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Zenith Angular Distributions of Atmospheric High-energy Neutrinos

A. A. Kochanov[a], **T. S. Sinegovskaya**[b], **and S. I. Sinegovskii**[c]
[a] *Institute of Solar Terrestrial Physics, Siberian Branch, Russian Academy of Sciences, Irkutsk, Russia*
[b] *Irkutsk State University of Means of Communication, Irkutsk, Russian*
[c] *Irkutsk State University, Irkutsk, Russia*

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Abstract—In this paper, we present a new calculation of the atmospheric neutrino flux in the energy range 10–10^7 GeV, which reveals sizable differences in muon neutrino flux predictions obtained with known hadronic models. The calculation is based on the method of solving nuclear cascade equations in the atmosphere, which takes into account the nonscaling behavior of inclusive cross sections for particle production, the increase in the total inelastic hadron–nucleus cross sections, and the non-power-law character of the primary cosmic ray spectrum. The efficiency of the method was recently tested in atmospheric muon flux calculations. The results of neutrino spectrum calculations have been compared with Frejus, AMANDA-II, and IceCube measurement data.

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INTRODUCTION

Atmospheric neutrinos are generated in the decays of charged pions, charged and neutral kaons, and 1 other heavier mesons and barions generated when cosmic rays interact with atomic nuclei of the Earth's atmosphere. Atmospheric neutrino fluxes in a wide energy interval have remained an object of heightened interest over the last two decades: in the comparatively low-energy region, a deficiency of muon neutrinos was discovered, which is interpreted as a manifestation of the neutrino oscillation effect (conversion of ν_μ to another type); high- and ultra-high-energy neutrinos represent an ineradicable background in the detection of neutrinos from remote astrophysical sources. Detection of high-energy neutrinos of galactic and extragalactic origin is a major problem in astrophysics; in order to solve it, in the last decade, the ÍÒ200+ (Aynutdinov et al., 2006; Aynutdinov et al., 2009), AMANDA-II (Achterberg et al., 2007; Ackermann et al., 2008; Abbasi et al., 2009, 2010), and ANTARES (Margiottaet al., 2009) large deep-water neutrino telescopes have been created. Construction is being completed on the new-generation giant IceCube detector (Berghaus et al., 2009) with an effective volume on the order of a cubic kilometer; other scale detectors (Km3NeT, NEMO, etc.) are also being designed.

Study of the atmospheric neutrino background is part of the problem of searching for astrophysical neutrinos and an essential problem both for experimenters (measuring the background is the first step, necessary also for debugging a neutrino telescope and developing techniques for reconstructing events from a neutrino flux, comparatively well studied only in energy regions of up to 1 TeV), as well as for theorists investigating the possible mechanisms for atmospheric neutrino generation and making atmospheric quantitative predictions of the energy spectrum and zenith-angular neutrino distributions in a wide energy range.

Despite the large number of published works with calculations of atmospheric neutrino spectra (see, e.g., Volkova, 1980; Buktevich, et al., 1989; Lipari, 1993; Naumov et al., 1998; Fiorentini et al., 2001: Barr et al., 2004; Honda et al., 2004; Enberg et al., 2008; Kochanov et al., 2009), as well as reviews (Naumov, 2002; Gaisser and Honda, 2002) of one-dimensional and three-dimensional calculations of an atmospheric neutrino flux, it remains obscure how large the differences are caused by the uncertainties of existing models of hadron–nuclear collisions at high energies, i.e., in the region where there are no direct measurements of particle interaction cross sections. Also unclear are the uncertainties caused by ambiguity in reconstructing the spectrum and composition of primary cosmic rays in the "knee" region based on experimental data from installations that record wide atmospheric showers.

