The comparison of calculated atmospheric neutrino spectra with measurement data of IceCube and ANTARES experiments

A.D. Morozova[1,2], A.A. Kochanov[3], T.S. Sinegovskaya[4], S.I. Sinegovsky[2]

[1]Lomonosov Moscow State University, Physics Faculty, Moscow, Russia
[2]Irkutsk State University, Physics Faculty, Irkutsk, Russia
[3]Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia
[4]Irkutsk State Transport University, Irkutsk, Russia

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Abstract

The problem of the atmospheric neutrino background became really important after observation with the IceCube detector of events induced by very high-energy neutrinos of extraterrestrial origin [1]. Comprehensive study of the high-energy neutrino spectrum and zenith angle distribution of atmospheric neutrinos is required since it is not improbable that the atmospheric neutrinos arising from decays of π, K mesons (conventional neutrinos) or from decays of charmed particles (prompt neutrinos), produced in collisions of cosmic ray particles with the Earth's atmosphere, and astrophysical neutrinos overlap.
We calculate the atmospheric neutrino spectra in the energy range of 100 GeV - 10 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 region uncertainties appear due to production cross sections and decays of the charmed particles which imprint on the prompt neutrino flux. It is also shown also in the calculations that rare decays of short-lived neutral кaons contribute about a third of the conventional ν_e flux at the energies above 100 TeV. Taking into account K-meson production in πA collisions gives addition $5-7\%$ to the ν_e flux in the energy range of 100 GeV - 100 TeV. The detailed comparison of our calculations, based on the $\mathcal{Z}(E,h)$-functions approach [2] with those of the MCEq method by A.Fedynitch et al. [3], shows the consistency on the whole at least in the energy range 100 GeV - 1 PeV. Calculated neutrino spectra agree rather well with the measurement data in IceCube [4, 5, 6, 7] and ANTARES [8]. 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) [2].

Sources of atmospheric neutrinos

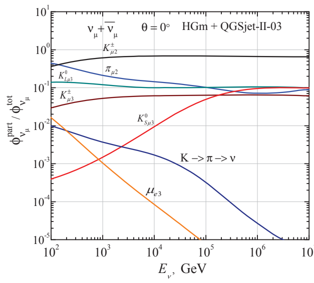
Conventional (π/K) neutrinos

	Decay modes	Fraction, Γ_i/Γ
$\mu^\pm$	$e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$	$\backsimeq$ 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	$\pi^+ + \pi^-$ $\pi^\pm + \mu^\mp + \bar{\nu}_\mu(\nu_\mu)$	69.20 % $4.66 \cdot 10^{-4}$

Prompt (D/Λ_c) neutrinos

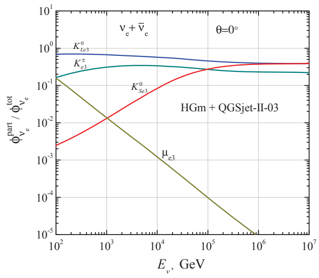
	Decay modes	Fraction
$D^\pm$	$\mu^\pm + \nu_\mu(\bar{\nu}_\mu) + X$	17.6 %
$D^0, \bar{D}^0$	$\mu^\pm + \nu_\mu(\bar{\nu}_\mu) + X$	6.7 %
$D_s^\pm$	$e^\pm + X$	6.5 %
Λ_c^+	$\Lambda + \mu^+ + \nu_\mu$ $\Lambda + e^+ + \nu_e$	2.0 ± 0.7 % 2.1 ± 0.6 %

Partial contributions to the flux of $(\nu_\mu + \bar{\nu}_\mu)$



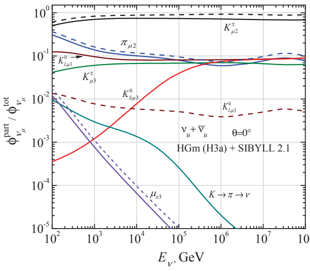
Atmospheric muon neutrinos near vertical: QGSJET-II-03 + Hillas-Gaissser cosmic ray spectrum (HGm)

Partial contributions to the $(\nu_e + \bar{\nu}_e)$ flux



Electron neutrinos near vertical: QGSJET-II-03 + Hillas-Gaissser CR spectrum (HGm)

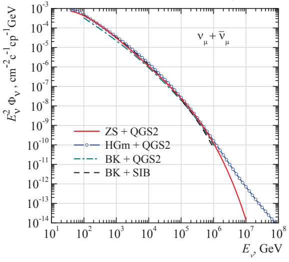
Contributions to the $(\nu_\mu + \bar{\nu}_\mu)$ flux: $\mathcal{Z}(E,h)$ compared to MCEq



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

Influence of CR spectrum on the $(\nu_\mu + \bar{\nu}_\mu)$

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

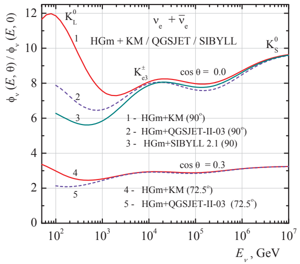


ZS: Zatsepin-Sokolskaya model (Astronomy & Astrophys. 458, 1 (2006));

HGm (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



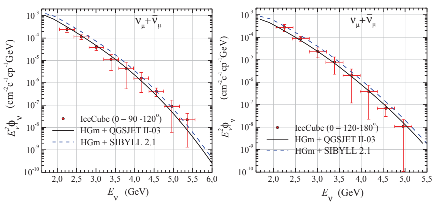
Zenith-angle enhancement of the $(\nu_e + \bar{\nu}_e)$ flux reflects successive "switching-on" of the kaon sources

Neutrino fluxes depending on the hadronic model

Atmospheric neutrino flux ratios calculated with SIBYLL 2.1, QGSJET II-03 and Kimel-Mokhov model (KM) for CR spectra ZS and HGm: 1 (4) – sib/qgs2; 2 (5) – km/qgs2; 3 (6) – sib/km.

