Flux of Atmospheric Neutrinos

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New calculations of the flux of neutrinos produced by cosmic rays in the atmosphere are reported. The authors have taken account of effects of the geomagnetic cutoff and of solar modulation separately for upward- and downward-going neutrinos of both electron and muon flavor with energies from 200 MeV to 10 GeV. The geomagnetic cutoff in particular must be handled carefully because it induces behavior very similar to a neutrino-oscillation signal.

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The calculation of the flux of ν_e, $\bar{\nu}_e$, ν_μ, and $\bar{\nu}_\mu$ produced by cosmic rays in the atmosphere which we present here substantially agrees with earlier calculations[1,2] on which background estimates for proton-decay detectors have been based. We find, however, that at high-latitude sites, the geomagnetic cutoff can suppress the flux of few-hundred-megaelectronvolt upward-going neutrinos by ~50%, and that solar modulation changes the flux of neutrinos above 200 MeV by ±10%. A difference in the total number of upward- and downward-going neutrinos is therefore not indicative of neutrino oscillations until after these substantial geomagnetic and solar-modulation corrections are applied. Because the ν_e/ν_μ ratio is relatively insensitive to geomagnetic effects, experimentally discriminating neutrino flavors is desirable.

Our calculation is motivated by the presence of nucleon-decay detectors underground which, for the first time, allow a direct observation of atmospheric neutrinos from the ν interactions in the large detector fiducial volume. Indeed, first reports of the Irvine-Michigan-Brookhaven (IMB) group[3] already show nearly one such ν interaction per day in agreement with the rate expected for their 3-kiloton fiducial volume and detector efficiencies.[3] Since there is apparently no unexpected source of neutrinos in the 0.2–2 GeV range, future observations distinguishing upward- and downward-going atmospheric neutrinos should soon allow an extension of the search for neutrino oscillations.[4] Even with a 10-kiloton fiducial volume producing 1200 neutrino events per year, however, a long running time will be needed to obtain detailed statistics on the angular distribution. For this reason, we divide the trajectories into downward- and upward-going cones of 60° zenith angle,[5] so that each cone sees $\frac{1}{4}\times 4\pi$ and the minimum distance traversed by an upward-going neutrino is $R_E = 6.5\times10^6$ m.

Neutrino oscillations are characterized[6] by a set of squared mass differences Δm^2 and a mixing-angle matrix α_{ij}. Any difference between neutrino mass eigenstates and flavor eigenstates leads to neutrino oscillations over a length $L(\mathrm{m}) = 2.5\,E(\mathrm{MeV})/\Delta m^2(\mathrm{eV}^2)$. If the Earth's diameter ($D = 1.3\times10^7$ m) is used as the path length, oscillations with $\Delta m^2 \gtrsim (10^{-4}\ \mathrm{eV}^2)\,[E_\nu/(300\ \mathrm{MeV})]$ should be observable provided that the strength of mixing, $\sin 2\alpha$, is not too small. (The minimum mixing observable underground is probably $\sin^2 2\theta_c \cong 0.2$.[5]) With a detector threshold below $E_\nu = 300$ MeV, $\Delta m^2 > 10^{-4}$ eV^2 can be explored. Atmospheric-neutrino observations can therefore reduce the present upper limit[7] (obtained in reactor and accelerator experiments) by at least two orders of magnitude. Boliev *et al.*[8] claim a limit for $\nu_\mu \to \nu_e$ of $\Delta m^2 < 10^{-2}$ eV^2 for $\sin^2 2\alpha > 0.5$ on the basis of a measurement of upward-going muons at Baksan and Volkova's calculation of ν flux.[2] Because of the relatively high-energy ν_μ required to produce a muon penetrating their detectors, this limit is not as restrictive as that possible with contained neutrino interactions. The present limits[7,8] thus insure that there are no oscillation effects on the flux of downward-going neutrinos which have traveled < 100 km.

