Flavor and "charge" ratios of high-energy atmospheric neutrinos depending on cosmic-ray spectrum and composition

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Abstract

High-energy neutrinos arising from decays of the cosmic ray-induced hadrons in the Earth's atmosphere form the background flux for astrophysical neutrinos. The problem of the atmospheric neutrino background is really important after detection in IceCube experiment of several tens events from extraterrestrial neutrinos with energies up to 4 PeV. We calculate the atmospheric neutrino spectra in the energy range of 100 GeV - 100 PeV using the set of the hadronic models and several parametrizations of cosmic ray spectra supported by experimental data. Above 100 TeV calculated spectra of muon neutrinos show the apparent dependence on the spectrum and composition of primary cosmic rays around to the knee. Also in this energy range uncertainties appear due to production cross sections and decays of the charmed particles which imprint on the prompt neutrino flux. Basing on this calculation we display the influence of the cosmic-ray spectrum and composition on the neutrino to antineutrino flux ratio as well the neutrino flavor ratio. These neutrino flux characteristics are sensitive to meson charge ratios as well as to π/K yield, which depend not only on cross-sections for hA-collisions but also on the cosmic-ray composition due to p/n ratio induced by elemental composition of cosmic rays. Comparative analysis of atmospheric neutrino fluxes, calculated in framework of the two methods $\mathcal{Z}(E,h)$ functions approach and the Matrix Cascade Equations method (MCEq), demonstrates the close agreement of both calculations in the spectra shape and values. It is shown that rare decays of short-lived neutral kaons contribute about a third of the conventional ν_e flux at the energies above 100 TeV. Calculated neutrino spectra agree rather well with the measurement data of IceCube and ANTARES experiments. Uncertainties of the experimental data above 500 TeV leave a window for the prompt neutrino component predicted with use of the quark-qluon string model (QGSM).

Sources of atmospheric neutrinos

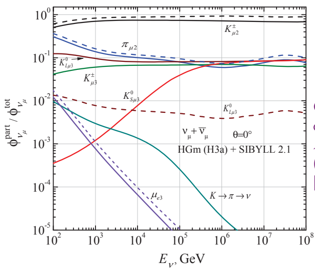
Conventional (π/K) neutrinos

	Decay modes	Fraction, Γ_i/Γ
$\mu^\pm$	$e^\pm + \nu_e(\bar\nu_e) + \bar\nu_\mu(\nu_\mu)$	$\simeq 100\,\%$
$\pi^\pm$	$\mu^\pm + \nu_\mu(\bar\nu_\mu)$	99, 99 %
$K^\pm$	$\mu^\pm + \nu_\mu(\bar\nu_\mu)$ $\pi^0 + \mu^\pm + \nu_\mu(\bar\nu_\mu)$ $\pi^0 + e^\pm + \nu_e(\bar\nu_e)$ $\pi^\pm + \pi^0$	63.55 % 3.35 % 5.07 % 20.66 %
K_L^0	$\pi^\pm + \mu^\mp + \bar\nu_\mu(\nu_\mu)$ $\pi^\pm + e^\mp + \bar\nu_e(\nu_e)$	27.04 % 40.55 %
K_S^0	$\pi^+ + \pi^-$ $\pi^\pm + \mu^\mp + \bar\nu_\mu(\nu_\mu)$ $\pi^\pm + e^\mp + \bar\nu_e(\nu_e)$	69.20 % $4.66 \cdot 10^{-4}$ $7 \cdot 10^{-4}$

Prompt (D/Λ_c) neutrinos

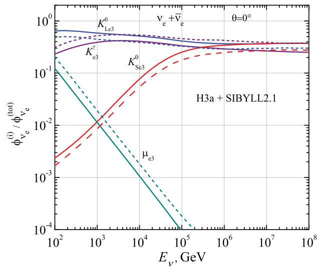
	Decay modes	Fraction
$D^\pm$	$\mu^\pm + \nu_\mu(\bar\nu_\mu) + X$	17.6 %
$D^0, \bar D^0$	$\mu^\pm + \nu_\mu(\bar\nu_\mu) + X$	6.7 %
$D_s^\pm$	$e^\pm + X$	6.5 %
Λ_c^+	$\Lambda + \mu^+ + \nu_\mu$ $\Lambda + e^+ + \nu_e$	$2.0 \pm 0.7\,\%$ $2.1 \pm 0.6\,\%$

Contributions to the $(\nu_\mu + \bar\nu_\mu)$ flux: $\mathcal{Z}(E,h)$ compared to MCEq



Comparison of two calculational methods: $\mathcal{Z}(E,h)$-approach [2, 9] (solid lines) vs. MCEq [3] (dashed).

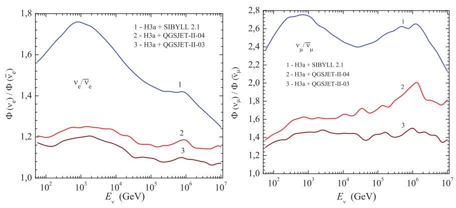
Partial contributions to the $(\nu_e + \bar\nu_e)$ flux



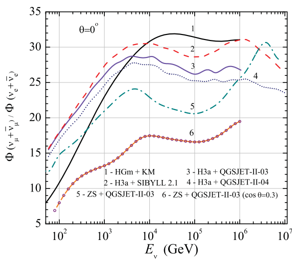
Atmospheric electron neutrinos near vertical: Hillas-Gaisser CR spectrum (H3a) + SIBYLL 2.1

Ratio $\nu_e/\bar\nu_e$

Atmospheric neutrino-to-antineutrino flux ratio for vertical direction: Hillas-Gaissser cosmic ray spectrum (H3a) + three hadronic models



