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ВЛИЯНИЕ ХАРАКТЕРИСТИК АДРОННЫХ ВЗАИМОДЕЙСТВИЙ НА СПЕКТРЫ АТМОСФЕРНЫХ НЕЙТРИНО ВЫСОКИХ ЭНЕРГИЙ

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THE HADRONIC INTERACTION DEPENDENCE OF HIGH-ENERGY ATMOSPHERIC NEUTRINO SPECTRA

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В работе исследуется влияние характеристик адронных взаимодействий на спектр атмосферных нейтрино высоких энергий. Расчеты выполнены с использованием известных высокоэнергетических моделей адронных взаимодействий (SIBYLL 2.1, QGSJET-II, Кимеля и Мохова) и параметризаций спектра первичных космических лучей, основанных на экспериментальных данных. Модели QGSJET-II и SIBYLL 2.1 приводят к существенному различию потоков нейтрино: вблизи энергии 1 ТэВ отношение потоков достигает величины ~1.8. Такое расхождение кажется довольно неожиданным, принимая во внимание вычисления потоков адронов и мюонов в том же самом диапазоне энергий [1]. Приведено сравнение расчета потока нейтрино с измерениями на установках AMANDA-II и Frejus, а также с результатами других расчетов.

We study the influence of the hadron interaction features on the high-energy atmospheric neutrino spectrum. The calculations are performed making use of the known high-energy hadronic models, SIBYLL 2.1, QGSJET-II, Kimel and Mokhov, for the parameterizations of primary cosmic ray spectra issued from the data of experiments. The models QGSJET-II and SIBYLL 2.1 lead to appreciable difference in the neutrino flux, up to the factor of 1.8 at 1 TeV. This discrepancy appears to be rather unexpected keeping in mind the hadron and muon flux calculations in the same energy region [1]. The results are compared with the AMANDA-II and Frejus measurements as well as with other calculations.

Introduction

Atmospheric neutrinos (AN) appear in decays of mesons (charged pions, kaons etc.) produced through collisions of high-energy cosmic rays with air nuclei. The AN flux in the wide energy range is still of great interest since the low-energy AN flux is a subject of the research into neutrino oscillations, and the high-energy atmospheric neutrino flux is now an unavoidable background for astrophysical neutrino experiments [2–7]. To date many calculations of atmospheric neutrino fluxes among which [8–16] have been made (see also [17–21] for a review of 1D and 3D calculations of the AN flux in the wide energy range).

In this work, we present results of a new one-dimensional calculation of the atmospheric muon neutrino flux in the range of $10–10^7$ GeV made using hadronic models QGSJET-II 03 [22, 23], SIBYLL 2.1 [24, 25] as well as Kimel and Mokhov (KM) [26] that were also tested in recent atmospheric muon flux calculations [1]. We make an attempt to learn how strongly the diversities of the hadronic interaction models influence on the high-energy spectrum of atmospheric neutrinos.

The method and input data

The calculation is performed on the basis of the method [27] for solving hadronic cascade equations in the atmosphere, which takes into account non-scaling behavior of inclusive particle production cross-sections, rise in total inelastic hadron-nuclei cross-sections, and non-power law primary spectrum (see also [1]). The primary cosmic ray spectra and composition in the wide energy range used is the model recently proposed by Zatsepin and Sokolskaya (ZS) [28, 29] that fits well the ATIC-2 experiment data [30] and is supposedly valid up to 100 PeV. The ZS proton spectrum at $E\gtrsim 10^6$ GeV is compatible with KASCADE data [31, 32] as well as the helium one is within the range of the KASCADE spectrum reconstructed with the help of QGSJET 01 and SIBYLL models. Alternatively, in the energy range of $1–10^6$ GeV we use the parameterization by Gaisser, Honda, Lipari and Stanev (GH) [19, 33], the version with a high fit to helium data. Note this version is consistent with the data from the KASCADE experiment at $E_0>10^6$ GeV obtained (through the EAS simulations) by SIBYLL 2.1.

