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Derivation of upward muon energy spectra in the TeV range produced by neutrinos from $3C273$ AGN and diffuse atmospheric sources

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Summary. — The neutrino-induced upward muon energy spectrum on Earth at the TeV energy range emitted by the point source $3C273$ AGN has been calculated using the AGN-emitted neutrino spectrum of Szabo and Protheroe and the result has been compared with that expected from background neutrinos. The QCD-based model of Berezinsky *et al.* has been fairly employed to estimate the muon contribution due to the charge current interactions in rock. The diffuse neutrino-induced upward muon energy spectrum from AGN sources has also been estimated and compared with the expected results from the spectra of prompt neutrinos and atmospheric backgrounds. It is found that the upward muon fluxes generated by AGN neutrinos are dominating the Universe beyond 10 TeV muon energy.

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1. – Introduction

Astrophysics of high-energy muons and neutrinos is dependent on the decay of non-prompt mesons and charm particles. The primary cosmic nuclei interact with the atmosphere producing pions and kaons which decay to give the muons and neutrinos. It is assumed that the TeV neutrino-induced upward muons have extragalactic origin and are produced in Active Galactic Nuclei (AGN) like $3C273$. The massive black hole in the center of the AGN acts as an accelerator and may be considered as a source of the jets that may be detected in radio observations. Active galactic nuclei (AGN) are the most luminous objects in the Universe and have been considered as possible sources of high-energy neutrinos. The luminosities of AGN usually range from 10^{42} to 10^{48} ergs/s, which corresponds to black-hole masses from 10^4 to $10^{10} M_\odot$, where $M_\odot$ is the solar mass, and are energised by accretion onto a black hole. The AGN is assumed as one of the main

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point sources of super-high-energy neutrinos apart from the atmospheric diffuse neutrinos coming from X-ray binaries, supernova remnants and also from the extra galactic cosmic-ray backgrounds. The simple model of AGN used for galactic neutrino spectrum calculation is based on approximate conditions in the AGN central engines in which accretion onto a supermassive black hole takes place. In general, the high-energy neutrino background and cosmic-ray proton intensity calculated using such models would be much less than given in [1] which may be considered as an estimate from AGN central engines, apart from the AGN jets. AGN may also be a source of cosmic rays in the region of the knee. The AGN γ-rays detected by EGRET [2] experiments have been blazers and the γ-ray emission from these objects is associated with jets. It may be assumed that the AGN are the sources of energetic cosmic rays with energies up to 10^{10} GeV. Such particles would interact with matter in the Galaxy or with the intergalactic medium or with the cosmic microwave background. The generated π^0 yields information on the upper limit of the emitted neutrino flux from AGN-based models on the observed X-ray and γ-ray fluxes. It is also assumed that AGN has confined sufficient matter to stop protons before they diffuse out of the Galaxy. AGN is considered as a potential source of high-energy ν-production. They may be influenced by gravitational energy of matter independent of supermassive black hole at the AGN center. The AGN is assumed to behave like a space ion accelerator and beam dumps which also act as an intense source of high-energy neutrinos. Investigation on atmospheric neutrinos is of pheneomenological importance for the background calibration in the under-earth detectors for studying the problems relating to the exploration of stellar collapse in neutrino astronomy [3]. In a recent survey, Gaisser *et al.* [4] have discussed different sources of atmospheric, galactic and extra-galactic (AGN) neutrinos.

A portion of neutrinos entering the Earth from the nadir direction usually interacts with Earth material generating upward muons which can be detected in underground detectors. The down-going muons produced by neutrinos incident from the zenithal direction are mixed with atmospheric backgrounds like meson decay muons. Usually, the neutrinos on Earth have to travel an average distance $\sim 1.3 \times 10^4$ km up the diameter of the Earth. The neutrino telescopes detect muons produced by neutrinos in the water or ice and also in the detector materials. The Cherenkov detectors are shielded by a thick layer of water or earth that helps the filtering of a substantial portion of atmospheric backgrounds. The neutrino telescopes underground the South Pole are investigating the interaction of neutrinos entering the Earth from the northern hemisphere. Recently, Barwick *et al.* [5] have discussed three kinds of underground detectors: some are under construction and some are proposed to be constructed to investigate the atmospheric and extra-galactic neutrino-induced interaction phenomena as carried out at the i) Antarctic Muon and Neutrino Detector Array (AMANDA [6]) using sterile ice, ii) Lake BAIKAL [7] detector in Siberia by eliminating background noise signals using photomultiplier tubes, iii) Deep Underwater Muon and Neutrino Detector (DUMAND [8]) located near Hawaii Islands, at a depth of 4.5 km of ocean water, iv) Neutrinos from Supernovae Experiment Ocean Range (NESTOR [9]) with more than 1 km of ocean water, in the deep Mediterranean Sea coast.