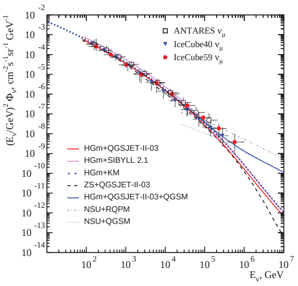
E_ν, TeV	1	2	3	4	5	6
	ZS: $(\nu_\mu + \bar{\nu}_\mu)$			ZS: $(\nu_e + \bar{\nu}_e)$		
1	1.70	1.05	1.62	1.41	0.51	2.76
10	1.53	1.04	1.47	1.32	0.48	2.75
10^2	1.53	1.10	1.39	1.29	0.54	2.39
10^3	1.79	1.64	1.09	1.41	0.84	1.68
10^4	1.85	2.08	0.89	1.38	1.06	1.30
	HGm: $(\nu_\mu + \bar{\nu}_\mu)$			HGm: $(\nu_e + \bar{\nu}_e)$		
1	1.59	0.85	1.87	1.39	0.49	2.84
10	1.57	1.12	1.40	1.33	0.50	2.66
10^2	1.57	1.27	1.24	1.31	0.57	2.30
10^3	1.63	1.63	1.00	1.31	0.70	1.87
10^4	1.47	1.53	0.96	1.23	0.59	2.08

Specta of the atmospheric $(\nu_\mu + \bar{\nu}_\mu)$ fluxes: IceCube

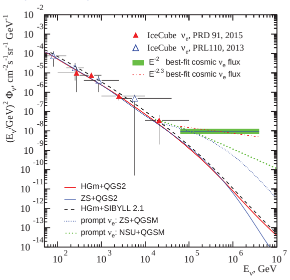


$(\nu_\mu + \bar{\nu}_\mu)$ fluxes averaged over zenith angle ranges 90 − 120° and 120 − 180°. Curves - the calculations with QGSJET II-03 and SIBYLL 2.1, symbols - IceCube measurements.

Energy spectra of the atmospheric $\nu_\mu + \bar{\nu}_\mu$ (averaged over the range $90-180°$): IceCube, ANTARES



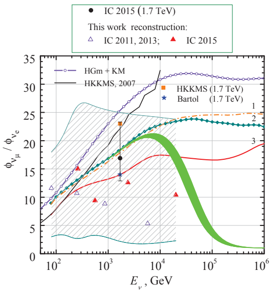
Atmospheric and astrophysical fluxes $(\nu_e + \bar{\nu}_e)$



The band and dash-dotted line – IceCube best fits for astrophysical neutrino flux $(\nu_e + \bar{\nu}_e)$ [1]:
$E_\nu^2\phi_\nu = (0.95 \pm 0.3) \cdot 10^{-8}$,
$E_\nu^2\phi_\nu = 1.5 \cdot 10^{-8}(E/100\,TeV)^{-0.3}$
$(\mathrm{cm}^2\,\mathrm{c\,sr})^{-1}$ GeV
$(\nu_e : \nu_\mu : \mu_\tau = 1 : 1 : 1)$

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

Ratio $R_{\nu_\mu/\nu_e} = \phi(\nu_\mu + \bar{\nu}_\mu)/\phi(\nu_e + \bar{\nu}_e)$



IceCube data:

the filled circle with error bars - IceCube measurement at $E_\nu = 1.7$ TeV [7]; triangles - this work reconstruction of R_{ν_μ/ν_e} based on the IceCube data [4, 5, 6, 7], hatched area - the error range.

Curves 1-3: 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):

1 - HGm + SIBYLL, 2 - HGm + QGSJET-II, 3 - ZS + QGSJET-II;

green band -

R_{ν_μ/ν_e} calculation taking into consideration the IceCube astrophysical neutrinos [1].

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%.
- Account for the production of K-mesons in the pions-nuclei interactions leads to $5-7\%$ increase of neutrino flux in the energy range $10^2 - 10^4$ GeV.
- The atmosperic muon neutrino spectrum data on obtained with neutrino telescopes allow for the prompt neutrino component calculated with use of the quark-gluon string model (QGSM).

References

[1] M.G. Aartsen et al. (IceCube Collaboration), Phys. Rev. Lett. **111**, 021103 (2013); Science **342**, 1242856 (2013); Phys. Rev. Lett. **113**, 101101 (2014); PoS (ICRC2015) 1081; arXiv:1510.05223

[2] T.S. Sinegovskaya, A.D. Morozova, S.I. Sinegovsky, Phys. Rev. D **91**, 063011 (2015)

[3] A. Fedynitch et al. EPJ Web Conf. **99**, 08001 (2015); arXiv:1503.00544; PoS (ICRC2015) 1129

[4] R. Abbasi et al. (IceCube Collaboration), Phys. Rev. D **83**, 012001 (2011)

[5] M.G. Aartsen et al. (IceCube Collaboration). Eur. Phys. J. C **75**, 116 (2015)

[6] M.G. Aartsen et al. (IceCube Collaboration), Phys. Rev. Lett. **110**, 151105 (2013)

[7] M.G. Aartsen et al. (IceCube Collaboration), Phys. Rev. D **91**, 122004 (2015)

[8] S. Adrian-Martinez et al. Eur. Phys. J. C **73**, 2606 (2013)

[9] A. A. Kochanov, T. S. Sinegovskaya, S. I. Sinegovsky, Astropart. Phys. **30**, 219 (2008); arXiv:0803.2943v2 [astro-ph]