Tam and Young[1] calculated the atmospheric ν flux from the muon spectrum observed[9] at given geomagnetic latitude and atmospheric depth, correcting for muon energy loss in the atmosphere. We take the alternative approach of calculating the yield $Y_f(E_\nu, E, \theta)$ per primary proton of energy E incident at zenith angle θ. The yield Y_μ

of muons is also calculated as a function of atmospheric depth, so that the observed muon flux serves as a check on our calculation. Particle production is calculated from a model based on data for collisions of nucleons and pions on light nuclear targets, including energy dependence of cross sections and of some individual inelastic channels near threshold. Separate yields of $\nu, \bar{\nu}$ from all decay channels of pions, kaons, and muons are computed with a Monte Carlo program that follows the charges and includes ionization energy losses down to threshold. We use a standard (nonisothermal) atmosphere[10] to convert altitude to depth in grams per square centimeter. This direct approach allows us to include explicitly the geomagnetic-cutoff and solar-modulation effects which are important for $E_\nu \lesssim 1$ GeV.

Figure 1 shows the $\nu_\mu + \bar{\nu}_\mu$ and $\nu_e + \bar{\nu}_e$ neutrino yields in three energy bands obtained from a single vertically incident primary proton of energy E. At low energies, where all the muons produced from $\pi, K \rightarrow \mu + \nu_\mu$ are slow enough to decay via $\mu \rightarrow e + \nu_\mu + \bar{\nu}_e$, the yields approach the ratio $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu) \sim \frac{1}{2}$, but this ratio decreases with increasing energy as muons start surviving down to the Earth's surface. Near pion threshold, Δ production dominates, so that the primary positive charge biases against $\bar{\nu}_e$ production.

The neutrino flux is

$$dN_f/dE_\nu = \int Y_f(E_\nu, E, \theta)\Omega(R, \theta, \varphi, \lambda)(dN/dE)dE, \quad (1)$$

where dN/dE is the primary proton spectrum and $\Omega(R, \theta, \varphi, \lambda)$ is the geomagnetic cutoff. The cutoff depends on azimuth φ, geomagnetic latitude λ, zenith angle θ, and magnetic rigidity $R = pc/e$, where p is the primary proton momentum.

The primary nucleon spectrum at high geomagnetic latitudes is labeled "down" in Fig. 2. The solid curve is for minimum solar activity; the lower curve for maximum activity.[11] The period for solar modulation of cosmic rays is about 11 yr with activity rising to maximum faster than it declines.[12] The cosmic-ray maxima (minima) lag solar minimum (maximum) activity by about a year. The most recent solar maximum was in 1979–1980, so that we are now near minimum cosmic-ray flux.

Figure 3(a) compares our results for vertically

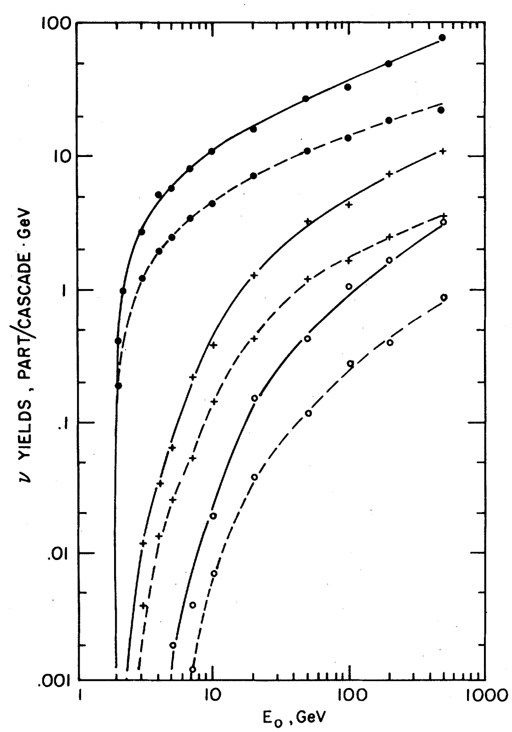

FIG. 1. Neutrino yields $\nu_\mu + \bar{\nu}_\mu$ (solid curves) and $\nu_e + \bar{\nu}_e$ (dashed curves) for three bins of neutrino energy (solid circles, 0.2–0.4; plusses, 1.0–1.2; open circles, 2.0–3.0 GeV) for vertically incident protons of energy E. Yields per primary nucleon are differential in neutrino energy.

