Abstract: High-energy neutrinos from decays of mesons, produced in collisions of cosmic ray particles with air nuclei, form unavoidable background for detection of astrophysical neutrinos. More precise calculations of the high-energy neutrino spectrum are required since measurements in the IceCube experiment reach the intriguing energy region where a contribution of the prompt neutrinos and/or astrophysical ones should be discovered. Basing on the referent hadronic models QGSJET II-03, SIBYLL 2.1, we calculate high-energy spectra, both of the muon and electron atmospheric neutrinos, averaged over zenith-angles. The computation is made using three parameterizations of cosmic ray spectra which include the knee region. All calculations are compared with the atmospheric neutrino measurements by Frejus and IceCube. The prompt neutrino flux predictions obtained with the quark-glueon string model (QGSM) for the charm production by Kaidalov & Piskunova do not contradict to the IceCube measurements and upper limit on the astrophysical muon neutrino flux. Neutrino flavor ratio, $\phi_\mu/\phi_\nu$, extracted from IceCube data decreases in the energy range $0.1-5$ TeV energy contrary to that one might expect from the conventional neutrino flux. Presumable reasons of such behavior are: i) early arising contribution from decays of charmed particle, differing from predictions of present models, ii) revealed diffuse flux of astrophysical electron neutrinos. The likely diffuse flux of astrophysical neutrinos related to the PeV neutrino events, detected in the IceCube experiment, leads to a decrease of the flavor ratio at the energy below 10 TeV, that is in qualitative agreement with a rough approximation for the flavor ratio obtained from the IceCube data.

Keywords: atmospheric neutrinos, astrophysical neutrino flux, high-energy hadronic interactions

1 Introduction

High-energy neutrinos produced in decays of muons, pions, kaons, and charmed particles of the extensive air shower induced by cosmic rays in the Earth atmosphere, form an unavoidable background for detection of astrophysical neutrinos. Search of extraterrestrial neutrino sources is a challenge to resolve which large-scale neutrino telescopes, NT200+ [1], IceCube [2,3,4], ANTARES [5], are designed. The high-energy atmospheric neutrinos became accessible to the experimental studies only last years. By now, the energy spectrum of high-energy atmospheric muon neutrinos has been measured in three experiments: Frejus [6] at energies up to 1 TeV, AMANDA-II [7] in the energy range 1–100 TeV, and IceCube40 [2] in the range 100 GeV–400 TeV. Recently the IceCube presents results for the electron neutrino spectrum measured in the energy range ~80 GeV–6 TeV [8]. Thus one has a possibility to obtain the neutrino flavour ratio from IceCube experiment and to compare this one with predictions.

The increasing with the energy contribution of charged particle decays to the neutrino flux becomes the source of the large uncertainty at energies above 100 TeV. Thus the comparison of the calculation for various hadron-interaction models with neutrino spectrum measurements is of interest, despite large statistical and systematic experimental errors in the high-energy region. 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 [9] and SIBYLL 2.1 [10], which are widely employed to simulate extensive air showers with the Monte Carlo method, and were also used to compute the cosmic-ray hadron and muon fluxes [11,12].

The calculation has been performed for three parameterizations of the experimentally measured spectrum and the composition of primary cosmic rays (PCR) in the energy range comprising the knee: 1) the model by Zatsepin & Sokolskaya [13], 2) the modified multi-knee model by Bindig, Bleve and Kampert [14], and 3) the novel model of primary spectrum by Gaisser [15], based on assumption that there are three classes of CR sources: i) Galactic supernova remnants, ii) Galactic high-energy sources different from the former, iii) extragalactic astrophysical objects.

2 Fluxes of atmospheric muon neutrinos

The calculation is performed on the basis of the method [16] of solution of the hadronic cascade equations in the atmosphere, which takes into account non-scaling behavior of inclusive particle production cross-sections, the rise of total inelastic hadron-nuclei cross-sections, and the nonpower law primary spectrum (see also [17]). Along with major sources of the muon neutrinos, $\pi_\mu$ and $K_\mu$ decays, we consider three-particle semileptonic decays, $K^\pm$, $K^0_{\pm}$, $\pi^0$, the contribution originated from decay chains $K \rightarrow \pi \rightarrow \nu_\mu \ (K^0_S \rightarrow \pi^+\pi^-\pi^0, K^+ \rightarrow \pi^+\pi^0)$, as well as small fraction from the muon decays. The sources of the conventional $\nu_\mu$’s are three-particle decays of kaons $K^\pm$, $K^0_{\pm}$ and also $\mu_3$ decay.