Gamma-rays and neutrinos are produced in beam dumps by primary cosmic accelerators colliding with different stellar targets. As a consequence, the neutrinos are produced by the decay of non-prompt mesons like π^+ and π^- into μ and ν_μ. The accelerated cosmic rays interact with the Earth atmosphere, the Sun, and Moon, interstellar gas in our galaxy and the cosmic photon background in the Universe. The diffuse neutrinos which are generated in the interactions of galactic cosmic rays with the microwave background is of special astrophysical importance. The cosmic rays of energies 10^{14} eV are assumed to be accelerated by shocks driven into the ISM by supernova explosions. Recently, Zas *et al.* [10] have pointed out that astrophysical neutrinos reside at the highest energies and have a flatter energy spectrum coming from extra-terrestrial sources. They are expected to dominate the atmospheric neutrino production. Theoretical calculations of the neutrino production at AGN have been done by Stecker *et al.* [11] and also by Szabo and Protheroe [12]. Berezinsky and Ginzburg [13] have pointed out that the AGN are the most luminous objects in the Universe and are the major sources of high-energy signals. The simple model [12] of AGN for galactic neutrino spectrum is based on the approximate conditions in the source AGN central engines in which accretion on supermassive black hole takes place. Usually, the high-energy neutrino background and cosmic-ray proton intensity derived from such models would be much less than that expected from ref. [13]. This may be considered as an estimate from AGN central engines as distinct from AGN jets. AGN may also be treated as a source of cosmic rays in the region of knee for energies up to 10^{10} GeV. Such particles would interact with the matter confined in the inter-galactic medium or with the cosmic microwave background. The generated neutral pions give an estimate on the upper limit of the produced neutrino flux from AGN-based model on the observed X-ray and γ-ray fluxes. It is also assumed that AGN has sufficient matter to stop protons before they diffuse out of the galaxy. Stanev [14] has suggested that the total high-energy neutrino signals depend on the power of AGN and on the number density. The knowledge of the hadronic interaction cross-sections is essential for the evaluation of the energy transport at AGN and on the shock acceleration models followed by photoproduction processes which accounts for the proton energy loss. So, the charged particles injected in the Galaxy are termed cosmic rays and some fraction of the photons and neutrinos escape the galaxy and reach the Earth in the form of directional beams.

The recent model of diffuse neutrino fluxes escaping from the production region at AGN tend to predict higher underground muon fluxes than those expected from prompt charm particle decays. The vertical up-coming underground muon signals from prompt neutrino fluxes are very close to the diffuse AGN signal. Neutrinos and gamma-rays are mainly generated from $\pi^+ \to \mu^+\nu_\mu$ and $\pi^0 \to 2\gamma$ decays and the subsequent meson decay $\mu^+ \to \bar{\nu}_\mu + \nu_e + e^+$. Bugaev and Osipova [15] have studied energy spectrum and intensities of extra-galactic neutrino-produced muons duly generated in the interactions of cosmic rays with relic photons of energies $E > 10^{17}$eV.

In the present work we have considered the neutrino spectra available from the point and diffuse AGN sources in the central region of $3C273$ after Szabo and Protheroe [12] and atmospheric neutrino background from Gaisser *et al.* [4] and Allkofer and Bhattacharyya [16]. By adopting the QCD-based weak-interaction model of Berezinsky *et al.* [17], the energy spectra of upward neutrino-induced muons from point and diffuse AGN sources have been calculated and compared with the atmospheric-background neutrino-induced upward muon energy spectra.

