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Influence of hadronic interaction models on characteristics of the high-energy atmospheric neutrino flux

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Abstract. The high-energy conventional atmospheric neutrino fluxes are calculated with the hadronic interaction models: Kimel & Mokhov, QGSJET II-03(04), SIBYL 2.1(2.3), EPOS LHC. The influence of hadron-nuclear interactions on the neutrino flux ratios, $\nu/\bar{\nu}$, $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$, is studied. A comparison of calculations obtained with use of two different approaches, $\mathcal{Z}(E, h)$-functions method and the Matrix Cascade Equations (MCEQ), demonstrates close agreement in whole but some of partial contrubutions. The comparison of calculated muon neutrino spectra with the latest experimental data justifies reliability of performed computation which describes correctly the atmospheric neutrino production. The calculation made with the model EPOS LHC, combined with Hillas & Gaisser parametrization of the cosmic ray spectrum, is in close agreement with the best fit of IceCube for energy spetrum of atmospheric muon neutrinos in the energy range $1-500$ TeV.

1. Introduction

High-energy neutrinos from decays of mesons and baryons are produced in collisions of cosmic rays with the the Earth's atmosphere forming unavoidable background for detecting of neutrinos from astrophysical sources. The calculation of the energy spectrum and zenith-angle distribution of the atmospheric neutrinos became really urgent problem since detecting in the IceCube experiment of 82 events, with energy deposition in the range 30 TeV–2 PeV, from neutrinos of cosmic origin [1–5].

We calculate the atmospheric neutrino spectra and neutrino flux ratios at energies $10-10^7$ GeV with the hadronic model by Kimel & Mokhov [6], and at 10^2-10^7 GeV using high-energy set of hadronic models QGSJET II [7,8], SIBYLL 2.1 [9], SIBYLL 2.3 [10], EPOS LHC [11,12]. Two known paramerizations of the cosmic ray spectrum, by Zatsepin & Sokolskaya [13] and by Hillas & Gaisser [14], are used in the computation.

The neutrino-to-antineutrino flux ratios $\Phi_\nu/\Phi_{\bar{\nu}}$ and flavor ratios $\Phi(\nu_\mu + \bar{\nu}_\mu)/\Phi(\nu_e + \bar{\nu}_e)$ depending on cross sections of the kaon production in hadron-nucleus collisions also bear the

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imprint of the cosmic ray elemental composition. The flavor ratio is important because of high sensitivity to the neutrino source addition – a rare decay mode, charmed particle decays, etc.

2. Methods of the calculation

Decay modes $\pi_{\mu 2}$, $K_{\mu 2}$ and $K^0_{\mu 3}$ dominate the flux of muon neutrinos. Also we consider minor contributions: $K^{\pm}_{\mu 3}$ (the fraction of 0.0335), μ_{e3} and those arise from decay chains $K \to \pi \to \nu_\mu$. Dominant sources of the electron neutrinos are three-particle decays of kaons: K^0_{e3} (0.405), $K^{\pm}_{e3}$ (0.0507). The semileptonic decays of K^0_S are a significant source of the ν_e flux though fraction of the decay mode $K^0_S \to \pi^{\pm} + e^{\mp} + \bar{\nu}_e(\nu_e)$ is very small ($7.04 \cdot 10^{-4}$). This mode gives a considerable contribution to the atmospheric ν_e flux at high energies, reaching 30% at $E_\nu = 500$ TeV for zenith angle $\theta = 0°$. Close to the vertical $(\nu_e + \bar{\nu}_e)$ flux from the K^0_S decay becomes nearly equal to that from K^0_L one at $E_\nu \approx 1$ PeV (see figure 1). The decay mode $K^0_S \to \pi^{\pm} + \mu^{\mp} + \bar{\nu}_\mu(\nu_\mu)$ (the fraction of $4.69 \cdot 10^{-4}$) contributes up to 10% of the $(\nu_\mu + \bar{\nu}_\mu)$ flux.

Main calculations were made with $\mathcal{Z}(E,h)$-method [15, 16], allowing the computation of atmospheric fluxes of hadrons, muons [17, 18] and neutrinos [19] in case of nonpower cosmic-rays spectrum, nonscaling behavior of inclusive cross-sections and growing with energy inelastic cross-sections of hadron-nucleus collision. Characteristics of the atmospheric neutrino flux, calculated with $\mathcal{Z}(E,h)$-method, we compare to those derived within the framework of different approach, Matrix Cascade Equations [20, 21]. All calculations necessary for this comparison we performed independently using the free access package MCEq [22]. Results of this comparison are shown in figures 1–3 (see also [23]).

