The comparison of the calculated atmospheric neutrino spectra with the measurements of IceCube and ANTARES experiments

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Abstract. We calculate the atmospheric neutrino spectra in the energy range of $10^2 - 10^7$ GeV using the hadronic models QGSJET-II, SIBYLL 2.1 and the parameterizations of cosmic ray spectra by Zatsepin-Sokolskaya and Hillas-Gaisser supported by experiments. It is shown that rare decay mode of short-lived neutral kaons produce about $30\%$ of the electron neutrino flux and up to $10\%$ of muon neutrinos at energies above $200$ TeV. Comparative analysis of our calculations based on the $Z(E,h)$-function approach and those obtained with use of the new MCEq-method (A.Fedynitch et al.) demonstrates the close agreement of both calculations. The comparison of calculated neutrino spectrum to the experimental data shows that IceCube and ANTARES measurements leave opened window for the prompt neutrino flux contribution obtained with the quark-gluon string model (QGSM).

1. Introduction

The problem of the atmospheric neutrino background became really important after observation in IceCube experiment of the events with deposited energies of $20$ TeV – $2$ PeV, induced by neutrinos of extraterrestrial origin [1, 2, 3]. Comprehensive study of the high-energy neutrino spectrum and zenith angle distribution of atmospheric neutrinos is required since it is possible that the astrophysical neutrino flux and the atmospheric prompt neutrinos (arising from decays of charmed particles) partly overlap.

We calculate the atmospheric neutrino spectra in the energy range $100$ GeV – $10$ PeV on basis of the method [4, 5, 6] to solve the hadronic cascade equations in the atmosphere taking into account the non-power energy spectrum of the cosmic rays, a violation of the Feynman scaling law and a growth with the energy of the total inelastic cross sections of hadron-nucleus collisions. Current computation was performed with use of the hadronic models QGSJET-II-03 [7], SIBYLL 2.1 [8] for parameterizations of the primary cosmic-ray spectra by Zatsepin-Sokolskaya (ZS) [9] and Hillas-Gaisser (HGm) [10, 11].
2. The calculation technique

High-energy spectra of the atmospheric neutrinos were computed with usage of $Z(E, h)$-method [4, 5, 6]. The approach allows one to compute the hadron, muon, and neutrino fluxes in the Earth’s atmosphere in a wide energy range. The method has been verified by comparing the calculated fluxes with a large number of experimental data (see [5]). The method is free of any normalization coefficients and allows to evaluate the impact of the primary spectrum and hadronic models on the neutrino flux values.

Major sources of the muon neutrinos are $\pi\mu_2$ (branching ratio 0.9988), $K\mu_2$ (0.635) and $K^0_{\mu 3}$ (0.27) decay modes. Also we consider minor contributions: $K^\pm_{\mu 3}$ (3.32 · $10^{-2}$), $\mu e_3$ and those arise from decay chains $K \rightarrow \pi \rightarrow \nu_\mu$. The sources of the electron neutrinos are three-particle decays of muons and kaons: $\mu e_3$, $K^0_{e 3}$ (branching ratio 0.405) – the dominant source of electron neutrinos below 10 TeV, $K_{e 3}^\pm$ (5.07 · $10^{-2}$). The semileptonic decays of short-lived $K^0_S$ is a significant source of the $\nu_e$ flux though branching ratio of the decay $K^0_S \rightarrow \pi^\pm + e^\mp + \bar{\nu}_e (\nu_e)$ is small ($7.04 \cdot 10^{-4}$). This decay gives a considerable contribution to the atmospheric $\nu_e$ flux at high energies, reaching 30% at $E_\nu = 500$ TeV for zenith angle $\theta = 0^\circ$. Close to vertical the $\nu_e$ flux from the $K^0_S$ decay becomes nearly equal to that from $K^0_L$ one at $E_\nu \approx 1$ PeV. The decay mode $K^0_S \rightarrow \pi^\pm + \mu^\mp + \bar{\nu}_\mu (\nu_\mu)$ (with branching ratio $4.69 \cdot 10^{-4}$) contributes up to 10% of the $\nu_\mu$ flux.

