# THREE DIMENSIONAL CALCULATION OF FLUX OF LOW ENERGY ATMOSPHERIC NEUTRINOS

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**Abstract;** Results of three-dimensional Monte Carlo calculation of low energy flux of atmospheric neutrinos are presented and compared with earlier one-dimensional calculations [1,2] valid at higher neutrino energies. These low energy neutrinos are the atmospheric background in searching for neutrinos from astrophysical sources. Primary cosmic rays produce the neutrino flux peaking at near $E_\nu$=40 MeV and neutrino intensity peaking near $E_\nu$=100 MeV. Because such neutrinos typically deviate by $20^0 \sim 30^0$ from the primary cosmic ray direction, three-dimensional effects are important for the search of atmospheric neutrinos. Nevertheless, the background of these atmospheric neutrinos is negligible for the detection of solar and supernova neutrinos.

## 1. Introduction

Recently one-demensional Monte Carlo calculations of cosmic ray production of neutrinos in the Earth's atmosphere, including geomagnetic and solar modulation effects, were reported [1,2]. These calculations agree well with the flux and angular distribution of neutrinos of energy $E_\nu$> 200 MeV observed in underground detectors. But these earlier one-dimensional cascade calculations are inapplicable to neutrinos of lower energy $E_\nu$< 50 MeV important in neutrino astronomy. In fact, we shall see (Fig. 3) that the mean angular deviation between the primary cosmic rays and neutrinos is appreciable even for neutrinos of several hundred MeV. The flux of low-energy atmospheric neutrinos we obtain (Fig. 2) in the present three-dimensional calculation is negligible compared with the known flux of solar or supernova neutrinos, but maybe significant in the case of other sources of astrophysical neutrinos.

The three-dimensional atmospheric neutrino flux is

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

where $y_\nu(E_\nu, \theta_\nu, \phi_\nu, E_p, \theta_p)$ is the yield of neutrinos of energy $E_\nu$, zenith angle $\theta_\nu$ and azimuth angle $\phi_\nu$ by primary cosmic rays of energy $E_p$ and zenith angle $\phi_p$. $dN_p/dE_p$ is the primary cosmic ray spectrum, and $\Omega\,(E_p, \theta_p, \phi_p)$ is the geomagnetic cut-off. This geomagnetic cut-off depends on geomagnetic latitude $\lambda$ and magnetic rigidity $R = pc/e$ where $p$ is the primary cosmic ray's momentum.

## 2. Calculational details

We modified the Gaisser-Protheroe-Stanev one-dimensional hadron interaction model [5] by assigning to secondary particles the transverse momentum distribution.

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

Here $a=2p/<p_p>-3$ for $p>1.5<p_t>$, $a=0$ for $p<1.5<p_t>$, $x_t=p_t/p$ and $p$ is the incident hadron's momentum. At high $p$, $W\sim p_t\exp(-ap_t)$. The angular deviation of secondary hadrons from the incident hadron direction produced by the above formula affects our results insignificantly.

In our computer program analytic formulae are used for the energy distribution of decay particles. For those energies, a microcanonical ensemble average is taken; total energy is conserved in each individual decay. The secondary directions are, however, assigned according to a canonical ensemble; the total momentum is conserved on average but not in individual decays. Interaction cases are treated similarly. We use energy-independent energy loss rates for charged particles by air ionization in a simple isothermal atmosphere to determine the decay height and energy, and energy-dependent formulae to determine the interaction height and energy. Our results are insensitive to these parameters.

For the comparison with the earlier one-dimensional calculation we calculated the yield function

$$Y_\nu(E_\nu,E^p,\theta_p)\equiv\int y_\nu(E_\nu,\theta_\nu,\phi_\nu,E_p,\theta_p)\,d\omega_\nu,$$

integrated over appropriate neutrino directions.

## 3. Results and Conclusions

Fig.1 shows the yield $Y_\nu$ of vertically incident protons of several energies $E_p$, integrated over the downward $2\pi$ solid angle of neutrino's directions. Because low-energy neutrinos are made mainly from low-enrgy pions and muons at rest, for all primary cosmic ray energies the peak flux occurs near 40 MeV and the peak intensity near 100 MeV. Because most muons decay at rest and $<E_{\nu_e}>=0.3E_\mu$, $<E_{\nu_\mu}>=0.35E_\mu$, the atmospheric neutrino flux peaks near 40 MeV.

Fig.2 shows the downward neutrino flux produced by vertically incident primaries at high geomagnetic latitude, where

$$dN_\nu/dE_\nu\approx\int Y_\nu\Omega\,(dN_p/dE_p)dE_p.$$

While this expression is not exact for a three-dimensional cascade, it compares simply with the one-dimensional calculations. The near-vertical neutrino flux is also insensitive to zenith angle. Because, if not supressed by geomagnetic cut-off, the primary cosmic rays have a steep power-law spectrum, the main contribution to the low-energy neutrino flux is from primary cosmic rays just above the pion-production threshold energy. The total flux is therefore very sensitive to geomagnetic cut-off [6].

