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High-energy neutrino fluxes and flavor ratio in the Earth's atmosphere

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We calculate the atmospheric neutrino fluxes in the energy range 100 GeV–10 PeV with the use of several known hadronic models and a few parametrizations of the cosmic-ray spectra which take into account the knee. The calculations are compared with the atmospheric neutrino measurements by Frejus, AMANDA, IceCube, and ANTARES. An analytic description is presented for the conventional $(\nu_\mu + \bar{\nu}_\mu)$ and $(\nu_e + \bar{\nu}_e)$ energy spectra, averaged over zenith angles, which can be used to obtain test data of the neutrino event reconstruction in neutrino telescopes. The sum of the calculated atmospheric ν_μ flux and the IceCube best-fit astrophysical flux gives the evidently higher flux as compared to the IceCube59 data, giving rise the question concerning the hypothesis of the equal flavor composition of the high-energy astrophysical neutrino flux. Calculations show that the transition from the atmospheric electron neutrino flux to the predominance of the astrophysical neutrinos occurs at 30–100 TeV if the prompt neutrino component is taken into consideration. The neutrino flavor ratio, extracted from the IceCube data, does not tend to increase with the energy as is expected for the conventional neutrino flux in the energy range 100 GeV–30 TeV. A depression of the ratio R_{ν_μ/ν_e} possibly indicates that the atmospheric electron neutrino flux obtained in the IceCube experiment contains an admixture of the astrophysical neutrinos in the range 10–50 TeV.

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I. INTRODUCTION

High-energy neutrinos produced in decays of pions, kaons, and charmed particles of the extensive air shower, induced by cosmic rays passing through the Earth's atmosphere, form an unavoidable background for the detection of astrophysical neutrinos. Sources of extra-terrestrial high-energy neutrinos is the challenge to solve which the large-scale neutrino telescopes, NT200+ [1], IceCube [2–4], ANTARES [5,6] are designed. The high-energy atmospheric neutrinos became accessible for experimental studies only in recent years. The energy spectrum of high-energy atmospheric muon neutrinos has been measured in the following four experiments: Frejus [7] at energies up to 1 TeV, AMANDA-II [8] in the energy range 1–100 TeV, IceCube [2,9] at 100 GeV–575 TeV, and ANTARES at energies 100 GeV–200 TeV [5]. Not long ago, IceCube also presented results for the electron neutrino spectrum measured in the energy range ~80 GeV–6 TeV [10]. Thus, a possibility appeared for evaluating the neutrino flavor ratio using the IceCube measurements and comparing this one with predictions.

Lately IceCube found the 37 high-energy neutrino events [11–13] in the energy range 30 TeV–2 PeV, most of which are hardly consistent with events expected from the atmospheric muons and neutrinos, 8.4 ± 4.2 and $6.6^{+5.9}_{-1.6}$, respectively. The neutrino events, three of which have energies above 1 PeV, were detected over the three years 2010–2013 (988 days), give the statistical significance of their astrophysical origin at the level of 5.7σ.

After the IceCube reported [11] on the detection of the first two neutrino-induced events with deposited energy 1.04 and 1.14 PeV, the prompt analysis of the origin of the highest energy neutrinos ever detected was performed [14–21].

Increasing with energy contribution of charmed particles to the atmospheric neutrino flux becomes the source of the large uncertainty at energies above ~200 TeV for muon neutrinos and above ~20 TeV for electron neutrinos. A more complicated picture is likely if the astrophysical neutrinos and the atmospheric conventional or prompt ones are entangled. It is quite possible that astrophysical neutrino flux becomes dominant over the atmospheric electron neutrino flux at energies 20–50 TeV. Thus, a comparison of atmospheric neutrino spectra calculated for various hadron-interaction models with high-energy neutrino spectra measurements can shed light on the most uncertain constituent of the atmospheric neutrino background, in spite of large statistical and systematic uncertainties.

Here we calculate atmospheric neutrino fluxes at energies $10^2 - 10^7$ GeV for zenith angles from 0° to 90° as well as the angle-averaged spectrum with the use of high-energy hadronic interaction models QGSJET II-03 [22] and SIBYLL 2.1 [23]. These models are widely employed to simulate extensive air showers (EAS) with the Monte Carlo method and were also applied to compute the cosmic-ray

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