Atmospheric Neutrinos Observed in Underground Detectors

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1. Introduction

Atmospheric neutrinos are produced when the primary cosmic ray beam hits the atmosphere and initiates atmospheric cascades. Secondary mesons decay and give rise to neutrinos. We have calculated the neutrino production and compare our predictions with the neutrino fluxes detected in underground detectors. Such a comparison will provide knowledge about the neutrino background for nucleon decay and for extraterrestrial neutrinos.

There are two ways to detect neutrinos in underground detectors: direct neutrino interaction within the volume of the detector (contained neutrino events) and detection of muons produced in a neutrino interaction in the rock surrounding the detector (neutrino induced muon).

Contained neutrino events are characterized by observation of an interaction within the fiducial volume of the detector when the incoming particle is not observed. The reconstruction of the event gives the energy and in some cases the flavor of the interacting neutrino. Because of the large angle between the neutrino and the produced lepton in quasielastic collisions at low energy the determination of the angle of the incoming neutrino is restricted in principle. Both the neutrino flux and the containment requirement restrict the energy of the neutrinos observed in contained interactions to less than several GeV. Our detailed calculations of neutrino fluxes emphasize this low energy region, though we have calculated fluxes up to 1000 GeV at specific angles to compare with earlier calculations.

Neutrinos interact with the rock surrounding the detector but only muon neutrino interactions can be observed, as the electron energy is dissipated too fast in the rock. The direction of the neutrino is preserved quite well in the interaction and at energies above 1 TeV the angular resolution is restricted mainly by the scattering of the muon in the rock. An energy measurement is, however, impossible and the muon rate reflects the neutrino spectrum above some threshold energy, determined by the detector efficiency for muons.

Contained Neutrino Events

All primary nucleons with energy above the production threshold contribute to the flux of neutrinos, which produce contained events. The low energy primary flux is subject to modulation while penetrating both the solar and terrestrial magnetospheres. Thus the intensity and the energy spectrum of the primary beam is different for each direction at each location at each epoch of the solar cycle.

We have calculated the flux of atmospheric neutrinos as

$$\frac{dN_\nu}{dE_\nu} = \int_{E_\nu}^{\infty} dE_o\, Y(E_\nu, E_o, \theta)\Omega(E_o, \theta, \phi)\frac{dN}{dE_o} \tag{1}$$

where $Y(E_\nu,E_o,\theta)$ is the yield of neutrinos in an atmospheric cascade generated by a primary cosmic ray of energy E_o incident at zenith angle θ. Ω is the geomagnetic cut-off and dN/dE_o is the flux of primary nucleons. For each primary energy and zenith angle we made a Monte Carlo simulation of atmospheric cascades and recorded the energy distribution of the four types of neutrinos. The program follows the secondary particles and their interactions down to the neutrino threshold energy in a realistic atmospheric model, accounting in detail for the decay kinematics and the energy loss of the charged particles. The major approximation of the calculation is its linearity, which does not affect significantly the neutrino fluxes above 50 MeV and the angular distribution above 200 MeV.

The interaction model is based on a parametrization of hadron-nucleus collisions and is tuned to fit the available data in both the GeV and TeV regions. The main features of the interaction model include: (a). Leading hadron elasticity skewed toward small values; (b). Energy dependent hadronic cross-sections, both around the production threshold and at high energy; (c). Energy dependent K/π ratio. Details of the model as well as comparison with data are discussed in Ref. 1.

The event rate due to the neutrino flux is

$$Rate = \sum_i \int_{E_i} \int_{E_\nu} dE_i \, dE_\nu \frac{dN_\nu}{dE_\nu} \frac{d\sigma_i}{dE_i} \epsilon_i(E_i) \tag{2}$$

where $d\sigma_i/dE_i$ is the cross-section for $\nu_i + N \rightarrow l_i + X$ with visible energy E_i in the detector and ϵ_i is the corresponding efficiency.

A correct calculation of the neutrino rates thus requires a proper knowledge not only of the neutrino cross-section, but also of the energy threshold and the efficiency of each detector, which are obtainable only through an extensive Monte Carlo study of the detector properties. Such studies have been performed for the detectors with significant neutrino statistics.[2,3]