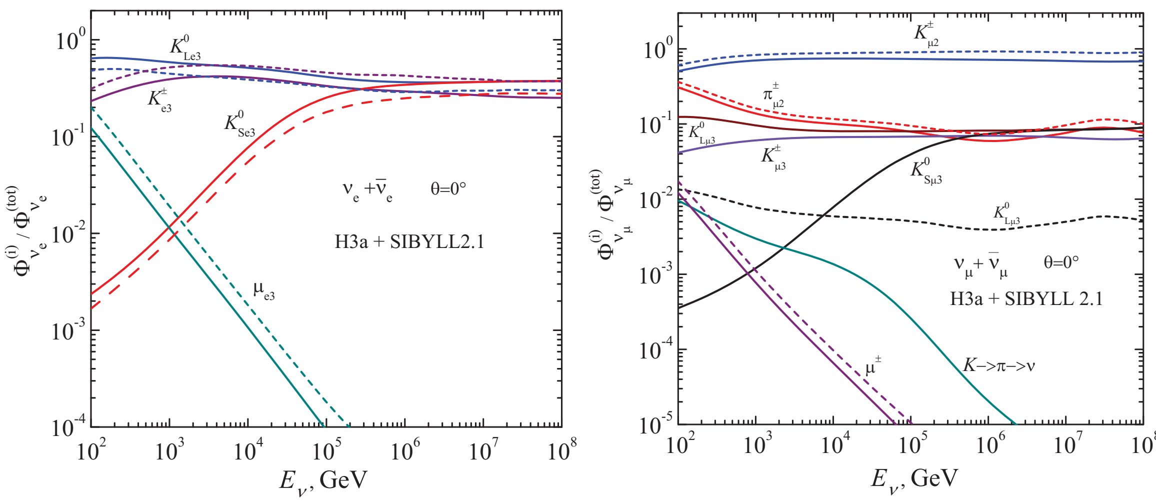

Figure 1. Partial contributions to the atmospheric $(\nu_e + \bar{\nu}_e)$ flux (left) and $(\nu_\mu + \bar{\nu}_\mu)$ (right) with SYBILL 2.1. Solid lines – $\mathcal{Z}(E,h)$-method, dashed – MCEq one.

3. Results and discussion

The neutrino flux ratios $\Phi_\nu/\Phi_{\bar{\nu}}$, $R_{\nu_\mu/\nu_e} = \Phi(\nu_\mu + \bar{\nu}_\mu)/\Phi(\nu_e + \bar{\nu}_e)$ at high energies depend on cross sections of kaons production in the atmospheric hadron cascade. Elemental composition of cosmic rays also impacts on these ratios through the primary proton-to-neutron ratio as well to π^+/π^-, K^+/K^- и π/K ratios of conventional neutrino sources.

Calculated neutrino flux ratios for the set of hadronic models are shown in figures 2, 3. The calculation of flavor ratio R_{ν_μ/ν_e} of atmospheric neutrino fluxes near vertical direction is performed for two models of the cosmic ray spectrum (figure 3, left panel): curves 1–5 are

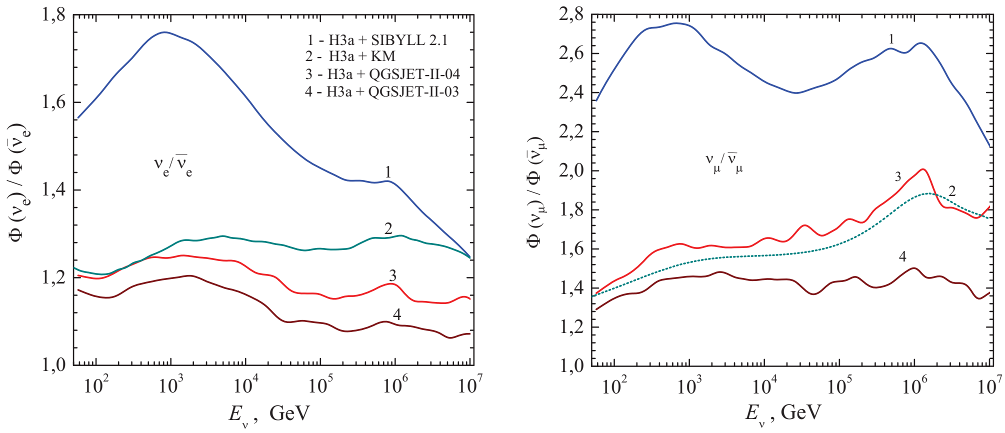

Figure 2. The neutrino-to-antineutrino ratio $\nu_e/\bar{\nu}_e$ (left) и $\nu_\mu/\bar{\nu}_\mu$ (right), calculated with Hillas & Gaisser cosmic ray spectrum (H3a) for zenith angle $\theta = 0°$.