To illustrate the distinction of the hadron models employed in the computations, it is appropriate to compare the spectrum-weighted moments (Table1) computed for proton-air interactions for $\gamma=1.7$:

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

where $x=E_C/E_0$, $c=p, n, \pi^{\pm}, K^{\pm}$. Values in Table 1 display approximate scaling law both in SIBYLL 2.1 and KM and little violation of the scaling in the QGSJET-II for p and $\pi^{\pm}$.

Table 1

Spectrum weighted moments $z_{pc}(E_0)$ calculated for $\gamma=1.7$.

Model	E_0, GeV	z_{pp}	z_{pn}	$z_{p\pi^+}$	$z_{p\pi^-}$	z_{pK^+}	z_{pK^-}
QGSJET-II	10^2	0.174	0.088	0.043	0.035	0.036	0.0030
	10^3	0.198	0.094	0.036	0.029	0.036	0.0028
	10^4	0.205	0.090	0.033	0.028	0.034	0.0027
SIBYLL 2.1	10^2	0.211	0.059	0.036	0.026	0.0134	0.0014
	10^3	0.209	0.045	0.038	0.029	0.0120	0.0022
	10^4	0.203	0.043	0.037	0.029	0.0097	0.0026
KM	10^2	0.178	0.060	0.044	0.027	0.0051	0.0015
	10^3	0.190	0.060	0.046	0.028	0.0052	0.0015
	10^4	0.182	0.052	0.046	0.029	0.0052	0.0015

Atmospheric muon neutrino fluxes

Along with major sources of the muon neutrinos, $\pi_{\mu 2}$ and $K_{\mu 2}$ decays, we consider three-particle semileptonic decays, $K^{\pm}_{\mu 3}$, $K^{0}_{\mu 3}$, the contribution originated from decay chains $K\to\pi\to\nu_\mu$ ($K^0\to\pi^+\pi^-$, $K^{\pm}\to\pi^{\pm}\pi^0$), as well as a small fraction from the muon decays.

One can neglect 3D effects in calculations of the atmospheric muon neutrino flux near vertical at energies $E \gtrsim 1$ GeV and at $E \gtrsim 5$ GeV in case of directions close to horizontal (see [20, 21]). Fractions of the neutrino flux near vertical from pion and kaon decays are shown in figure 1. These calculations are made for the model primary spectrum by GH [19] (Fig. 1, *a*) as well as for the model by ZS [28, 29] that comprises the results of ATIC-2 experiment [30] (Fig. 1, *b*). Note that the similar ratio for muon fluxes differs from that of neutrino fluxes: at 10^3 GeV the ratio μ_K/μ_π is about 0.25, while ν_K/ν_π is about 4 (see also Fig. 2 in Ref. [19]).

The ratio $\nu_\mu / \bar{\nu}_\mu$ calculated with the KM model for the two primary spectra, GH and ZS, is plotted in Fig. 2. The wavy shape of the ratios apparently visible in Figs. 1, *b*, 2 reflects peculiarities of the ZS spectra.

A comparison between ($\nu_\mu + \bar{\nu}_\mu$) flux calculations for the three hadronic models under study is made in Table 2: column 1 presents the flux ratio, $\varphi_{\nu_\mu}^{(SIBYLL)} / \varphi_{\nu_\mu}^{(KM)}$, calculated for the GH and ZS primary spectra both at θ=θ° and θ=90° (in brackets); 2 – the QGSJET-II flux comparatively to KM one; 3 – the SIBYLL flux comparatively to the QGSJET-II one. One can see that using QGSJET-II and SIBYLL models leads to apparent difference of the muon neutrino flux (as well as in the case of SIBYLL as compared to KM, unlike the muon flux [1], where SIBYLL and KM lead to very similar results). On the contrary, the QGSJET-II neutrino flux is very close to the KM one: up to 100 TeV the difference does not exceed 5 % for the GH spectrum and 10 % for the ZS one at θ=θ°. While the muon flux discrepancy in the QGSJET-II and KM predictions is about 30 % at vertical [1]. The origin of differences is evident: an ambiguity of the kaon production.