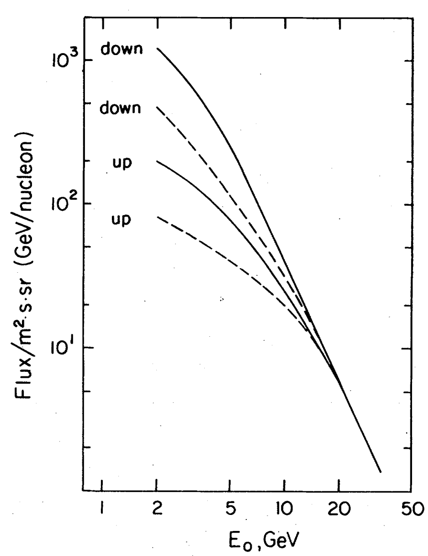

FIG. 2. Primary nucleon spectrum at solar minimum (solid curves) and at solar maximum (dashed curves). Curves labeled "down" are without geomagnetic cutoff, appropriate for computing the flux of downward neutrinos at a high-latitude site. Curves labeled "up" are used to compute upward-going neutrinos at Cleveland. See text.

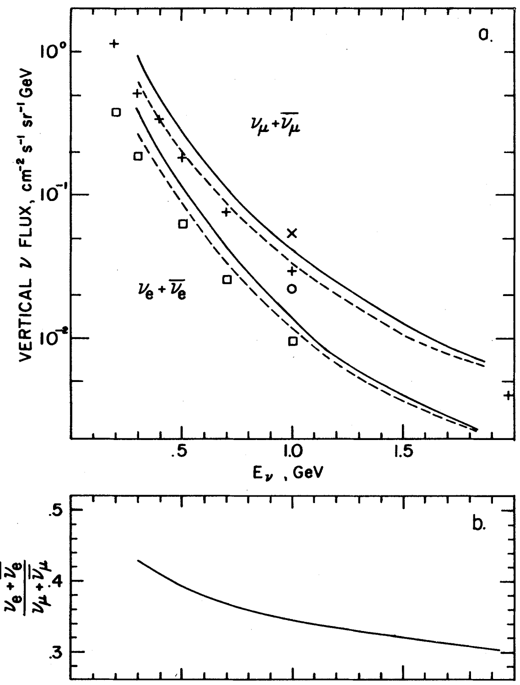

FIG. 3. (a) Differential vertically downward fluxes of $\nu_\mu+\bar\nu_\mu$ (upper curves) and $\nu_e+\bar\nu_e$ (lower curves) without geomagnetic cutoff. Present calculation, full lines for solar minimum, and dashed lines for solar maximum; Tam and Yound, plusses and squares; and Volkova, cross and circle. (b) $(\nu_e+\bar\nu_e)/(\nu_\mu+\bar\nu_\mu)$ ratio.

downward fluxes of neutrinos at high geomagnetic latitude with the results of Refs. 1 and 2. The $(\nu_e+\bar\nu_e)/(\nu_\mu+\bar\nu_\mu)$ ratio on a linear scale is shown on Fig. 3(b). To understand the small (20–50%) differences among the three calculations requires discussing the normalization and shape of the primary spectrum, primary composition, solar modulation, details of the particle production model, etc. We defer discussion of these details and of angular distributions and muon fluxes to a fuller publication.