obtained with the MCEQ technique [21] for Hillas & Gaisser cosmic ray spectrum (H3a ≡ HGm); curves 6, 7 represent the calculations for Zatsepin & Sokolskaya spectrum (ZS) with $\mathcal{Z}(E,h)$-method. Right panel of figure 3 displays R_{ν_μ/ν_e} averaged over zenith angles, and also only point derived in IceCube experiment [24] is plotted (●) on the figure ($R_{\nu_\mu/\nu_e} = 16.9$ at $E_\nu = 1.7$ TeV). The square at upper boundary of the experimental error marks value obtained by Honda [25], the symbol $\star$ close to lower error boundary marks the Bartol group calculation (borrowed from [24]).

Impact of semileptonic decay of K_S^0 on the flavor ratio of atmospheric neutrinos at 50−100 TeV is unexpectedly strong: this contribution in SIBYLL 2.1 leads to lowering of R_{ν_μ/ν_e} by factor ~ 1.28 at ~ 100 TeV (the curve 4 in figure 3, right) as compared to that if no K_S^0 decay is taken into consideration (upper dashed curve). Probably, neglect this contribution led to high value of R_{ν_μ/ν_e} in the calculation [26], performed with usage of CORSIKA 6.990 (no K_S^0 decay option).

The $(\nu_\mu + \bar{\nu}_\mu)$ flux calculation for Hillas & Gaisser cosmic ray spectrum H3a (HGm) with

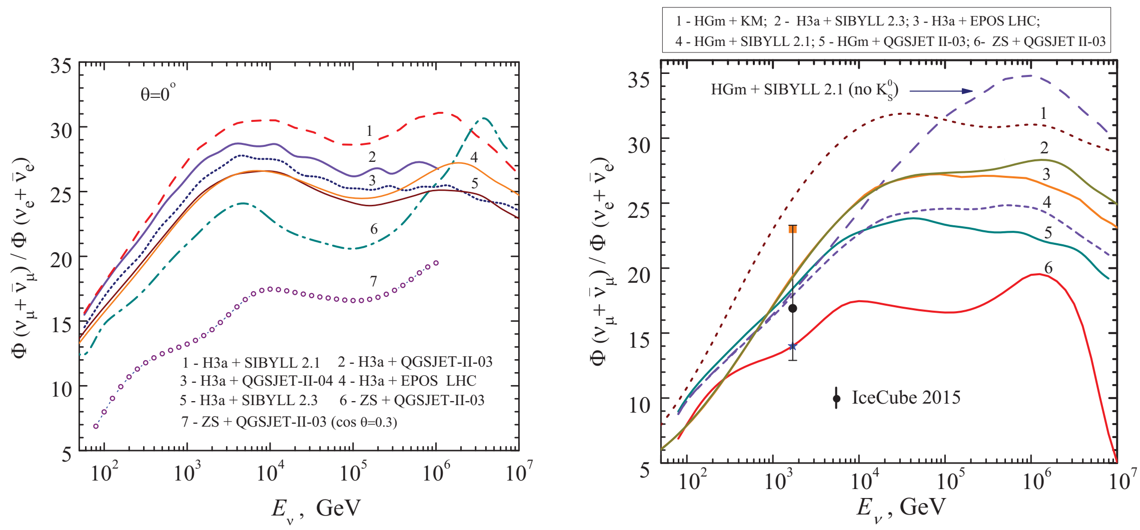

Figure 3. Atmosperic neutrino flavor ratio at $\theta = 0°$ (left) and zenith angle averaged one (right) calculated for the hadronic models KM, SIBYLL 2.1 (2.3), QGSJET II-03 (04) and EPOS LHC.

