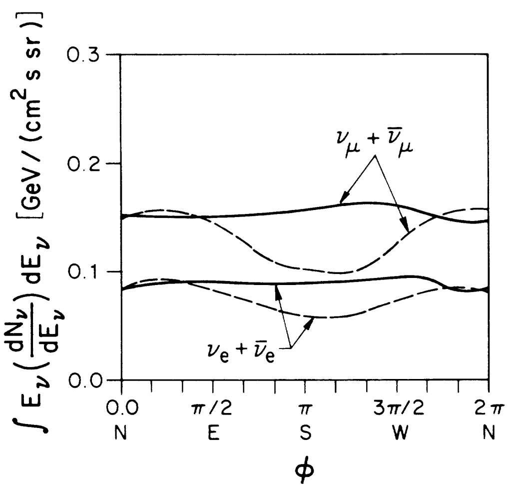

FIG. 8. Azimuthal-angle dependence of neutrino intensity at Kamioka. Solid curves show intensities averaged over zenith angle $60° < \theta < 90°$, dashed curves, intensities averaged over zenith angle $90° < \theta < 120°$. Upper curves refer to $\nu_\mu + \bar{\nu}_\mu$, lower curves to $\nu_e + \bar{\nu}_e$.

trinos, this follows directly from the Störmer formula (3). Upward-going neutrinos, however, are produced at distant sites of different geomagnetic latitude, including the geomagnetic equator. Figures 7 and 8 show, for Cleveland and Kamioka, respectively, the azimuthal dependence of the $\nu_\mu + \bar{\nu}_\mu$ and $\nu_e + \bar{\nu}_e$ intensities, each averaged over zenith angles 30° above the horizon (heavy curves) and below the horizon (dotted curves). For $\lambda > 60.4°$, primary cosmic rays arrive from any direction above the horizon with energies above the pion production threshold energy and are not cut off. Consequently, at Cleveland (Fig. 7), there is imperceptible azimuthal dependence for nearly horizontal downward-going neutrinos, and an only moderate north-south effect for nearly horizontal upward-going neutrinos. At Kamioka (Fig. 8), however, there is a pronounced azimuthal angular dependence.

ACKNOWLEDGMENTS

We thank T. K. Gaisser for his helpful comments on an earlier version of this paper. We wish to acknowledge the hospitality of the Aspen Center for Physics summer workshop. S.A.B. acknowledges the hospitality of the Institute for Theoretical Physics, University of California, Santa Barbara where his research was supported in part by the National Science Foundation under Grant No. PHY 82-17853 supplemented by funds from the National Aeronautics and Space Administration. The work at the University of Pennsylvania was supported in part by the U.S. Department of energy under Contract No. EY-76-C-02-3071.

---

*Present address: Department of Physics, Chungnam National University, Daejon 300-31, Korea.

†Present address: Department of Physics, University of Pennsylvania, Philadelphia, PA 19104.

[1]T. K. Gaisser, T. Stanev, S. A. Bludman, and H. Lee, Phys. Rev. Lett. **51**, 223 (1983); in *Fourth Workshop on Grand Unification,* edited by H. A. Weldon, P. Langacker, and P. J. Steinhardt (Birkhauser, Boston, 1983).

[2]T. K. Gaisser and Todor Stanev, in *ICOBAN 1984,* proceedings of the International Colloquium on Baryon Nonconservation, Salt Lake City, edited by D. Cline (University of Wisconsin, Madison, 1984).

[3]H. Lee and S. A. Bludman, in *Proceedings of the 19th International Cosmic Ray Conference,* La Jolla, 1985, edited by F. C. Jones, J. Adams, and G. Mason (NASA Conf. Publ. 2376) (Goddard Space Flight Center, Greenbelt, MD, 1985).

[4]T. K. Gaisser, R. J. Protheroe, and Todor Stanev, in *Proceedings of the 18th International Cosmic Ray Conference,* Bangalore, India, 1983, edited by N. Durgaprasad *et al.* (Tata Institute of Fundamental Research, Bombay, 1983), Vol. 5, p. 174.

[5]T. K. Gaisser and T. Stanev, in *Neutrino '84,* Proceedings of the 11th International Conference on Neutrino Physics and Astrophysics, Dortmund, 1984, edited by K. Kleinknecht and E. A. Paschos (World Scientific, Singapore, 1984), p. 370.

[6]J. M. LoSecco *et al.*, Phys. Rev. Lett. **54**, 2299 (1985).