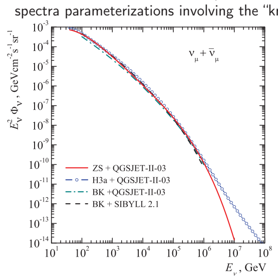
Influence of CR spectrum and hadronic model on the neutrino flavor ratio



Flavor ratio of atmospheric neutrinos for the vertical and oblique direction ($cos\theta = 0.3$) : calculations for four hadronic models and two CR spectra parameterizations – Hillas-Gaissser (H3a, HGm) and Zatsepin-Sokolskaya (ZS)

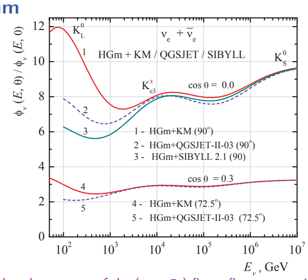
Influence of CR spectrum on the $(\nu_\mu + \bar\nu_\mu)$ flux

Comparison of the calculations (zenith-angle averaged) for the CR spectra parameterizations involving the "knee"



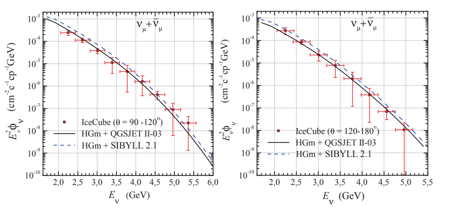
ZS: Zatsepin-Sokolskaya model (Astronomy & Astrophys. 458, 1 (2006));
H3a: Three sources model by A.M. Hillas astro-ph/0607109 and T.K. Gaisser AP, 24, 801 (2012);
BK: Modified polygonato model by D.Bindig, C.Bleve and K.-H. Kampert, 32 ICRC, Beijing, 2011, v. 1, p. 161.

Zenith-angle enhancement of the $(\nu_e + \bar\nu_e)$ spectum



Zenith-angle enhancement of the $(\nu_e + \bar\nu_e)$ flux reflects successive "switching-on" of the kaon sources

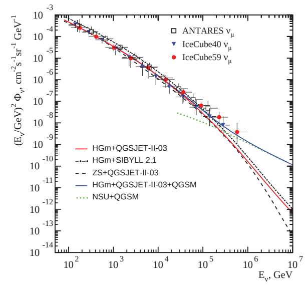
Specta of the atmospheric $(\nu_\mu + \bar\nu_\mu)$ fluxes: IceCube



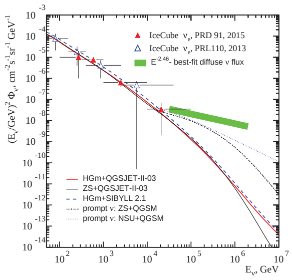
$(\nu_\mu + \bar\nu_\mu)$ fluxes averaged over zenith angle ranges 90 − 120° and 120 − 180°. Curves - the calculations with QGSJET II-03 and SIBYLL 2.1, symbols - IceCube measurements.

Energy spectra of the atmospheric $\nu_\mu + \bar\nu_\mu$

(zenith angle averaged): IceCube, ANTARES



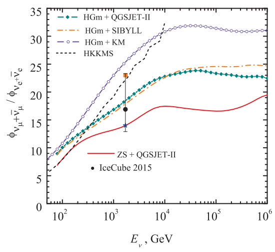
Atmospheric and astrophysical $\nu_e + \bar\nu_e$ fluxes



The band – IceCube best fit for astrophysical neutrino flux $(\nu_e + \bar\nu_e)$ [7]: $E_\nu^2\phi_\nu = (2.06^{+0.35}_{-0.26}) \cdot 10^{-8}(E/100\,TeV)^{-(0.46\pm0.12)}$, $(\mathrm{cm}^2\,\mathrm{s\,sr})^{-1}$ GeV;

Prompt neutrinos: calculations with QGSM for CR spectra by Nikolsky-Stamenov-Ushev (NSU) and Zatsepin-Sokolskaya (ZS) (dotted)

Neutrino flavor ratio $R_{\nu_\mu/\nu_e} = \phi_{\nu_\mu+\bar\nu_\mu}/\phi_{\nu_e+\bar\nu_e}$



IceCube data:

the circle with error bars - IceCube measurement at $E_\nu = 1.7$ TeV [7]; small square – the calculation by Honda [10], star – the Bartol group calculation (see [7]).

Curves: R_{ν_μ/ν_e} calculated with QGSJET II-03, SIBYLL 2.1, Kimel and Mokhov (KM) for ZS and HGm parametrizations of the CR spectrum):

Summary

- The kaon yield difference due to hadronic models is the source of the most uncertainty in the neutrino flux calculation above 500 TeV: SIBYLL 2.1 vs. QGSJET-II leads to 60% higher ν_μ flux (40% for the ν_e one).
- The three-particle semileptonic decays of short-lived K_S^0-mesons at energies above 100 TeV contribute to the $(\nu_e + \bar\nu_e)$ flux about 30%.
- Calculated neutrino spectra agree rather well with the experimental data obtained by IceCube and ANTARES.
- The detailed comparison of the calculations, based on the $\mathcal{Z}(E,h)$-functions approach [2] with those of the MCEq method [3], shows the consistency in the energy range 100 GeV - 1 PeV.
- The atmosperic muon neutrino spectrum data on obtained with neutrino telescopes allow of the prompt neutrino component $(\nu_e + \bar\nu_e)$ at $E > 30$ TeV and $\nu_\mu + \bar\nu_\mu$ at $E > 400$ TeV) calculated with use of the quark-gluon string model (QGSM).

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