Computation of atmospheric neutrino production*

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Abstract

Atmospheric neutrinos are created by the interactions of primary comic rays, mainly composed by protons, with the nuclei in the atmosphere. The energy spectrum of cosmic rays, from 200 MeV up to about 10^{20} eV, is approximately proportional to a power-law $E^{-\alpha}$. We computed atmospheric neutrinos flux from about 1 GeV to about 1 TeV, whose cosmic ray flux is sufficiently high to generate an observable flux of atmospheric neutrinos. After, we compared the results with numerical calculations and we accomplished good agreement with semi-analytical methods. As an original work, we extended the calculations including a neutrino-neutrino-scalar vertex that it will modify the rate of neutrino production compared with Standard Model prediction. We observe that this new interaction have a equal production of electron and muon neutrinos that in principle can be tested in present and future atmospheric neutrino experiments.

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INTRODUCTION

We start with a differential flux of protons given by

$$\phi_N(E) \simeq \phi_N(E = 1\text{GeV}) \left(\frac{E}{\text{GeV}}\right)^{-\alpha} \tag{1}$$

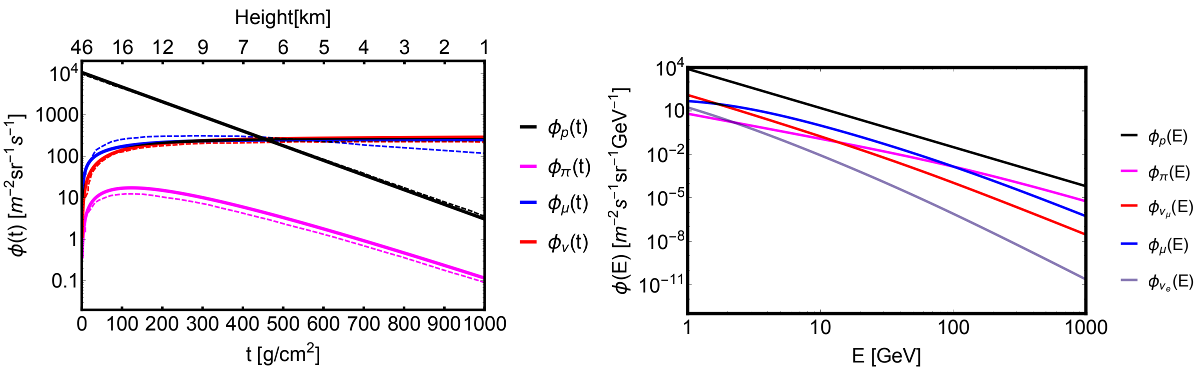
where $\phi_N(E = 1\text{GeV}) \simeq 1.8 \times 10^4 \frac{\text{nucleons}}{\text{m}^2 \text{ sr s GeV}}$ and $\alpha = 2.7$ to describe the processes of absorption, scattering and decay of secondary particles produced until neutrino creation. In a one-dimensional approximation, the evolution in the atmosphere of the flux ϕ_j of a cosmic ray of type j is given by the cascade equation [1].

$$\frac{\phi_j(E,t)}{dt} = -\frac{\phi_j(E,t)}{\lambda_j(E)} - \frac{\phi_j(E,t)}{d_j(E,t)} + \sum_k S_{k\to j}(E,t), \tag{2}$$

where t is so-called *slant depth*, measured in units of g/cm^2. $\lambda_j(E)$ in g/cm^2 is the *interaction length* which describes the disappearance of the particle j due to interactions with atmosphere, $d_j(E,t)$ describes the decay of the particle in g/cm^2 and it is called *decay length* and $S_{k\to j}(E,t)$ describes the generation of a secondary particle j due to the interaction of a particle k with atmosphere (*source term*). We use the Cascade Equation (2) to compute flux of particles in the atmosphere, using a power law for the initial protons, to describe evolution of the proton flux in function of energy and slant depth. Proton interactions resulted in pions, which are the most light and abundant mesons produced in this interactions. Pions decay into neutrinos and charged leptons, mainly muons, which decay into electrons and neutrinos.

RESULTS

The results are in Figure (1). In Figure (1a), we compare the calculations with the work of Gaisser *et al* who use the same proton flux as input, but performed numerical calculations. We digitalized the curves from Ref.[2] and compare with our results for the particles: proton (which is the same for both calculations), pion, muon and muon neutrino fluxes. The dashed and solid curves are for Gaisser *et al* and our work, respectively. We accomplish a reasonably good agreement for neutrino fluxes and less for muons and pion fluxes. In Figure (1b), we show our results for the energy dependence. Notice that all energies the flux of muon neutrinos is bigger than electron neutrinos. In our computation there is a equality between neutrino and antineutrino fluxes.