A comparison of the calculations performed with different technique is of undoubted interest. In figure 1 we compare the calculation results obtained with $Z(E, h)$-method to those with use of Matrix Cascade Equations (MCEq) code recently developed by A.Fedynitch et al. [12]. The neutrino fluxes are calculated for the same hadronic models (QGSJET-II-03, SIBYLL 2.1) and the same parameterizations of the cosmic rays spectra (Zatsepin-Sokolskaya and Hillas-Gaisser). These compared results are in very close agreement (both in the flux values and the curve shape) except for the energy range 50 – 100 GeV at large zenith angles, where the difference reaches 15%. Most likely this deviation is due to a difference in used atmospheric profiles.

![Figure 1](image_url)

Figure 1. Comparison of $\nu_e$ and $\bar{\nu}_e$ flux (left panel) and $\nu_\mu$ and $\bar{\nu}_\mu$ (right) calculated with two methods: $Z(E, h)$-method [6] (solid lines) and MCEq one [12] (symbols).

3. Comparison of the calculation with the experiment

In 2011-2015, the IceCube collaboration published the results of the atmospheric neutrino spectra measurements: for $(\nu_e + \bar{\nu}_e)$ flux in the energy range 80 GeV – 20 TeV [13] and for $(\nu_\mu + \bar{\nu}_\mu)$ flux at 100 GeV – 575 TeV [14, 15]. Figure 2 shows (full circles) the muon neutrino flux measured in
zenith-angle ranges $90 - 120^\circ$ and $120 - 180^\circ$ [15]. The spectrum calculated for near-horizontal directions ($90 - 120^\circ$) with SIBYLL 2.1 (dashed line) gives a better agreement with the data at $E_\nu \geq 10$ TeV in comparison with QGSJET-II-03 (solid line), and vice versa, for directions $120 - 180^\circ$ the calculation with QGSJET-II-03 agrees better with the experiment at all energies (figure 2, right panel).

Figure 2. The $(\nu_\mu + \bar{\nu}_\mu)$ fluxes at zenith angles $90 - 120^\circ$ (left) and $120 - 180^\circ$ (right). Curves - the calculations with QGSJET II-03 and SIBYLL 2.1, full circles - IceCube measurements [15].

The spectrum of muon neutrinos in the energy range $10^2 - 10^5$ GeV measured by the ANTARES neutrino telescope [16] is shown in figure 3 (open squares). Being comparable on the whole with the IceCube data (full circles and down triangles), the ANTARES data exhibit a slight excess of the $(\nu_\mu + \bar{\nu}_\mu)$ flux at energies above 10 TeV.

The prompt neutrino flux (due to decays of the charmed particles) was computed using the quark-gluon string model (QGSM) [17, 18] (dotted and chain lines in figures 3, 4). The contribution of prompt neutrinos evidently makes better agreement between the calculation and

Figure 3. The $(\nu_\mu + \bar{\nu}_\mu)$ spectrum measured by IceCube [14, 15] and ANTARES [16].

Figure 4. The atmospheric and astrophysical $(\nu_e + \bar{\nu}_e)$ fluxes measured in IceCube [13, 1, 2].
the experimental data – blue solid line (figure 3) presents the total atmospheric ($\nu_e + \bar{\nu}_e$) flux. It is worth to stress that calculated neutrino spectra were obtained irrespective of the experimental data, i.e. without use of any normalizing factor.

