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High-Energy Spectra of Atmospheric Neutrinos

O. N. Petrova[a], *, T. S. Sinegovskaya[b], **, and S. I. Sinegovsky[a], ***
[a] Irkutsk State University, Irkutsk, 664003 Russia
*e-mail: *redponick@gmail.com, ***sinegovsky@api.isu.ru*
[b] Irkutsk State Railway University, Irkutsk, 664074 Russia
***e-mail: tanya@api.isu.ru*

Abstract—A calculation of the atmospheric high-energy muon neutrino spectra and zenith-angle distributions is performed for two primary spectrum parameterizations (by Gaisser and Honda and by Zatsepin and Sokolskaya) with the use of QGSJET-II-03 and SIBYLL 2.1 hadronic models. A comparison of the zenith angle-averaged muon neutrino spectrum with the data of Frejus, AMANDA-II, and IceCube40 experiments makes it clear that, even at energies above 100 TeV, the prompt neutrino contribution is not apparent because of the considerable uncertainties of the experimental data in the high-energy region.

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High- and ultrahigh-energy neutrinos produced in decays of muons, pions, kaons, and charmed particles of an extensive air shower caused by cosmic rays in the earth's atmosphere make up an irremovable background for the detection of astrophysical neutrinos: an important problem that might be addressed using the large NT200+ [1], ANTARES [2], and IceCube40 [3] deep-water telescopes. It was not until recently that the region of high and ultrahigh energies has become open to an experimental investigation of atmospheric neutrinos. As of now, the energy spectrum of high-energy atmospheric muon neutrinos has been measured with three facilities: Frejus [4] at energies up to 1 TeV, AMANDA-II [5] in the energy range 1–100 TeV, and IceCube40 [3] in the range 100 GeV to 400 TeV. The increasing contribution to the neutrino flux at energies above 100 TeV must come from decays of charmed particles (the source of the largest uncertainty). Therefore, a comparison of the calculation for various hadron-interaction models with neutrino spectrum measurement results is of interest despite large statistical and systematic experimental errors in the high-energy region.

In the present paper, we calculate atmospheric neutrino fluxes at energies $10–10^7$ GeV for zenith angles from 0° to 90° and the zenith angle-averaged energy spectrum with the use of SIBYLL 2.1 [6] and QGSJET-II-03 [7] hadron-interaction models, which are widely employed for simulating extensive air showers (EASs) following the Monte Carlo method and were also used to calculate cosmic-ray hadron and muon fluxes [8]. A calculation has been performed for two parameterizations of the experimentally measured spectrum and the composition of primary cosmic rays. The model by Zatsepin and Sokolskaya (ZS) [9] describes data of ATIC-2 direct measurements in the range $10–10^7$ GeV well [10] and gives a motivated extrapolation of these data onto an energy region up to 100 PeV, where the spectrum and composition are reconstructed on the basis of the measured characteristics of EASs. The other version used is the well-known parameterization of primary cosmic-ray spectrum and composition by Gaisser and Honda (GH) [11] (a version with a high content of helium nuclei). Both models are consistent with the KASCADE experiment data [12].

A comparison of the calculated spectra of $\nu_\mu + \bar{\nu}_\mu$ from (μ, π, K) decays (averaged over zenith angle) with the data obtained at the Frejus, AMANDA-II, and IceCube49 facilities is shown in Figs. 1 and 2. The distinction between the GH and ZS primary spectra becomes apparent after 100 TeV, where the neutrino flux is affected by the kink of the cosmic-ray primary spectrum (Fig. 1). At 1 PeV, the designed neutrino flux for the GH spectrum is five times as great as the flux for the ZS spectrum. The predicted neutrino fluxes obtained using the SIBYLL 2.1 hadron-interaction model is half that of the predictions of the QGSJET-II-03 model (Fig. 2).

The combined spectrum of ordinary and direct neutrinos calculated with QGSJET-II-0.3 and the quark–gluon string model (QGSM) [13] describes the IceCube40 data well enough (Fig. 3). The QGSM-predicted muon neutrino fluxes in the range 200–400 TeV do not violate the limitation on the diffuse flux of astrophysical neutrinos ($7.2 \times 10^{-9}\, E^{-2}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}) determined by IceCube59 [14] for an energy range from 160 TeV to 40 PeV. Unlike the QGSM, the recombination quark–parton model (RQPM in Fig. 3) predicts an overrated muon neutrino flux inconsistent with the spectrum measured in the IceCube40 experiment.