2. – Nuclear physics and results

Szabo and Protheroe [12] have calculated the neutrino production spectra from radio-quiet AGN by spherical accretion shocks normalized to the luminosity at the galactic central region of $3C273$ escaping and derived the neutrino production spectrum from the point source, which has been found to follow the form

$$E(\mathrm{d}N/\mathrm{d}E) = 1.26 \times 10^{-8}(E/\mathrm{GeV})^{-1}(\mathrm{cm}^2\ \mathrm{s})^{-1}\,, \tag{1}$$

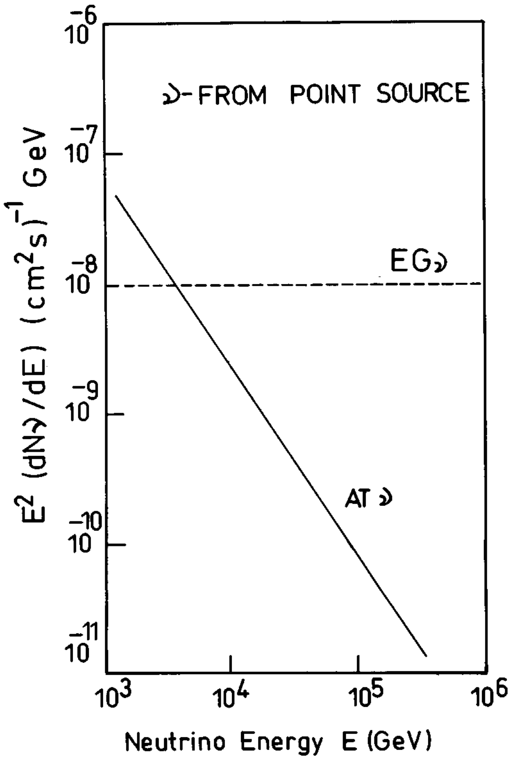

Fig. 1. – The energy spectra neutrinos from point source: The atmospheric background neutrinos within 1° after Gaisser *et al.* [4]—ATν; neutrinos from the Active Galactic Nuclei (AGN) sources after Szabo and Protheroe [12]—EGν.

and the diffuse atmospheric source background neutrino spectrum after Gaisser *et al.* [4] follows the form

$$E(\mathrm{d}N/\mathrm{d}E = 1.42 \times 10^{-3}(E/\mathrm{GeV})^{-2.45}(\mathrm{cm}^2\ \mathrm{s})^{-1}\,. \tag{2}$$

We have compared those neutrino spectra in fig. 1 which shows that the neutrino spectra from AGN sources dominate beyond the 10 TeV energy. The diffuse atmospheric neutrino spectrum from the decay of non-prompt and prompt meson decay after Allkofer and Bhattacharyya [16] has been found to follow the form

$$E(\mathrm{d}N/\mathrm{d}E) = 2.34E^{-2.7}(\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}\,, \tag{3}$$

for vertical incidence and the prompt neutrino spectrum obeys the relation

$$E(\mathrm{d}N/\mathrm{d}E) = 5.95 \times 10^{-6}E^{-1.7}(\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}\,. \tag{4}$$

The extra-galactic AGN-emitted diffuse neutrino spectrum [12] follows the form

$$E(\mathrm{d}N/\mathrm{d}E) = 4.29 \times 10^{-8}E^{-1.1}(\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}\,. \tag{5}$$