Figure 4 presents the spectrum of atmospheric electron neutrinos measured in IceCube experiment [13] (triangles) and the results of our calculations (curves). The diffuse flux of neutrinos detected in IceCube experiment [1, 2] is shown in this figure by green band with use of the IceCube best fit per flavor in the range $25 \text{ TeV} < E_\nu < 1.4 \text{ PeV}$ [19]:

$$E_\nu^2\phi_\nu = (2.06^{+0.4}_{-0.3}) \cdot 10^{-8}(E_\nu / 100 \text{ TeV})^{-0.46^{+0.12}_{-0.1}} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}.$$  

As it is seen in the figure 4, the astrophysical electron neutrinos and the prompt atmospheric ones (obtained with use of QGSM) give rise competitive contributions to neutrino events in the energy range $25 - 100 \text{ TeV}$.

4. Conclusions

Our calculation demonstrates rather weak dependence on the model of primary cosmic-rays spectrum in the energy range of $10^3 - 10^5 \text{ GeV}$. The major uncertainty in the calculated neutrino fluxes with energies up to 500 TeV is due to differences of hadronic interaction models, QGSJET-II, SIBYLL 2.1, which lead to significant discrepancy – up to 60% for the $(\nu_\mu + \bar{\nu}_\mu)$ flux and to $\sim 40\%$ for the $(\nu_e + \bar{\nu}_e)$ one. These differences are mainly due to the cross sections of K meson production. The rare semileptonic decays of $K^0_S$ provide about one third of the $(\nu_e + \bar{\nu}_e)$ flux and contribute about 10% to the $(\nu_\mu + \bar{\nu}_\mu)$ flux at energies beyond 400 TeV.

Comparison of the absolute calculated values of the neutrino spectra (averaged over zenith angle) to the IceCube and ANTARES measurements shows a validity of basic mechanism of the atmospheric neutrino production used in this computation. Both methods under study, $Z(E, h)$ [6] and MCEq [12], demonstrate consistent results and confirm the reliability of performed calculations. The additional contribution to the $(\nu_\mu + \bar{\nu}_\mu)$ flux from the decays of charmed particles, produced according to QGSM, improves the agreement with experiment at $E_\nu > 100 \text{ TeV}$ and does not contradict the data for the $(\nu_e + \bar{\nu}_e)$ flux above 10 TeV.

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References

[1] Aartsen M G et al. 2013 Phys. Rev. Lett. 111 021103
   Aartsen M G et al. 2013 Science 342 1242856
[2] Aartsen M G et al. 2014 Phys. Rev. Lett. 113 101101
[3] Aartsen M G et al. 2015 PoS (ICRC2015) 1081 (arXiv: 1510.05223)
[4] Naumov V A and Sinegovskaya T S 2000 Phys. Atom. Nucl. 63 1927
[5] Kochanov A A, Sinegovskaya T S and Sinegovsky S I 2008 Astropart. Phys. 30 219
[6] Sinegovskaya T S, Morozova A D and Sinegovsky S I 2015 Phys. Rev. D 91 063011
[7] Kalmykov N N, Ostapchenko S S and Pavlov A I 1997 Nucl. Phys. Proc. Suppl. B 52 17
[8] Ahn E J et al. 2009 Phys. Rev. D 80 094003
[9] Zatsarin V I and Sokolskaya N V 2006 Astron. Astrophys. 458 1
[10] Hillas A M 2006 arXiv: astro-ph/0607109v2
[11] Gaisser T K 2012 Astropart. Phys. 35 801
[12] Fedynitch A et al. 2015 EPJ Web Conf. 99 08001 (arXiv: 1503.00544); 2015 PoS (ICRC2015) 1129
[13] Aartsen M G et al. 2013 Phys. Rev. Lett. 110 151105
   Aartsen M G et al. 2015 Phys. Rev. D 91 122004
[14] Abbasi R et al. 2011 Phys. Rev. D 83 012001
[15] Aartsen M G et al. 2015 Eur. Phys. J. C 75 116
[16] Adrian-Martinez S et al. 2013 Eur. Phys. J. C 73 2606
[17] Kaidalov A B and Piskunova O I 1986 Z. Phys. C 30 145
[18] Bugaev E V et al. 1989 Nuovo Cim. C 12 41
[19] Aarsten M G et al. 2015 Phys. Rev. D 91 022001