We conclude by considering the effect of geomagnetic fields, which affect downward- and upward-going neutrinos much differently. With use of Cleveland as a typical high-latitude site, downward-going protons are magnetically cutoff for $p<1.8$ GeV/c, nearly independently of θ and φ. The upward cone, however, receives trajectories from $\frac{3}{4}$ of the Earth's surface, much of which is equatorial with vertical cutoffs up to 17 GeV. (At an equatorial site, however, the effective cutoff for upward primaries is lower than for downward primaries,[13] producing, at the Kolar gold fields, for example, a geomagnetic up/down asymmetry opposite to that expected from neutrino oscillations.)

TABLE I. Upward (↑) and downward (↓) neutrino fluxes (in cones of half-angle 60°) at Cleveland for solar maximum (max) and solar minimum (min). Here $\nu=\nu_e+\bar\nu_e+\nu_\mu+\bar\nu_\mu$.

	$E_\nu \geq 200$ MeV	$E_\nu \geq 1$ GeV
$(\nu\uparrow/\nu\downarrow)_{\rm min}$	0.57	0.84
$(\nu\uparrow/\nu\downarrow)_{\rm max}$	0.66	0.88
$(\nu_{\rm max}/\nu_{\rm min})\downarrow$	0.70	0.90
$(\nu_{\rm max}/\nu_{\rm min})\uparrow$	0.80	0.94

Cooke[13] has recently computed the effective geomagnetic cutoffs for a variety of upward and downward cones at various sites:

$$\Omega(E,\lambda)=\int_0^{\theta} d\cos\theta \int_0^{\theta} d\varphi\, \Omega(R,\theta,\varphi,\lambda). \qquad (2)$$

Here, $\Omega(E,\lambda)$ is the fraction of the cone of upward-going trajectories that is accessible to primary cosmic rays with energy E. Neglecting the dependence of yield on zenith angle (which is permissible for $\theta<60°$) we obtain

$$\int (dN_f/dE_\nu)d\Omega = \int Y_f(E_\nu,E)\Omega(E,\lambda)(dN/dE)dE. \qquad (3)$$

The curves labeled "up" in Fig. 2 show $\Omega(E,\lambda)dN/dE$ for $\theta_{\rm max}=60°$.

The geomagnetic effect is most noticeable at solar minimum (years 1965, 1976, and 1987) when low-energy primaries are most abundant. The solar-modulation effect is largest for downward neutrinos for which low-energy primaries are most abundant. Table I shows typical results for the Cleveland site. We note that the upward flux can be suppressed by as much as a factor of 2. The exact size of these effects depends on neutrino energy and therefore on detector response, but we estimate that the values shown should bracket those relevant to nucleon-decay detectors. Uncertainties in flux due to uncertainties in the yield function Y cancel to first order in the up/down ratios of Table I.

Because of their different genealogies, the ν_e/ν_μ ratio can also differ for up and down. We find, however, that the geomagnetic effect largely cancels out of this ratio and $\nu_e+\bar\nu_e$ is suppressed by no more than 2 relative to $\nu_\nu+\bar\nu_\mu$ for upward- as compared to downward-going neutrinos. Thus, oscillation effects which change the ν_e/ν_μ ratio will not be geomagnetically obscured. In thinking about these ν_e/ν_μ ratio effects, the unitarity diagram of Ref. 4 is helpful: If there is no ν_e-ν_μ mixing, the point A ($\nu_\mu=1.0$,

$\nu_e = 0.5$) is moved to $\nu_\mu = 0.7$, $\nu_e \cong 0.35$ by geomagnetic effects at Cleveland. In general, at a high-latitude site, the geomagnetic effect shrinks the scale of the diagram for upward-going neutrinos. Since this simulates a neutrino-oscillation signal, the geomagnetic effects (including details of angular dependence of trajectories in a nondipole field) will have to be taken carefully into account in performing this type of neutrino-oscillation search.

Finally, we note that observation of the various angular-dependent effects can serve as a useful calibration of a nucleon-decay detector and as an aid to understanding the background for the nucleon-decay search.[14]

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