The high and ultra-high-energy region has only now become accessible to experimental study. At present, the energy spectrum of atmospheric muon neutrinos in the AMANDA-II experiment is measured in the energy interval of 1–100 TeV (Achterberg et al., 2007; Ackermannet al., 2008; Abbasi et al., 2009, 2010); earlier, neutrino spectra were measured in the Frejus experiment at energies of up to 1 TeV (Daum et al., 1995). Preliminary results of processing the data obtained at the IceCube installation in the energy interval of 10^2–3×10^6 GeV are now being published (Chirkin et al., 2009; Montaruli, 2009). The main contribution to a neutrino flux near the upper boundary of the specified interval should give decays of

Table 1. z_{pc} moments calculated for $\gamma = 1.7$

Model	QGSJET II-03			SIMBYLL 2.1			KM		
E_0, Gev	10^2	10^3	10^4	10^2	10^3	10^4	10^2	10^3	10^4
z_{pp}	0.174	0.198	0.205	0.211	0.209	0.203	0.178	0.190	0.182
z_{nn}	0.088	0.094	0.090	0.059	0.045	0.043	0.060	0.060	0.052
$z_{p\pi^+}$	0.043	0.036	0.033	0.036	0.038	0.037	0.044	0.046	0.046
$z_{p\pi^-}$	0.035	0.029	0.028	0.026	0.029	0.029	0.027	0.028	0.029
z_{pK^+}	0.0036	0.0036	0.0034	0.0134	0.0120	0.0097	0.0051	0.0052	0.0052
z_{pK^-}	0.0030	0.0028	0.0027	0.0014	0.0022	0.0026	0.0015	0.0015	0.0015

charmed particles, whose contribution remains the source of the largest uncertainty owing to the insufficient level of studying charm generation processes.

This work presents the results of a new calculation of the energy spectrum of muon neutrinos in the energy range of 10–10^7 GeV for zenith angles from 0° to 90° and angular distributions of fluxes for different energy values. Calculation uses several high- and ultra-high-energy hadron interaction models (SIBYLL 2.1 (Fletcher et al., 1994; Ahn E.-J. et al., 2009), QGSJET-II (Ostapchenko, 2006à,b), and Kimel and Mokhov (KM) parametrization (Kimel and Mokhov, 1974, 1975; Kalinovsky et al., 1989)), which have been checked in recent calculations of cosmic-ray hadron and muon fluxes (Kochanov et al., 2008; Sinegovsky et al., 2010). Results of calculating neutrino fluxes are compared both with the data of the Frejus, AMANDA-II, and IceCube experiments, and with calculations in recent years.

CALCULATION METHOD AND MODEL OF HADRON–NUCLEAR COLLISIONS

Calculation is performed based on a method (Naumov and Sinegovskaya, 2000) for solving hadron–nuclear cascade equations, which in general make it possible to consider the nonpower character of the primary spectrum of cosmic rays, scaling violation of particle-generation cross sections, and increase with the energy of total inelastic cross sections of hadron–nuclear collisions (see also (Kochanov et al., 2008, 2009; Sinegovsky et al., 2010)).

As the basic spectrum of primary cosmic rays, we used direct measurement data obtained in the ATIC-2
2 experiment (Panov et al., 2007) and the Zatsepin and
2 Sokolskaya (ZS) model (Zatsepin and Sokolskaya, 2006;
2 Zatsepin and Sokolskaya, 2007), which well describes the
ATIC-2 data in the interval of 10–10^4 GeV and offers motivated extrapolation to an energy range of up to 100 PeV. The ZS model supposes the existence of three classes of galactic cosmic ray sources—supernova explosions and new, different types of flares in which power spectra with different maximum rigidities and spectral indices are generated. Relying on ATIC data to a significant degree, the model makes it possible to describe experimental data on the cosmic ray spectra obtained in direct measurements and to pass to the ultra-high-energy region, where measurements are conducted by the method of wide atmospheric showers. The proton and helium nuclei spectrum in the ZS model at $E > 10^6$ GeV agrees with KASCADE experiment measurements (Antoni et al., 2005; Apel et al., 2009).