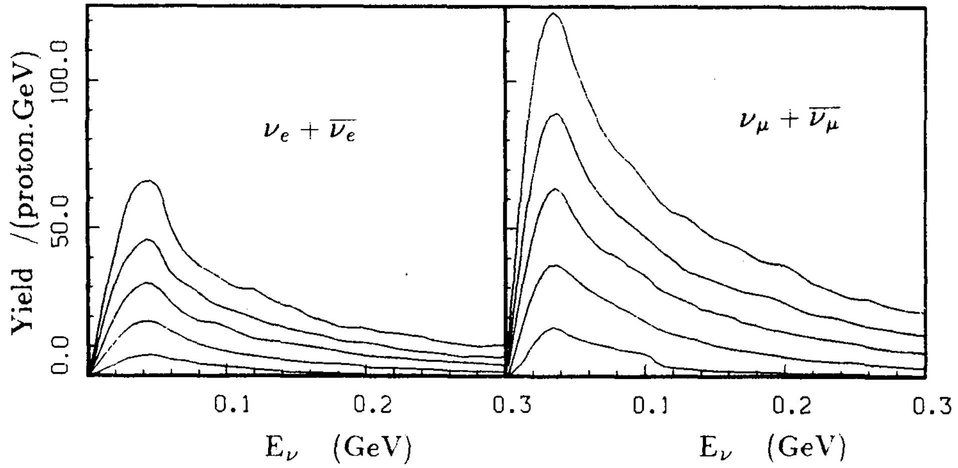

Fig. 1. Integrated neutrino yields from vertically incident protons. 2 5 10 20 50 GeV cases from bottom to top.

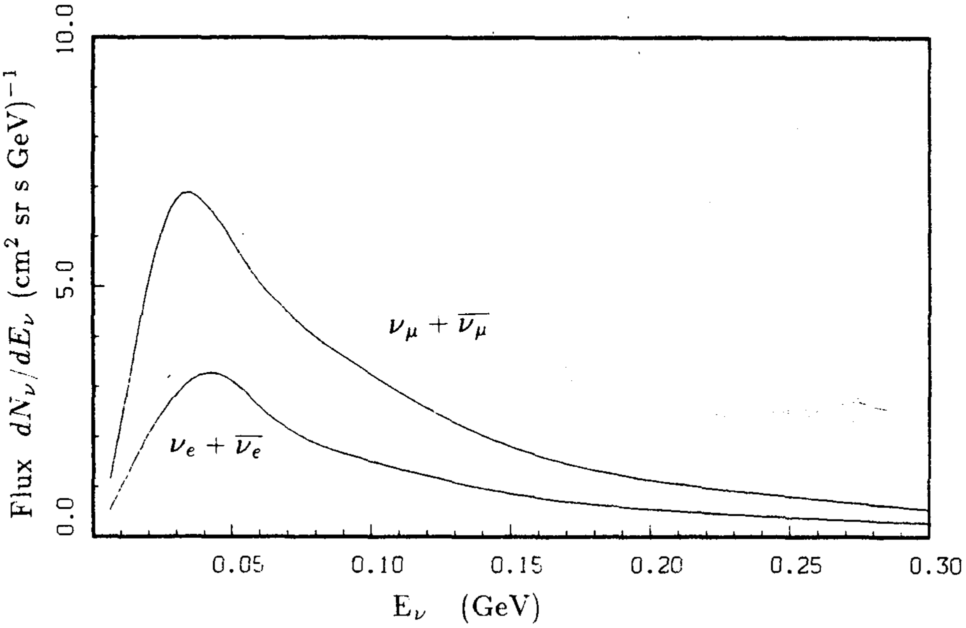

Fig. 2. Calculated downward neutrino flux at high geomagnetic latitude

For neutrinos above $E_\nu$=200 MeV, this three-dimensional calculation agrees with earlier one-dimensional calculations [1,2]. At lower energies ($E_\nu$< 50 MeV), however, we now obtain neutrino fluxes significantly lower than those one-dimensional calculations would give.

This atmospheric neutrino background is totally negligible compared to the solar neutrino flux and the flux of neutrinos expected from supernova at any reasonable distance (< $10^3$ Mpc).

Fig.3 shows the average angular deviation of down-going $\nu_e$s of energy $E_\nu$ produced by vertically incident protons of energy $E_p$ =2, 10, 50 GeV. Other neutrino types have similar spectra. While average angular deviation is $20^0\sim 30^0$, neutrino direction at neutrino energy below 50 MeV is near isotropic and a long tail of more energetic neutrinos deviating by $5^0\sim 10^0$ is produced at $E_\nu$> 200 MeV.

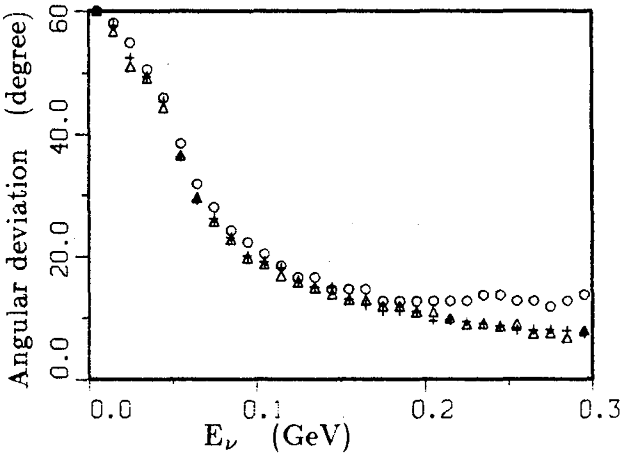

Fig. 3. $\nu_e$ angular deviation from primary proton.
2 GeV (○), 10 GeV (△), 50 GeV (+) cases.

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