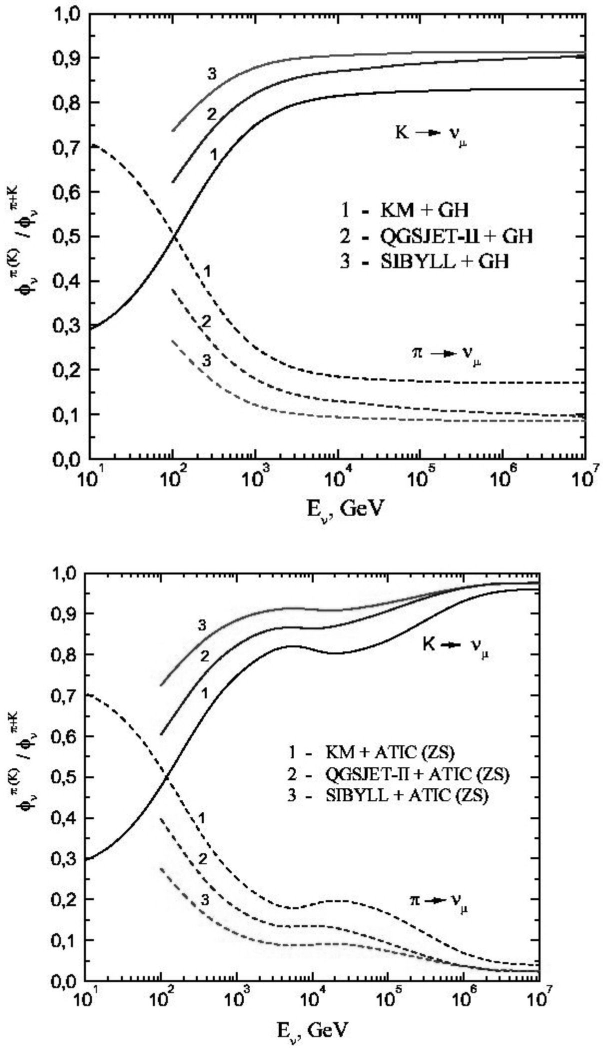

Fig. 1. Fraction of the $\nu_\mu + \bar{\nu}_\mu$ flux from kaon decays (solid lines) and pion ones (dashed) calculated for θ=θ°: a) calculation for the GH primary spectrum [19]; б) calculation for Zatsepin and Sokolskya model [28, 29].

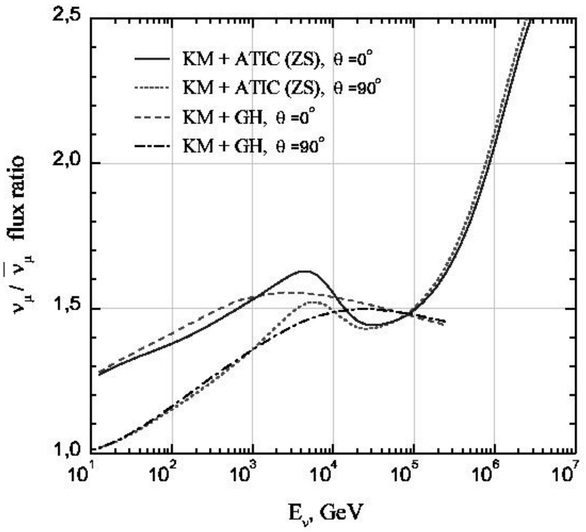

Fig. 2. Ratio of the ν_μ and $\bar{\nu}_\mu$ fluxes calculated with KM model for GH and ZS primary spectra.

Table 2

Ratio of the ν_μ fluxes at θ=θ° (90°) calculated with the SIBYLL 2.1, QGSJET-II, and KM.