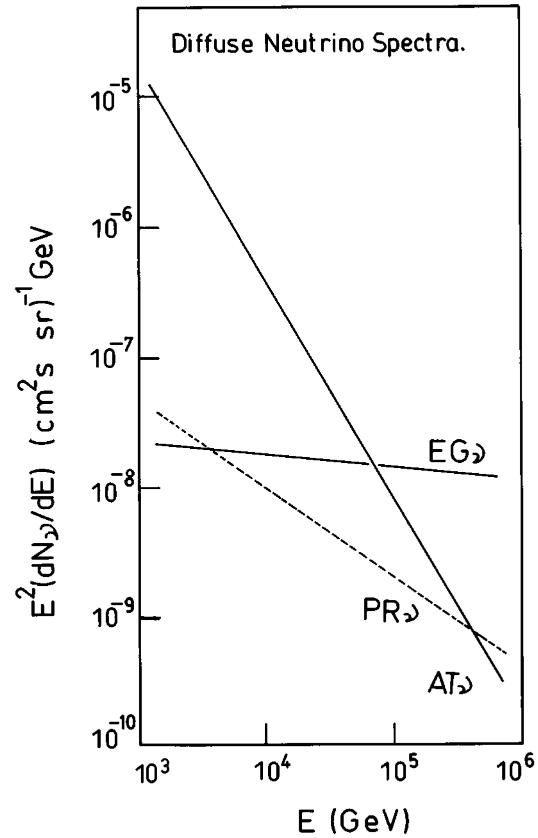

Fig. 2. – Energy spectra of isotropic neutrinos: Atmospheric diffuse neutrino spectra at zenith angles 0°—ATν; prompt neutrino spectrum obtained from the decay of charm mesons [16] —PRν. The neutrino spectrum available from the AGN diffuse source $3C273$ after Szabo and Prothero [12]—EGν.

The diffuse neutrino spectra from different sources have been compared in fig. 2 and it is found that the background atmospheric neutrinos are decreasing in the high-energy region. The diffuse extragalactic neutrino spectrum is dominant beyond 50 TeV energy. In fig. 3 we have compared the diffuse AGN neutrino spectrum [12] with the neutrino flux distribution at the bright phase for the redshifts $z_{\rm f} > 10$ in the Galaxy [18]. The bright phase of the galactic evolution enhances the generation of ultra-high-energy particles which occur due to collisions of the primary cosmic rays with the high-density relic photons and which are created through a chain of meson decay energetic neutrinos. The atmospheric neutrino spectra derived from non-prompt and prompt particle decay after Allkofer and Bhattacharyya [16] have also been presented in the same figure. By using the BCG [17] method and treating the Earth as a target, the deep underground or underwater TeV upward neutrino flux $N_{\nu_\mu+\bar{\nu}_\mu}(>E)$ producing the muon flux $N_\mu(>E)$ reaching the detector may be calculated using the relation

$$N_\mu(>E) = N_{\nu_\mu+\bar{\nu}_\mu}(>E)[\sigma_0 N_{\rm A}/b_{\rm T}][\eta Y_{\mu^-}(\gamma\,,E) + \bar{\eta} Y_{\mu^+}(\gamma\,,E)]\,, \tag{6}$$

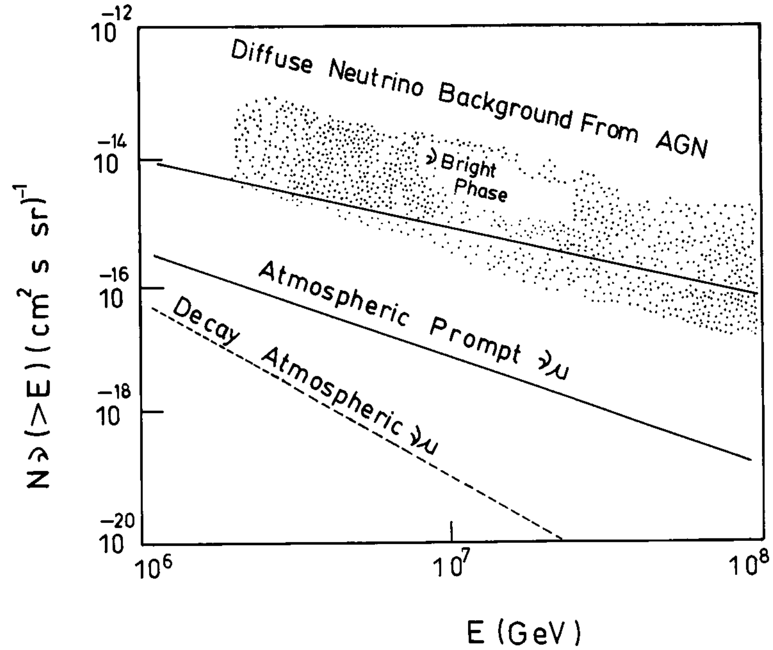

Fig. 3. – Spectra of diffuse neutrinos from AGN [12] has been compared with the bright phase neutrino spectrum (for large redshifts $z_f = 30$) after Berezinsky and Ozernoy [18]. The neutrino spectra expected from the non-prompt and prompt meson decay after Allkofer and Bhattacharyya [16] have been displayed in the same figure.