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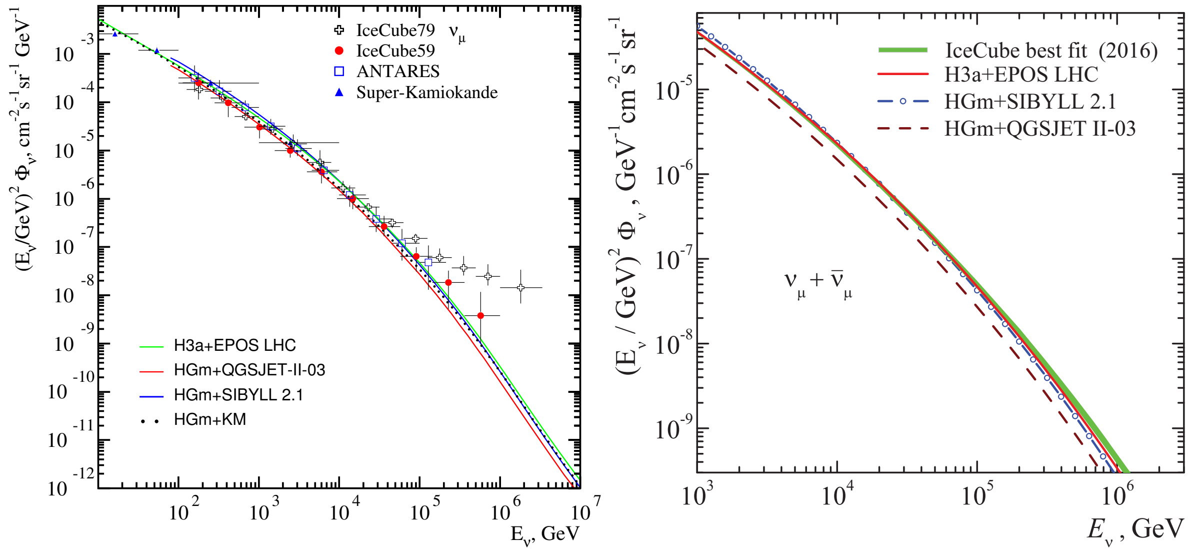

Figure 4. Energy spectrum of atmospheric muon neutrinos ($\nu_\mu + \bar{\nu}_\mu$) (zenith-angle averaged). Left: symbol – experimental data of IceCube [27, 28], ANTARES [29], Super-Kamiokande [30]; curves – the calculations. Right: the calculations as compared to IceCube best fit for the ($\nu_\mu + \bar{\nu}_\mu$) spectrum [4] (green band). Closest curve to the best fit is derived for EPOS LHC (red line).

use of hadronic models Kimel & Mokhov (KM), QGSJET II-03, SIBYLL 2.1 and EPOS LHC is shown in figure 4. The calculation for EPOS LHC [11, 12] is performed using the program MCEq by Fedynitch et al. [22]) (green line). At energies $E_\nu \leq 100$ GeV the prediction made with KM (dotted) is rather close to that with EPOS LHC, and above 10 TeV the former one is close to that of SIBYLL 2.1 (dashed line). The data obtained with the 79-strings configuration of IceCube detector [28] display the change of spectral index of the muon neutrino flux, caused by addition of the astrophysical neutrinos to the atmospheric ones (figure 4, left); the former dominate at energies above 500 TeV. The best fit of the IceCube data [4] on the atmospheric muon neutrino spectrum, averaged over zenith angles, is shown in right panel of figure 4 by thick green line (width corresponds to one-sigma error of the measured spectrum). The rest three curves present calculations, performed with EPOS LHC (red line), SIBYLL 2.1 и QGSJET II-03 for the Hillas & Gaisser cosmic-rays spectrum. The hadronic interaction model EPOS LHC in combination with Hillas & Gaisser parametrisation of the cosmic ray spectrum is in closest agreement with the the IceCube best fit in the energy range $1 - 500$ TeV.

4. Conclusions

The atmospheric neutrino spectra and the flavor ratio in the energy range $10^2 - 10^8$ GeV are calculated with high-energy hadron interaction models (QGSJET-II, SIBYLL 2.1, EPOS LHC, etc) using two parametrizations of the primary cosmic ray spectrum, Zatsepin & Sokolskaya and Hillas & Gaisser. Calculation results show rather weak dependence on the model of primary cosmic rays in the energy range of $10 - 10^5$ GeV, while high-energy interaction models lead to the discrepancy in the calculated neutrino fluxes, sequent from differences in K-meson production. On the contrary, the neutrino flavor ratio is more sensitive to the cosmic-rays spectrum.

Both calculation schemes used in the study, $\mathcal{Z}(E, h)$ [19] and MCEq [20], demonstrate consistent results at least in the range of 100 GeV – 1 PeV. Compatibility of two methods allows one to examine calculation results made for the same primary spectrum and hadronic model, identifying possible sources of differences – a model of the atmosphere, secondary particles spectra in kaon decays, minor neutrino sources.

The comparison of calculated neutrino spectra with available experimental data justifies reliability of the computation that describes correctly the neutrino production in the Earth's atmosphere. The calculation of the atmospheric muon neutrino flux, performed with the hadronic interaction model EPOS LHC in combination with Hillas & Gaisser parametrization of the cosmic ray spectrum, agrees well with the the IceCube best fit in the energy range $1 - 500$ TeV.

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