The spectrum and composition of primary cosmic rays in the KASCADE experiment have been reconstructed from SHAL measurements using the QGSJET01 and SIBYLL 2.1 interaction models. In additon, in this calculation, the renowned Gaisser et al. parametrization of the spectrum and composition of primary cosmic rays (Gaisser and Honda, 2002; herein, GH) has also been used. We have taken the parametrization version with the so-called high contribution of helium nuclei as that most adequately corresponding to KASCADE experiment data (the version of the spectrum and composition reconstructed according to the SIBYLL 2.1 model). To visually illustrate differences in the interaction models used in this calculation, it is convenient to compare weighted moments $z_{pc}(E_0)$ with the power spectrum ($\gamma = 1.7$), calculated for proton interactions with atmospheric atomic nuclei $p + A \longrightarrow c + X$:

$$z_{pc}(E_0) = \int_0^1 x^{\gamma} \frac{1}{\sigma_{hA}(E_0)} \frac{d\sigma_{pc}(E_0, x)}{dx} dx,$$

where $x = E_c/E_0$, $c = p, n, \pi^{\pm}, K^{\pm}$.

The obtained values (Table 1) indicate the approximated Feynman scaling of cross sections in the SIBYLL 2.1 and KM models and its soft violation in the QGSJET model for protons and π mesons.

Table 2. Ratio of neutrino fluxes for the SIBYLL 2.1, QGSJET, and KM interaction models calculated for zenith anges of 0° and 90°

E_ν, Gev	1	2	3
Cosmic ray spectrum GH			
10^2	1.65 (1.22)	0.97 (0.85)	1.65 (1.36)
10^3	1.71 (1.46)	0.96 (0.92)	1.73 (1.50)
10^4	1.60 (1.57)	0.96 (0.96)	1.58 (1.55)
10^5	1.54 (1.49)	0.99 (0.96)	1.46 (1.46)
Cosmic ray spectrum ATIC-2+3C			
10^2	1.58 (1.26)	1.00 (0.91)	1.58 (1.38)
10^3	1.64 (1.39)	0.95 (0.92)	1.73 (1.51)
10^4	1.55 (1.46)	0.96 (0.95)	1.61 (1.54)
10^5	1.37 (1.23)	0.91 (0.83)	1.51 (1.48)
10^6	1.10 (0.95)	0.61 (0.55)	1.80 (1.73)
10^7	0.89 (0.75)	0.48 (0.43)	1.85 (1.74)

MUON NEUTRINO FLUXES IN THE EARTH'S ATMOSPHERE

In addition to the main sources of usual muon neutrinos, μ_{e3}-, $\pi\mu_2$-, and $K\mu_2$- decays, we consider the contributions from three-particle semileptonic decays of $K^{\pm}_{\mu 3}$, $K^0_{\mu 3}$ kaons, as well as small contributions of decay chains $K \longrightarrow \pi \longrightarrow \nu_\mu$. The effects of cascade three-dimensionality can be neglected at energies of ($K^0_S \longrightarrow \pi^+\pi^-$, $K^0_S \longrightarrow \pi^{\pm}\pi^0$) $E \geq 1$ GeV for directions close to a vertical, and $E \geq 5$ GeV for directions close to horizontal (see, e.g., (Barr et al., 2004; Honda et al., 2004)).

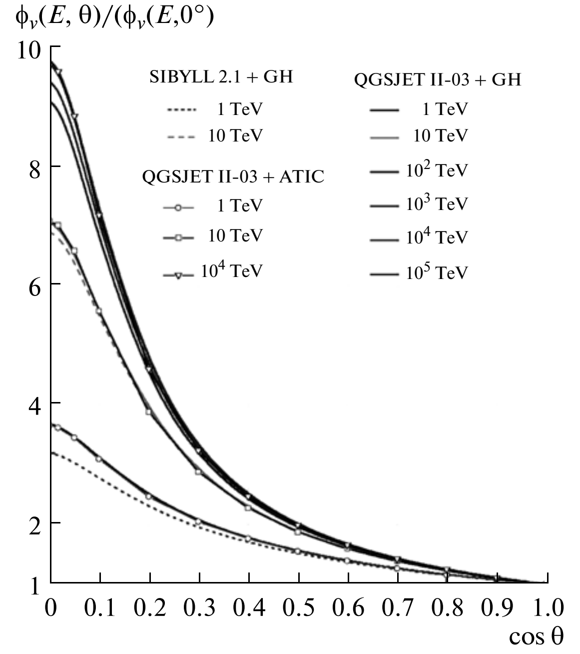

Fig. 1. Zenith-angular distribtions of the total muon and antineutrino fluxes calculated for two hadron–nuclei interaction models.