where we took $\sigma_0 = 1.11 \times 10^{-34}(m_W/81\mathrm{GeV})^2\mathrm{cm}^2; m_W = 81\mathrm{GeV}$, $N_\mathrm{A} = 6.024 \times 10^{23}$; $\eta = \bar{\eta} = 0.5; \gamma = 1, 1.1$ for Extra Galactic AGN neutrinos and 1.7, 2.7 for atmospheric prompt and non-prompt neutrino spectra, respectively; b_T is the muon energy loss parameter in earth material which is a sum of the muon energy loss coefficients for pair production, bremsstrahlung and nuclear interactions, *viz.* b_P, b_B and b_N, and in the TeV energy region one can safely assume that the relative energy losses are independent of the muon energy E, *viz.*

$$\frac{1}{E}(\mathrm{d}E/\mathrm{d}t) = b_\mathrm{T}\,, \tag{7}$$

where t is the thickness of the absorbing medium. We have chosen those numerical values from the QED-based estimates of Bezrukov and Bugaev [19]. The generation integral muon moments $Y_{\mu^+}(\gamma, E)$ and $Y_{\mu^-}(\gamma, E)$ have been computed for μ^- and μ^+ mesons at different TeV energies for $\nu_\mu + \mathrm{N} \to \mu^- + \mathrm{X}$ and $\bar{\nu}_\mu + \mathrm{N} \to \mu^+ + \mathrm{X}$ reactions using the formulation of Berezinsky and Gazizov [20]. In this affair the charge current cross-sections have been considered from the QCD quark distribution. These moments are adoptable for the estimation of the probability of interaction of cosmic neutrinos with the Earth producing an upward muon which has enough energy to reach the underground detector. The derived vertical integral equilibrium spectrum of upward muons on Earth produced by AGN neutrinos from $3C273$ is shown in fig. 4 along with the derived background neutrino-induced upward muon spectrum.

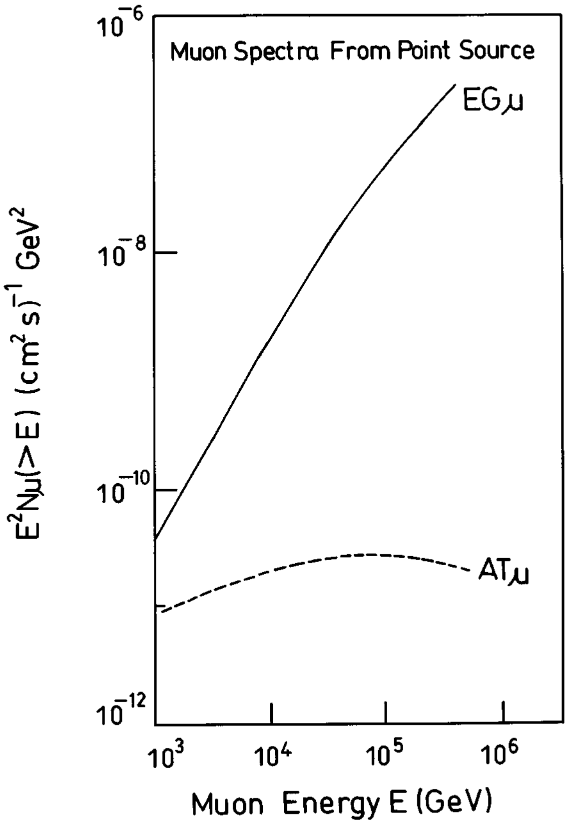

Fig. 4. – The derived upward muon energy spectra produced by AGN neutrinos from point source: Muon spectrum generated by AGN source neutrinos [12]—EGμ; muon spectrum derived from atmospheric neutrino background sources [4]—ATμ.