(a) (b)

FIG. 1: (a) Integral fluxes of cosmic rays with $E > 1$ GeV as a function of the slanth depth. (b) Energy spectra of particles produced in the atmosphere at slant depth $= 100$ g/cm^2 due to a primary proton with a power-law energy spectrum.

Since we have the particle energy spectra (with only interactions of Standard Model), we will observe how the neutrino flux changes if we consider an exotic decay in the flux.

MAJORON COUPLING AND $\pi \rightarrow l\nu\chi$ DECAY CHANNEL

Majoron (χ) is a massless Goldstone boson that arises in extended gauge theories that have spontaneous symmetry breaking. The Yukawa coupling of majoron to neutrino is given by [3]

$$\mathcal{L}_{\nu\chi} = \frac{1}{2} \sum_{ll'} g_{ll'} \overline{\nu_l} (i\gamma^5 \chi) \nu_{l'} \tag{3}$$

where $g_{ll'}$ is the majoron-neutrino coupling, $\overline{\nu_l}$ and $\nu_{l'}$ are neutrino spinors, and l, l' go over e, μ and τ. Majoron has not been observed yet, but majoron theory can be tested if we consider exotic decays with majoron as final particle and evaluate the branching ratio between exotic and known process to constrain the limits of $g_{ll'}$ coupling constant. As pion decay is the main source of neutrinos in Earth atmosphere, we calculated the exotic process $\pi \rightarrow l\nu\chi$ and compare with conventional decay to observe the changes in the process with majoron addition. The result is shown in Figure (2).

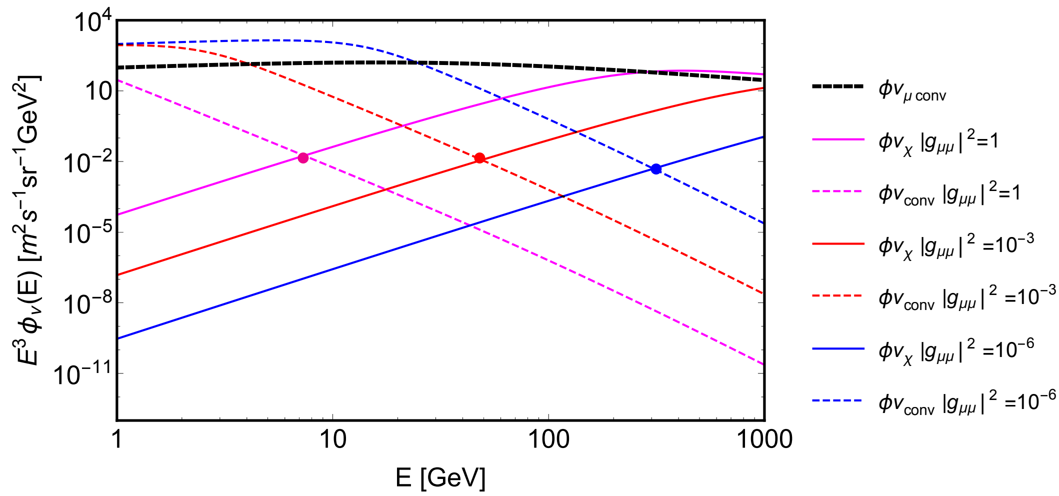


FIG. 2: Energy spectra of neutrinos from pion decay. Dashed lines are the neutrino fluxes from pion conventional decay, now normalized by the two channels: $\Gamma_{\pi\rightarrow\mu\nu} + \Gamma_{\pi\rightarrow\mu\nu\chi}$. Black dashed line is neutrino flux with no majoron emission (spectrum in Fig. 1b) and solid lines are neutrino flux from majoron emission to three different values for $|g_{\mu\mu}|^2$. Dots show the energies which conventional and exotic flux are identical.

We see that the renormalized fluxes depend on energy and coupling constant $|g_{\mu\mu}|^2$, so it is possible put limit on it by observing in which energies the exotic flux start to be significant and compare with experimental data provided i.e. by *ICECUBE* and *SuperKamiokande*.

CONCLUSIONS

In this work, we concluded that using semi-analytical method for calculating atmospheric neutrino flux we had a good agreement with numerical results, that it is time consuming. We also compute the contribution the exotic decay channel for pion decay and we compare with the conventional one. We have found that we have appreciable changes in the muon neutrino flux that for higher enough energies most of neutrinos came from this exotic decay. From this we can put a limit on $|g_{\mu\mu}|^2$ coupling from the atmospheric neutrino data from ICECUBE and SuperKamiokande experiment.

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