E_ν, GeV	1	2	3
		GH	
10^2	1.65 (1.22)	0.97 (0.85)	1.70 (1.44)
10^3	1.71 (1.46)	0.96 (0.92)	1.78 (1.59)
10^4	1.60 (1.57)	0.96 (0.96)	1.67 (1.64)
10^5	1.54 (1.49)	0.99 (0.96)	1.56 (1.55)
		ZS	
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)

Figure 3 shows this work's calculations of the neutrino flux (lines) in comparison with the result of Barr, Gaisser, Lipari, Robbins and Stanev (BGLRS) [20] obtained using TARGET 2.1 (symbols). All these computations are performed for the GH primary spectra. One can see that the calculations for KM and TARGET 2.1 are in close agreement in the range of 10–10^4 GeV (near horizontal) as well as at E_ν<200 GeV near vertical.

Figure 4 presents the comparison between different calculations of the AN flux along with the data of the AMANDA-II [4, 5] and Frejus [34] experiments. More comparisons of the low- and high-energy flux calculations may be found in Refs. [13, 14, 17, 18, 20].

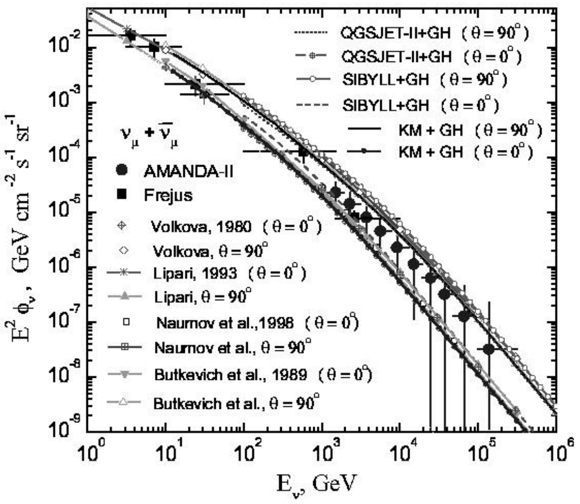

Fig. 3. Comparison of the present calculation as well as previous ones (by Volkova [8], Butkevich et al. [11], Lipari [12], Naumov et al. [14]) with the data from the AMANDA-II [5] and Frejus [34] experiments. This work calculation codes are in the right top corner.

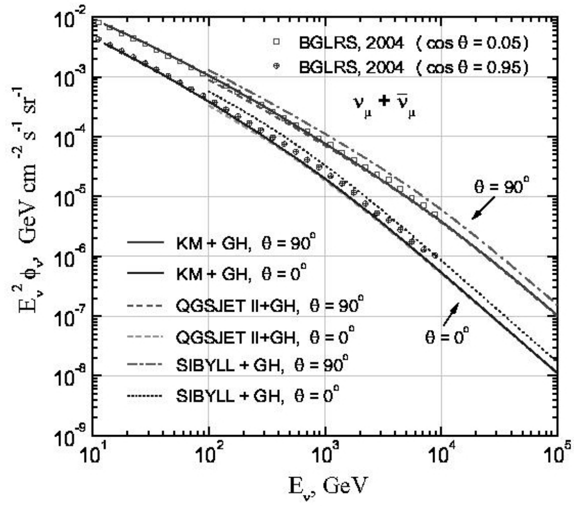

Fig. 4. Comparison of the two independent calculations for the GH spectrum.

Figure 5 presents the comparison of this work calculation of the conventional (from μ- and π, *K*-decays) and prompt muon neutrino fluxes with some of previous ones [14, 18, 35–38]. The conventional flux here was calculated using QGSJET-II combined with the Zatsepin and Sokolskaya primary spectrum (thin lines). Dashed lines mark the calculation by Naumov, Sinegovskaya and Sinegovsky [14, 18] of the conventional muon neutrino fluxes for θ=θ° and 90°. Bold dotted line (curve 1) shows the sum of the prompt neutrino flux by Volkova and Zatsepin (VZ) [36, 37] and the conventional one due to the QGSJET-II + ZS model at θ=90°. Dash-dotted line (2) indicates the sum of the QGSJET-II conventional flux (θ=90°) and the prompt neutrino contribution due to the recombination quark-parton model (RQPM) [35]. Solid line 4 shows the same for the prompt neutrino flux due to the quark-gluon string model (QGSM) [35] (see also [14, 18, 39]). Also shown are the two of the prompt neutrino predictions by Gelmini, Gondolo and Varieschi (GGV) [38] (curves 3 and 5).