As the primary cosmic ray spectra and composition in wide energy range following models are used: 1) the model by Zatsepin & Sokolskaya (ZS), 2) the modified multi-knee model by Bindig, Bleve and Kampert (BK) based
Comparison of the muon neutrino fluxes calculated for three recent primary spectrum models (Fig. 1) shows that they are rather close each other up to 1 PeV.

Comparison of calculation results with IceCube experimental data is shown in Figs. 2 and 3. The difference of muon neutrino flux predictions resulted from the primary cosmic ray spectra becomes apparent at high neutrino energies: the flux obtained with QGSJET II for ZS spectrum at 2 PeV is less by a third of the flux for HGm spectrum. More results of the muon neutrino calculations, including a comparison with the AMANDA measurements, were presented in Ref. [21, 22].

The calculation of conventional $\nu_\mu + \bar{\nu}_\mu$ fluxes averaged over zenith angles as compared with Frejus [6] and IceCube [2] measurement data is shown in Figs. 2 and 3. In Fig. 2 curves displays the conventional $\nu_\mu + \bar{\nu}_\mu$ energy spectrum calculated with usage of QGSJET-II model for BK primary spectrum and composition (solid line) as well as for ZS one (dashed). The prompt neutrino flux was calculated using the quark-gluon string model (QGSM) by Kaidalov & Piskunova [24] to describe the charmed particle production in nucleon-nucleus collisions at high energies. This calculation was performed with NSU primary spectrum [25], therefore they can serve here as upper limits for the prompt

| Model | $E_{\nu}^{2} \phi_{\nu} \, \text{GeV cm}^{-2} \, \text{s sr}^{-1}$ |
|-------|--------------------------------------------------|
| conventional $\nu_\mu + \bar{\nu}_\mu$ | $200 - 400$ TeV |
| ZS+SIBYLL 2.1 | $9.4 \times 10^{-9} - 2.2 \times 10^{-9}$ |
| ZS+QGSJET-II-03 | $6.1 \times 10^{-9} - 1.3 \times 10^{-9}$ |
| HGm+QGSJET-II-03 | $6.7 \times 10^{-9} - 1.5 \times 10^{-9}$ |
| prompt $\nu_\mu + \bar{\nu}_\mu$ | $200 - 400$ TeV |
| RQPM [23] | $2.1 \times 10^{-8} - 9.3 \times 10^{-9}$ |
| QGSM [23] | $5.1 \times 10^{-9} - 2.9 \times 10^{-9}$ |
| IC59 limit [27] | $1.4 \times 10^{-8}$ |
| (35 TeV - 7 PeV) | |
| ANTARES limit [5] | $5.3 \times 10^{-8}$ |
| (20 TeV - 2.5 PeV) | |

Table 1: Atmospheric neutrino flux and upper limit for diffuse ($\nu_\mu + \bar{\nu}_\mu$) flux obtained with neutrino telescopes.
Figure 4: Calculated conventional and prompt ($\nu_e + \bar{\nu}_e$) spectra compared to Frejus [6] and IceCube data [8].

Figure 5: Atmospheric ($\nu_e + \bar{\nu}_e$) spectrum and diffuse flux of cosmic neutrinos.

Figure 6: Neutrino flux ratio ($\nu_\mu + \bar{\nu}_\mu$)/($\nu_e + \bar{\nu}_e$).

neutrino flux due to RQPM or QGSM. Notice that estimate of the prompt neutrino flux obtained with the dipole model [26] is in close agreement to the QGSM predictions [23] above 1 PeV. The prompt neutrino flux due to QGSM in the energy range $5 \text{ TeV} \leq E_\nu \leq 5 \cdot 10^3 \text{ TeV}$ was approximated by the expression

$$\Phi_A^{\nu_\nu}(E_\nu) = A(E_\nu/E_1)^{-3.01}[1 + (E_\nu/E_1)^{-2.01}]^{-0.165},$$

(1)

where $A = 1.19 \cdot 10^{-18} \text{(GeV cm}^2 \text{ sr})^{-1}, E_1 = 100 \text{ TeV}.$

Calculated atmospheric muon neutrino fluxes for the energy range 200 – 400 TeV are presented in Table 1 along with upper limits on the astrophysical muon neutrino diffuse flux obtained with the IceCube59 [27] and ANTARES [5]. Note that calculated total atmospheric neutrino flux – sum of the prompt neutrinos due to RQPM or QGSM and the conventional ones, – does not contradict to these limits.