Table 2 shows the comparison of neutrino fluxes calculated with the three hadron interaction models and two variants of the primary spectrum, as well as the following relations for 0° and 90°:

$$1 - \phi^{(\mathrm{SIBYLL})}_{\nu_\mu}/\phi^{(\mathrm{KM})}_{\nu_\mu},\ 2 - \phi^{(\mathrm{QGSJET})}_{\nu_\mu}/\phi^{(\mathrm{KM})}_{\nu_\mu},$$
$$3 - \phi^{(\mathrm{SIBYLL})}_{\nu_\mu}/\phi^{(\mathrm{QGSJET})}_{\nu_\mu}.$$

Muon neutrino fluxes obtained from the SIBYLL 2.1 and QGSJET-II models (column 3) are obviously different, whereas the KM and QGSJET-II models yield very close results (column 2). At first glance, this is quite unexpected, since calculation of muon fluxes (Kochanov et al., 2008) has demonstrated the closeness of the KM and SIBYLL 2.1 models. From Table 1, however, we can see that the difference in the calculated neutrino fluxes is related to the z_{pK} values, i.e., with the departure of kaons in nucleon–nuclei collisions, a factor that more strongly influences a high-energy neutrino flux than a flux muon with the same energies. Thus, the necessity of careful accelerator research of the processes of strange particle generation at average and high energies is obvious. Figure 1 shows the zenith-angular distributions of atmospheric neutrinos $\phi_{\nu_\mu}(e, \theta)/\phi_{\nu_\mu}(E, 0°)$ for the energy interval of 1–10^5 TeV. Calculations are performed using the QGSJET-II and SIBYLL 2.1 interaction models for two versions of the spectrum and composition of primary cosmic rays (GH and ZS). As expected, the shape of the angular distribution changes with energy (in region to 100 TeV); the energy dependence at large angles is especially significant. The influence of the considered primary spectra and hadron models on the angular distribution of neutrinos at energies above 1 TeV is barely noticeable.

Figure 2 shows the results of our calculation of muon neutrino spectra (lines) in comparison with the calculation (symbols) performed in (Barr et al., 2004) by the Monte Carlo method with the TARGET 2.1 program. Such comparison is interesting, because these two calculations, differing in method and hadron interaction model, have been performed for the same parametrization of the spectrum and nuclear composition of primary cosmic rays (GH) (Gaisser and Honda, 2002). As can be seen from the figure, our predictions of the neutrino spectrum for two hadron interaction models, QGSJET-II and KM, agree well with the results of the TARGET program in a wide energy interval of 10–10^4 GeV for directions close to horizontal. For directions close to vertical, there is agreement for a narrower energy interval of $E_\nu < 400$ GeV.

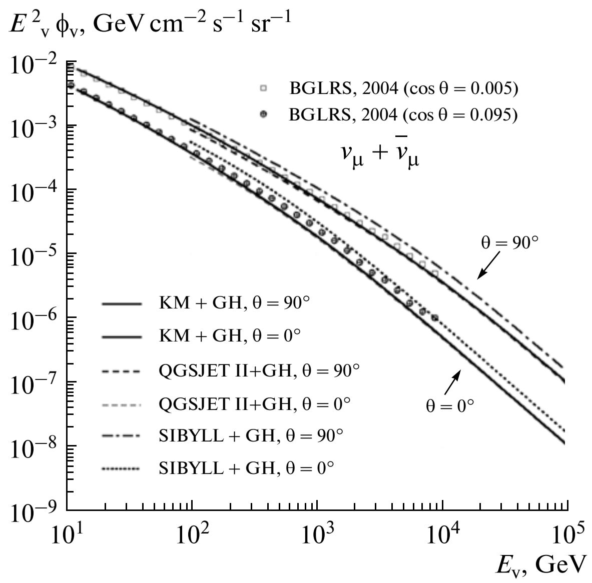

Fig. 2. Two independent calculations for muon neutrino fluxes for the primary spectrum and composition of the GH model (Gaisser and Honda, 2002).