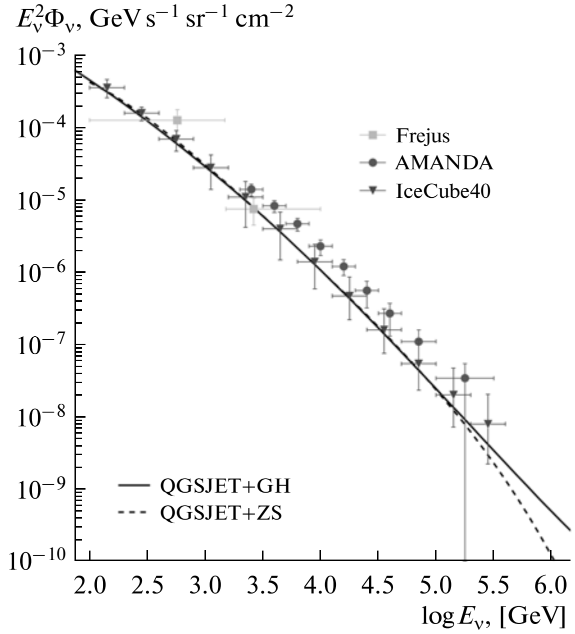

Fig. 1. Zenith angle-averaged atmospheric $\nu_\mu + \bar{\nu}_\mu$ flux, depending on the primary cosmic-ray spectrum. Dots are the data of the Frejus, AMANDA-II, and IceCube40 experiments.

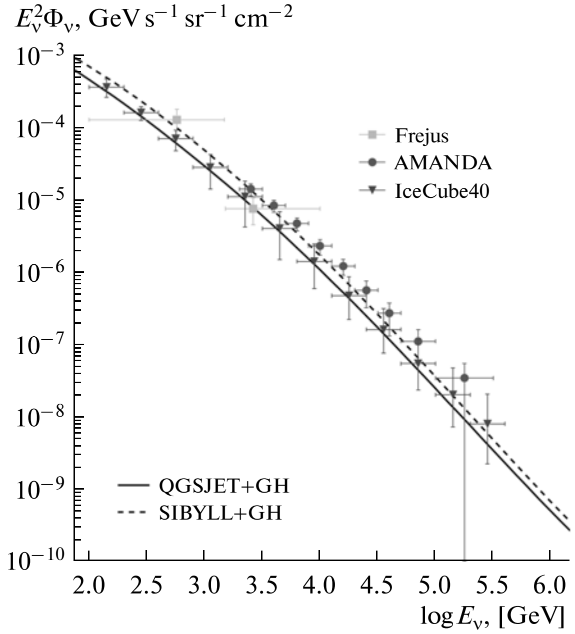

Fig. 2. The zenith angle-averaged energy spectrum of $\nu_\mu + \bar{\nu}_\mu$, depending on the hadron-interaction model.

Thus, the calculated spectra of muon neutrinos showed a weak dependence on the spectrum model and composition of primary cosmic rays in the range 10–10^5 GeV, which ignores the cosmic-ray spectrum kink. However, the use of the QGSJET-II and SIBYLL 2.1 hadron-interaction models in this energy region results in a pronounced distinction in fluxes of neutrinos, the major source of which at energies up to 100 TeV is likely to be kaon production processes. However, at higher energies uncertainties appear due to the production cross sections of charmed particles.

A comparison of the predicted muon neutrino flux with the IceCube40 measurements shows that the QGSJET-II-03 model is more preferable. Taking into account the contribution of direct neutrinos within the quark–gluon string model (QGSM) leads to an improved agreement between the calculation and experiment. The upper limit on the diffuse fluxes of astrophysical neutrinos, determined by the IceCube59 [14] for the range from 160 TeV to 40 PeV, allows limitations on the charmed-particle production models. The quark–gluon string model is not in conflict with this limit; however, the prediction of direct neutrinos within the recombination quark–parton model (RQPM) lacks support.

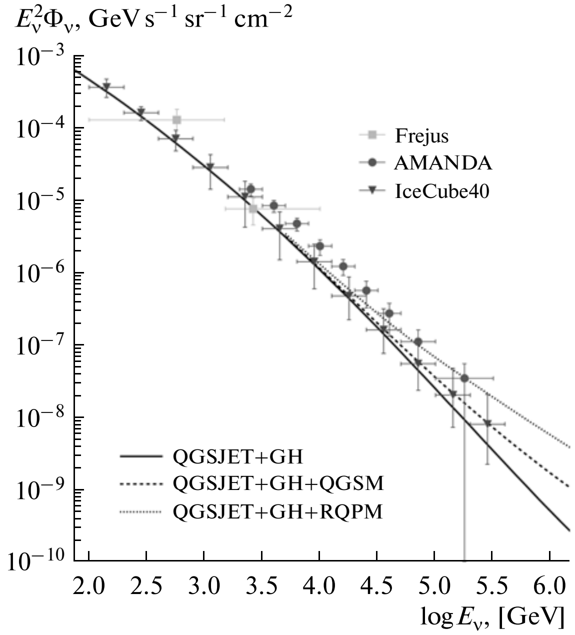

Fig. 3. Fluxes of muon neutrinos from (μ, π, K, D) decays. Experimental data from Frejus, AMANDA-II, and IceCube40. Calculations for ZS primary spectrum: the solid line is ordinary neutrinos (from (μ, π, K) decays), the dotted line is the sum of ordinary neutrinos and neutrinos from charm within the RQPM, and the dashed line is the same but for “direct” neutrinos in QGSM.

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