3 Electron neutrino fluxes and neutrino flavor ratio

Recently the IceCube publish results for the electron neutrino spectrum measured in the energy range $\sim 80 \text{ GeV} - 6 \text{ TeV}$ [8], making possible evaluation the neutrino flavour ratio and comparison it with predictions. Results of calculation of the atmospheric ($\nu_e + \bar{\nu}_e$) flux with QGSJET II-03 and SIBYLL 2.1 for three parameterisations of cosmic ray spectra are presented in Figs. [4] along the measurement data. In Fig. 5 is shown also the contribution of diffuse flux (red dashed and dash-dotted lines) of cosmic neutrinos added to the atmospheric conventional neutrino flux which are calculated with usage of QGSJET-II-03 for the Gisser spectrum (HG). Upper dashed red line in this figure depicts the the sum of the atmospheric electron neutrino flux and the diffuse flux of cosmic neutrinos with an the $E_\nu^{-2}$-spectrum, $E^2 \Phi_\nu = 3.6 \cdot 10^{-8} \text{(cm}^2 \text{ s sr})^{-1}$ GeV (assuming a flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0$), dash-dotted red line corresponds to sum of atmospheric electron neutrinos and astophysical ones, $E^2 \Phi_\nu = 1.2 \cdot 10^{-8} \text{(cm}^2 \text{ s sr})^{-1}$ GeV, for the assumption $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$). This limit obtained by IceCube [4] for the energy range above 1 PeV is compatible with the two PeV neutrino events [28] with energies $1.04 \pm 0.16$ and $1.14 \pm 0.17 \text{ PeV}$ which were detected by the IceCube neutrino telescope.

Since IceCube has measured energy spectra both of muon and electron neutrino, we may try to construct the neutrino flavour ratio ($\nu_\mu + \bar{\nu}_\mu$)/($\nu_e + \bar{\nu}_e$) and check for agreement the calculations with experimental data. The conventional neutrino flavour ratio, $\phi_{\nu_\mu + \bar{\nu}_\mu}/\phi_{\nu_e + \bar{\nu}_e}$, calculated for different parameterisations of cosmic ray spectra, as it is seen in Fig. 5 is more sensitive to hadronic models than to the primary spectrum. The difference of neutrino flux predictions related to choice of hadronic models is clearly seen: curves display the scale of difference between the conventional ($\nu_\mu + \bar{\nu}_\mu$) and ($\nu_e + \bar{\nu}_e$) spectra, calculated with usage of QGSJET II, SIBYLL for all of the 3 PCR models, HGm, ZS and BK. Monte Carlo calculations give the high ratio, $25 \sim 30$ (see Fig. 2 in [29]), unlike to...
that of present work, 10 − 16.

Thick dashed line (green) corresponds to the IceCube data, the solid curves above and below the green one signify a rough estimate of the IceCube data uncertainties. Curves marked as 1 and 2 in Fig. depict the total neutrino flavor ratio comprising the conventional, prompt and astrophysical neutrinos (these last were added in line with two assumptions indicated in Fig. 5). Thus one may assume that IceCube atmospheric neutrino measurement data give an indication that astrophysical electron neutrinos are probably visible in the energy region 1 − 10 TeV. There is obscure behavior of the flavor ratio in the range 100 GeV - 1 TeV, probably related to neutrino oscillations: the oscillation signal was detected within a low-energy muon neutrino sample (20 − 100 GeV) in data collected by DeepCore [30].

4 Summary

The calculations of the high-energy atmospheric neutrino flux demonstrate rather weak dependence on the primary spectrum models in the energy range 102 − 105 GeV. However the picture appears less steady because of sizable flux differences originated from the models of high-energy hadronic interactions. As it can be seen by the example of the models QGSJET-II-03 and SIBYLL 2.1, the major factor of a discrepancy in the conventional neutrino flux is the kaon production in nucleon-nucleon collisions.

Calculated spectra of muon neutrinos show apparent dependence on the spectrum model and composition of primary cosmic rays in the range above 100 TeV, which includes the “knee”. Also in this region uncertainties appear due to production cross sections of charged particles. The prompt neutrino contribution due to QGSM leads to better agreement with the IceCube data above 100 TeV. The total flux of the conventional and prompt neutrinos calculated with QGSJET-II-03 and QGSM describes the IceCube data well enough. The QGSM predicted muon neutrino flux in the range 200 − 400 TeV as well as the RQPM one does not violate the upper limit on the diffuse flux of astrophysical neutrinos obtained by IceCube59 [27].

However, observation of the PeV-energy neutrino events by IceCube [28] changes drastically the situation concerning the prompt neutrino contribution. If the first indication of astrophysical neutrinos by IceCube would be confirmed in further studies (particularly in the measurement of electron neutrino flux above 10 TeV), then the atmospheric νe flux uncertainty due to the charm production becomes negligible at the energy above 10 TeV (see Fig. 5).