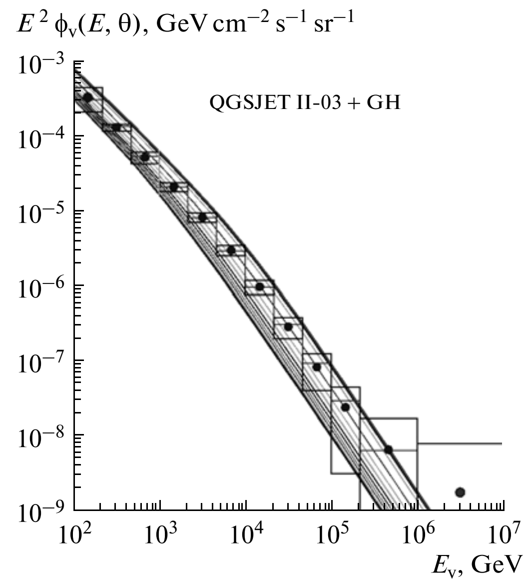

Fig. 3. Atmospheric neutrino flux for different zenith angles. Points are prelimary results of measuring the spectrum of muon neutrinos at the IceCube installation, averaged over zenith angle (Chirkin et al., 2009.

Figure 3 shows the comparison of fluxes calculated for different zenith angles of atmospheric neutrinos ($\nu_\mu + \bar{\nu}_\mu$) (from μ, π, and K decays) with the preliminary results of the IceCube experiment. Curves (for cosθ = 0–1.0, top to bottom) are calculation for the primary spectrum and GH composition using the QGSJET-II interaction model. Points with uncertainties in the spectrum and neutrino energy represent the IceCube data (Chirkin et al., 2009) averaged over the an zenith angle (see also (Montaruli, 2009)).

Figure 4 compares the calculated neutrino spectra with AMANDA-II data (Achterberg et al., 2007). Results of calculating the spectra for both usual neutrinos (from μ, π, and K decays) and direct generation neutrinos (from charmed particle decays) are shown. A flux of atmospheric π and K neutrinos has been calculated with the QGSJET-II model in combination with the ZS primary spectrum (continuous "conv." lines). Dashed "conv." lines are the results of calculating π and K neutrinos for zenith angles of 0° and 90° from (Naumov et al., 1998). The thick dotted line (curve *1*) represents the sum of usual π and K neutrino spectra obtained by us with the QGSJET-II + ZS model for an zenith angle of 90°, and direct neutrino
2 generation from (Volkova and Zatsepin, 1999) (VZ); the dash–dot curve *2* gives the sum of usual neutrinos from the QGSJET-II model and direct generation neutrinos calculated by the recombination quark–parton model (Bugaev et al., 1989) (RQPM in Fig. 4). The continuous line (4) shows the same, but for a quark–gluon string model (QGSM) (Bugaev et al., 1989) (see also (Bugaev et al., 1998; Naumov et al., 1998; Naumov, 2002;)). Figure 2 presents direct generation neutrino spectra predictions in the quantum chromodynamic model (QCD) from (Gelmini et al., 3
2000) (GGV): curves *3* and *5*, corresponding to gluon distribution parameter values of λ = 0.5(0.1) at small Bierkin *x*. The lower-lying curves *3*, *4* and *5*, show corresponding fluxes for θ= 0°.

Table 3 shows the calculated values of μ, π, and K neutrino fluxes and neutrino fluxes from charmed particle decays at E_ν = 100 TeV and restriction on diffuse flux of astrophysical neutrinos, obtained in the AMANDA-II experiment (Achterberg et al., 2007). Note that the neutrino flux obtained by us with the QGSJET-II interaction model and GH primary spec-

Table 3. Atmospheric neutrino fluxes ν_μ at $\bar{\nu}_\mu$ = 100 TeV and the upper limit in the Amanda-II experiment on diffusion flux of atmospheric neutrinos