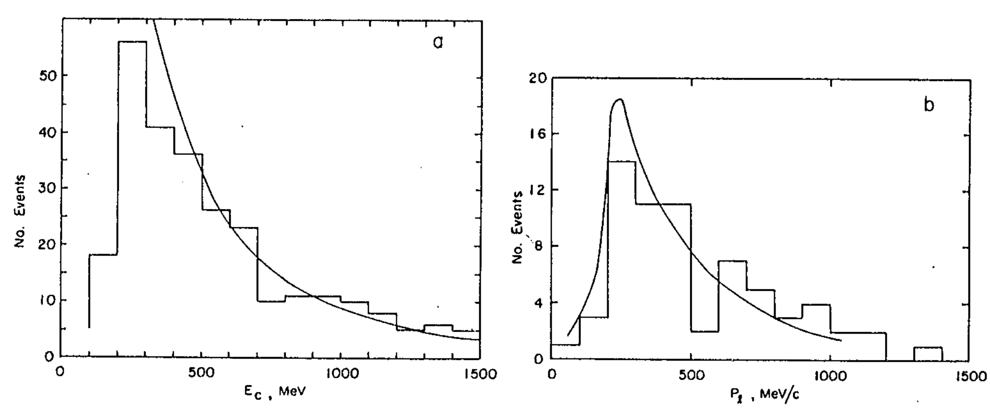

Fig. 1. Comparison of the calculated lepton energy spectrum in quasielastic neutrino interactions with data. In the case of IMB (a) the histogram shows Cherenkov energy distribution ($E_c = E_e$ for electrons and $E_c = E_\mu$ - 200 MeV for muons) for neutrino interactions with assymetry > 0.6. The Kamioka data[3] show the lepton energy distribution in single ring events.

Even without a detector Monte Carlo, however, we can compare the detected lepton energy spectrum to our prediction for quasielastic neutrino interactions for lepton energies above 100 MeV, where neutrino cross-sections on bound nucleons are not drasticly different from the free nucleon cross sections. The comparison for the IMB and Kamiokande detectors is shown in Fig.

1[a,b]. A more detailed comparison would require accounting for the detector efficiency, which is estimated to be 80 per cent for IMB[4]. There appears to be a lack of leptons at Kamioka at energies below 300 MeV, which comes from the low number of electrons detected in this region.

Neutrino Induced Muons.

The flux of muons produced by interactions of ν_μ with energy E_ν in the surrounding rock is

$$\frac{dN_\mu}{dE_\mu dE_\nu} = N_A \int_0^\infty dX \int_{E_\mu}^{E_\nu} dE_\mu' g(X,E_\mu,E_\mu') \frac{d\sigma}{dE_\mu'} \frac{dN_\nu}{dE_\nu} \tag{3}$$

where $g(X,E_\mu,E_\mu')$ is the probability that a muon starts with energy E_μ' and ends up with energy E_μ after propagating a distance X in rock. Because the muon production cross-section and range both increase in proportion to the energy up to a several TeV, muons are produced by neutrinos with a large range of energies. On average the correlation between the neutrino and lepton direction is quite good. The dependence of the flux of neutrino induced muons on the detection energy threshold is remarkably small.

At high energies our neutrino fluxes are in very good agreement with previous work, which use the kinematic relations between production of muons and neutrinos and the measured muon flux as a normalization. The most detailed of these is the one by Volkova [5], who gives the angular dependence of the neutrino fluxes up to very high energy. We have used Volkova's high energy neutrino fluxes to calculate the rates of neutrino induced muons as a function of the muon energy and angle. The comparison with experimental results is shown on Fig. 2.

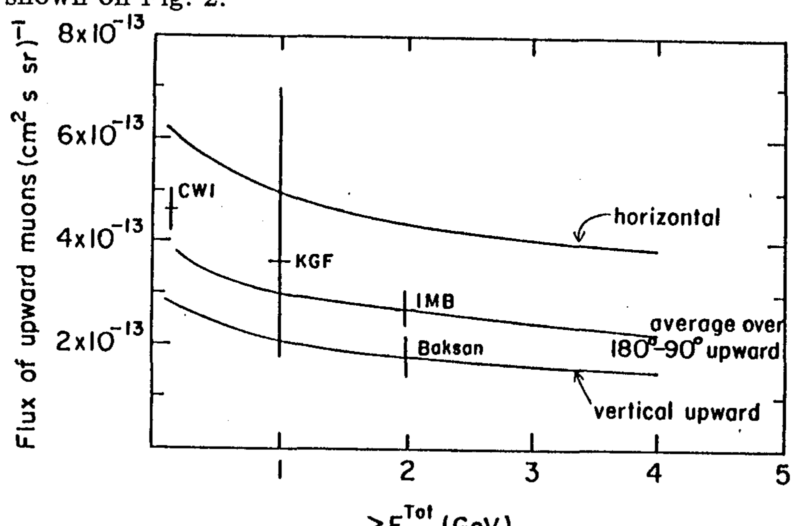

Fig. 2. Comparison to data on upward muons. CWI[6] and KGF[7] data are horizontal, Baksan[8] - vertical and IMB[9] is averaged over all $\theta > 90°$.

Discussion and Conclusions

The absolute and relative rates and the energy distribution of the contained neutrino events, as well as the fluxes of neutrino induced muons, are fully consistent with the predicted neutrino fluxes of atmospheric origin. The uncertainty of the absolute normalization of our calculation is 10 to 20 per cent. On the basis of the observed rates alone one cannot exclude the possibility that a similar fraction of events has a more exciting origin - nucleon decay candidates or extraterrestrial neutrinos.

The agreement between the predicted and observed angular and energy distributions, however, suggests that the majority of detected neutrinos are of atmospheric origin and leaves little room for point neutrino sources. The identification of nucleon decay candidates requires a better knowledge of the neutrino-nucleus cross-sections and interaction properties.

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