We have used our earlier estimate on local atmospheric vertical muon neutrino spectrum arising from the decay of pions and kaons [16] which follows the form

$$N^{\text{atm}}_{\nu_\mu+\bar{\nu}_\mu}(>E) = 0.8667E^{-2.7}(\text{cm}^2\ \text{s sr})^{-1}\,. \tag{8}$$

Using the source spectrum (5) and formula (6), the vertical non-prompt meson decay atmospheric diffuse neutrino-induced integral muon spectrum has been calculated and the result is displayed in fig. 5. The derived spectrum of muons by diffuse neutrinos from $3C273$ AGN source is found flatter than that obtained from the background neutrino-induced muon spectrum and beyond 10 TeV the diffuse AGN neutrino-induced muon spectrum is dominanting. The plot also exhibits the steeper spectrum of upward diffuse neutrino-induced muons arising from the neutrinos produced from the decay of non-prompt mesons. The calculated vertical muon flux above 2 TeV has been found to be $4.67 \times 10^{-16}(\text{cm}^2\text{s sr})^{-1}$ which is lower than the upper-limit value $8 \times 10^{-15}(\text{cm}^2\text{s sr})^{-1}$ obtained from the Frejus experiment [21]. The underground detectors can detect the muon flux produced by the galactic VHE neutrinos moving through the Earth in the direction of the upper hemisphere and the background muon flux is mainly arising from the

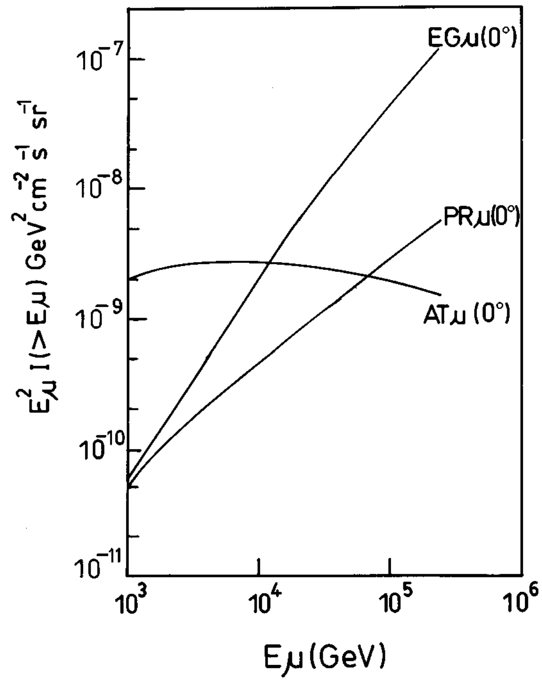

Fig. 5. – Integral energy spectra of upward muons initiated by diffuse atmospheric non-prompt, prompt and extragalactic AGN neutrinos: Spectra of muons initiated by the fluxes of atmospheric neutrinos [16] at zenith angles 0° represented by the curve—ATμ. The muon spectrum calculated from the prompt neutrinos—PR$\mu(0^0)$. Muon spectrum estimated from the isotropic neutrinos emitted from the $3C273$ region of the Galaxy [12]—EGμ.

atmospheric neutrinos. The effective target area of the underground muon detectors is usually large and the high-energy muons are produced mostly outside the detectors. For the detection of galactic neutrinos a higher threshold muon energy is required to separate neutrinos from the background ones. The direct AGN neutrino contribution is dominant for neutrino energies $E_\nu \geq 10^5$ GeV.

3. – Conclusion

The BCG model can be fairly used for the estimation of AGN neutrino-induced upward muon spectra near the Earth. It is found that the AGN neutrino-induced muon spectrum exhibits a flatter spectral index when compared to the background neutrino-induced muon spectrum results. The present analysis reveals the fact that AGN neutrino-induced muon fluxes exceed the background atmospheric neutrino-induced muon fluxes beyond 10 TeV energy. The derived muon flux above 2 TeV is found lower when compared to the measured upper limit result obtained from Frejus experiment.

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