Model	$E^2_\nu\phi_{\nu_\mu}$, (cm^2 s sr)$^{-1}$ GeV	
μ-, π-, K-neutrinos:	0°	90°
QGSJET II+03	1.20×10^{-8}	10.5×10^{-8}
QGSJET II+GH	1.11×10^{-8}	9.89×10^{-8}
Direct neutrinos	90°	
(ν_μ at $\bar{\nu}_\mu$):		
QGSM	1.22×10^{-8}	
RQPM	4.61×10^{-8}	
VZ	8.12×10^{-8}	
Limit AMANDA-II	$<7.4 \times 10^{-8}$	

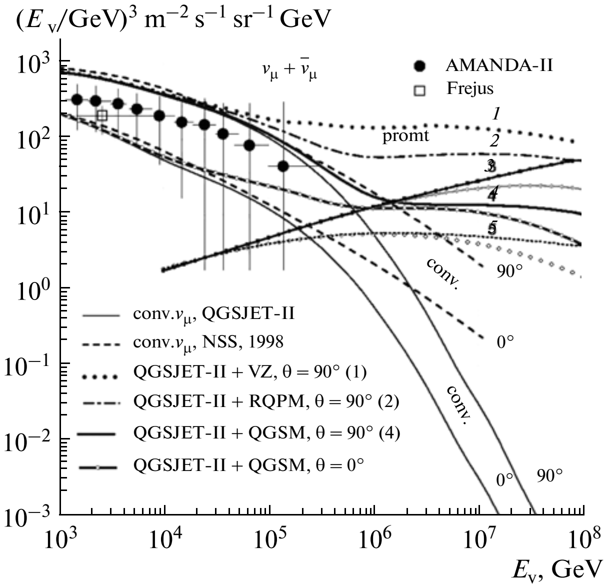

Fig. 4. Atmospheric neutrino fluxes from μ, π, and K decays and direct generation neutrinos. Experimental data: AMANDA-II (Achterberg et al., 2007) (circles) and Frejus (Daum et al., 1995) (squares). Calculations: neutrinos from μ, π, and K decays, thin curves (this work) and dashed curves (calculations of (Naumov et al., 1998),
2 NSS); direct generation neutinos—VZ (Volkova and Zatsepin, 1999) (curve *1*), RQPM (Bugaev et al., 1989) (curve *2*), GGV (Gelmini et al., 2000) (curves *3*, *5*), and QGSM (Bugaev et al., 1989) (curve *4*).

trum model is lowest of those presented here. Muon neutrino fluxes at an energy of 100 TeV predicted by the RQPM and QGSM do not contradict the restriction on diffuse fluxess astrophysical neutrinos established in the AMANDA-II experiment (Achterberg et al., 2007).

CONCLUSIONS

Calculation of muon neutrino spectra in the Earth's atmosphere shows a weak dependence on the model of the spectrum and composition of primary cosmic rays, at least in the energy interval of 10–10^5 GeV, the region not including a break ("knee") in the cosmic ray spectrum. However, application of different high-energy hadron interaction models leads to a signifcant difference in muon neutrino fluxes calculated within the limits of one computing scheme. With the example of the QGSJET-II and SIBYLL 2.1 hadron interaction models, it was clear that the main source of more than a 50% difference in neutrino fluxes are kaon generation processes in nucleon–nuclei collisions.

The widespread hope that calculations of atmospheric hadron and muon fluxes, supported by experimental measurements, can serve as a good tool for choosing a reliable high-energy hadron–nuclei interaction model is most likely groundless, since the main differences in the generation of the π and K components influence the muon and neutrino flux characteristics differently. The behavior of kaon-generation cross sectionss in nucleon–nuclei interactions at high energies is a more significant factor for high-energy neutrino generation in comparison with muon flux generation.

Fluxes of atmospheric neutrinos from charmed particle decays ("direct" neutrinos) depend weakly on the zenith angle (near 100 TeV), which gives grounds to consider the upper limit on diffuse fluxes of astrophysical neutrinos established in the AMANDA-II experiment as a restriction on charmed particle generation models. Thus, it is possible to state that both unperturbed models (RQPM and QGSM) do not contradict the upper limit in the experiment AMANDA-II on a diffuse neutrino flux.

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SPELL: 1. barions, 2. Zatsepin, 3. chromodynamic