Notice that recent evaluation of the prompt neutrino flux obtained with the dipole model (DM) [40] is rather

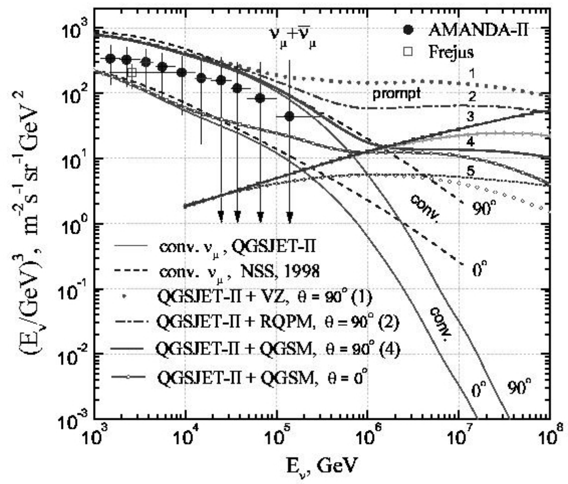

Fig. 5. Fluxes of the conventional and prompt muon neutrinos along with data points from the AMANDA-II [5] and Frejus [34] experiments. Codes of curves marking the prompt neutrino flux at θ=90° are as follows: 1 – VZ [36, 37]; 2 – RQPM [35]; 3 – GGV [38] (the case of λ=0.5, where λ is exponent of the gluon distribution at low Bjorken x); 4 – QGSM [35]; 5 – GGV (λ=0.1). Curves just below the 3, 4 and 5 display the coresponding flux at θ=θ°.

close to the QGSM prediction at $E \gtrsim 10^6$ GeV, keeping in mind that the theoretical uncertainty absorbs a difference between the DM and QGSM fluxes.

The prompt neutrino fluxes at E_ν=100 TeV are presented in Table 3 along with the upper limit on the astrophysical muon neutrino diffuse flux obtained in AMANDA-II experiment [5]. Note that the QGSJET-II+GH flux appears to be the lowest flux of conventional atmospheric neutrinos at high energies.

Table 3

Atmospheric neutrino flux at E_ν = 100 TeV vs. the AMANDA-II restriction for the $\nu_\mu + \bar{\nu}_\mu$ flux.

Model	$E_\nu^2 \varphi_\nu$, (cm²s sr)⁻¹ GeV	
conventional $\nu_\mu + \bar{\nu}_\mu$:	0°	90°
QGSJET-II + ZS	1.20×10^{-8}	10.5×10^{-8}
QGSJET-II + GH	1.11×10^{-8}	9.89×10^{-8}
prompt $\nu_\mu + \bar{\nu}_\mu$:	90°	
VZ [32]	8.12×10^{-8}	
RQPM [31]	4.61×10^{-8}	
QGSM [31]	1.22×10^{-8}	
AMANDA-II upper limit [4]	7.4×10^{-8}	

Summary

The calculations of high-energy atmospheric muon neutrino flux demonstrate rather weak dependence on the primary specrtum models in the energy range of 10–10^5 GeV. However, the picture seems to be less steady because of sizable flux differences originated from the models of high-energy hadronic interactions. As it can be seen by the example QGSJET-II and SIBYLL 2.1, the major factor of the discrepancy is the kaon production in nucleon-nucleus collisions.

A common hope that atmospheric muon fluxes might be reliable tool to promote the discrimination between the hadron production models seems to be rather illusive as the key differences in the π, *K* production impact variously on the neutrino flux and muon one. For the high-energy neutrino production at the atmosphere the kaon yield in nucleon-nucleus interactions is the stronger factor in comparison with that for production of the atmospheric muons, despite their common to neutrinos origin.

Inasmuch as the atmospheric prompt neutrino flux weakly depends on the zenith angle (near 100 TeV), one may refer the AMANDA-II restriction just to the prompt neutrino flux model. Thus one may consider both RQPM and QGSM to be consistent with the AMANDA-II upper limit for diffuse neutrino flux.

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