Neutrino flavor ratio extracted from IceCube data at energies up to 5.7 TeV decreases in the energy range 0.1 − 5 TeV energy contrary to the conventional neutrino flux computation (Fig. 6). Presumably there are three reasons of such behavior: 1) the neutrino oscillations in low-energy part of this energy range, 2) early arising contribution from decays of charged particle (the prompt neutrinos), and at last iii) increasing with energy contribution of the diffuse neutrino flux at higher energies.

Preliminary and superficial analysis leads to the assumption: IceCube atmospheric neutrino data give indication that astrophysical electron neutrinos should be observable at the energy some 10 TeV. If the power law $E^{-2}$ is valid for astrophysical neutrino spectrum in this range. Whether this optimism has any grounding in reality remains to be seen.

Acknowledgments: We thank Prof. V.A. Naumov for useful discussion, Dr. A.A. Kochanov, Ms. O.N. Petrova for the help in the early stage of the work.

Work is supported by the Russian Federation Ministry of Education and Science, agreement No.14.B37.21.0785.

References

[1] V. Aynutdinov et al., Nucl.Instrum. Meth. A588 (2008) 99-106.
[2] R. Abbasi et al. (IceCube Collaboration), Phys. Rev. D 83 (2011) 012001.
[3] R. Abbasi et al.(IceCube Collaboration), Phys.Rev. D84 (2011) 082001.
[4] R. Abbasi et al. (IceCube Collaboration), Phys.Rev. D 83 (2011) 092003.
[5] S. Biagi et al. Nucl. Phys. Proc. Suppl. 212-213 (2011) 109-114.
[6] K. Daum et al., Z. Phys. C 66 (1995) 417-428.
[7] R. Abbasi et al. (IceCube Collaboration), Astropart. Phys. 34 (2010) 48-58.
[8] M. G. Aarsten et al. (IceCube Collaboration), Phys. Rev. Lett. 110 (2013) 151105.
[9] S. Ostapchenko, Nucl. Phys. B (Proc. Suppl.) 151 (2006) 143-146; Nucl. Phys. B (Proc. Suppl.) 175-176 (2008) 73-80; Phys. Rev. D 74 (2006) 014026.
[10] E.-J. Ahn et al. Phys. Rev. D 80 (2009) 094003.
[11] A.A. Kochanov, T.S. Singegovskaya, S.I. Singegovsky, Astropart. Phys. 30 (2008) 219-233.
[12] A.A. Kochanov, T.S. Singegovskaya, S.I. Singegovsky, J. Exp. Theor. Phys. 116 (2013) 395-413.
[13] V.I. Zatsepin, N.V. Sokolskaya, Astronomy & Astrophys. 458 (2006) 1-5.
[14] D. Bindig, C. Bleve, K.-H. Kampert Proc. 32nd ICRC, Beijing, 2011, vol.1. pp. 161-164.
[15] T. Gaisser, Astropart. Phys. 24 (2012) 801-806; T. Gaisser, arXiv:1303.1431.
[16] V. A. Naumov, T. S. Singegovskaya, Phys. Atom. Nucl. 63 (2000) 1927-1935; hep-ph/0106015.
[17] T. Antoni et al., Astropart. Phys. 24 (2005) 1-25.
[18] J. Horandel, Astropart. Phys. 21 (2004) 241-265.
[19] A. D. Panov et al., Bull.Russ. Acad. Sci.Phys. 71 (2007) 494-497.
[20] A. D. Panov et al., Bull. Russ. Acad. Sci. Phys. 73 (2009) 564-567.
[21] S. Singegovsky, O. Petrova, T. Singegovskaya, Proc. 32nd ICRC, Beijing, 2011, vol.4. p. 291; arXiv: 1109.3576.
[22] O. N. Petrova, T. S. Singegovskaya, S. I. Singegovsky, Phys. Part. Nucl. Lett. 9 (2012) 766-768.
[23] E. V. Bugaev et al. Nuovo Cim. C 12 (1989) 41-73.
[24] A. B. Kaidalov, O. I. Piskunova, Sov. J. Nucl. Phys. 41 (1985) 816; Z. Phys. C30 (1986) 145.
[25] S.I. Nikolsky, I.N. Stamenov, S.Z. Ushev, Sov. Phys. JETP 60 (1984) 10-21.
[26] R. Enberg, M.H. Reno, I. Sarcevic, Phys. Rev. D 78 (2008) 043005.
[27] A. Schukraft (IceCube Collaboration) Nucl. Phys. B (Proc.Suppl.) 237-238 (2013) 266-268.
[28] M. G. Aartsen et al. (IceCube Collaboration), arXiv:1304.5356.
[29] A. Fedynitch, J. Becker Tjus, P. Desiati, Phys.Rev. D 86 (2012) 114024.
[30] M. G. Aartsen et al. (IceCube Collaboration), arXiv:1305.3909.