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Estimation of the detectable flux of astrophysical neutrinos at the Pierre Auger observatory by means of horizontal air showers

J. C. Arteaga-Velázquez and A. Zepeda
Department of Physics, Cinvestav, Apartado Postal 14-740, 07000, Mexico, DF, Mexico.
Presenter: A. Zepeda (zepeda@fis.cinvestav.mx), mex-zepeda-A-abs2-he22-poster

Several astrophysical models and extensions of the Standard Model of elementary particles predict the existence of important sources of very high energy neutrinos across the universe. The detection of these energetic particles will open a new astronomical window and will constitute a new tool to probe deeply into several thick and energetic regions of the universe which can be hardly studied by using only the electromagnetic radiation. When the Pierre Auger Observatory is completed, it will be able to detect ultrahigh energy astrophysical neutrinos ($E_\nu > 1$ EeV) by observing the air showers of secondary particles induced by the neutrinos in collisions with the atmosphere on their route to the detector. In particular, the observatory will look for those events traveling near the horizontal direction. In this work we calculated the detectable flux of ultrahigh energy muon neutrinos at the Pierre Auger Observatory for several particle physics and astrophysical models. Based on these estimates, we found that, in some scenarios, the diffuse flux of active galactic nuclei and topological defects have the greatest possibility of detection of all the spectra which we analyzed and that the muon neutrinos from the GZK cut off will be very difficult to observe by using the above technique and only muon neutrinos.

1. Introduction

Although, the southern Pierre Auger observatory (PAO) has not been completed yet, it is already the largest working surface array in the world to study ultrahigh energy cosmic rays (UHECR) by means of the air shower technique. This observatory is now under construction in Mendoza, Argentina [1]. In its final stage, It will cover a total surface of $3000\,\mathrm{km}^2$ with an array of 1600 water Cherenkov detectors (separated by 1.5 km) and four stations with fluorescent telescopes [1]. The above instruments will study the properties of the secondary air showers induced in the atmosphere by UHECR to infer the energy and direction of these particles: The Cherenkov detectors will sample the lateral distribution of the cascades at ground level and the fluorescent detector will measure the longitudinal development of the air shower [1].

In addition to cosmic ray research, the PAO will have the possibility to study ultrahigh energy neutrinos (UHEν) [2]. The information obtained in this way will be complementary to that resulting from neutrino telescopes based on the Cherenkov technique [3]. The PAO will observed neutrinos indirectly. In particular, muon neutrinos will be detected through the secondary air showers that they induce in the atmosphere on their way to the detector. The search of UHEν will be focused on the horizontal direction in the PAO, since, in this way, it will be easier to separate the showers induced by neutrinos from those of cosmic rays [2].

In order to explore the potential of the PAO to muon neutrinos, we calculate the detectable flux of extraterrestrial ν_μ neutrinos at ultrahigh energies under several astrophysical and exotic scenarios with the Cherenkov array.

2. Detection of muon neutrinos at the PAO

When a muon neutrino with energy E_ν interacts weakly with a nucleon (N) of the atmosphere, it produces a hadronic shower (X) with energy $E_{sh} = yE_\nu$ that generates the cascade that is expected to be observed with the PAO. At ultrahigh energies the interaction with the hadron is deeply inelastic and it is mediated by charged

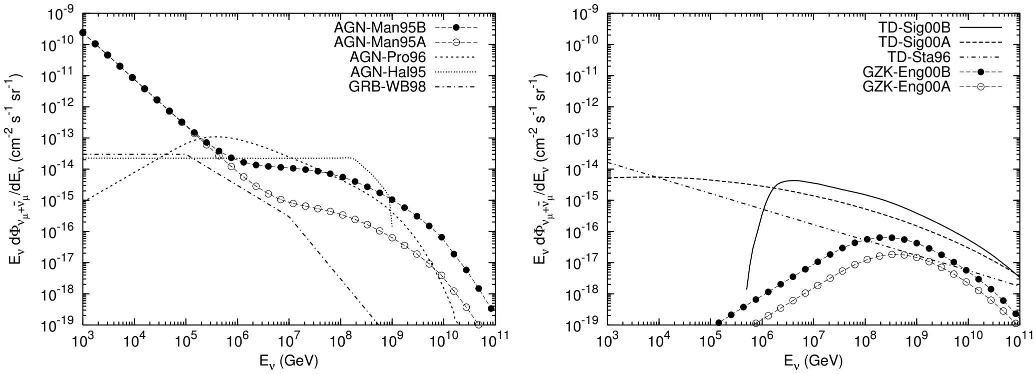


Figure 1. Astrophysical and exotic fluxes of high energy muon neutrinos. See text for description.

or neutral currents. In the first case, we have the following reaction: $\nu_\mu N \to \mu^- X$, and in the second one, $\nu_\mu N \to \nu_\mu X$.

Following Gandhi *et al.* [3] and neglecting neutrino absorption in the atmosphere (which is valid since at the energies considered here the $\nu_\mu N$ interaction length surpasses more than 10^2 times the horizontal atmospheric depth [3]), the rate of detectable muon neutrinos at the PAO is given by the expression

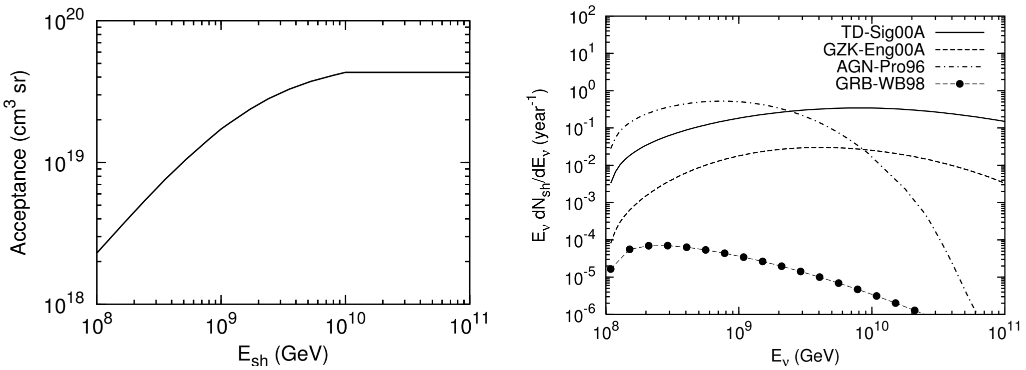
$$N_{sh} = N_A \rho_{air} \int_{E_{sh}^{min}}^{E_\nu^{max}} \int_{E_{sh}^{min}/E_\nu}^{1} dE_\nu \, dy \, \Phi^0_{\nu_\mu}(E_\nu) \times \mathcal{A}(E_{sh}) \times \frac{d\sigma^{Tot}_{\nu N}(E_\nu, y)}{dy}, \tag{1}$$

where $E_{sh}^{min} = 10^8, 10^9$ GeV is the threshold energy for horizontal air shower observations and $E_\nu^{max} = 10^{11}, 10^{12}$ GeV, the maximum neutrino energy. N_A is the Avogadro number, while $\rho_{air} \sim 10^{-3}$ g/cm^2 is the density of the atmosphere [3]. Finally, the quantities $\Phi^0_{\nu_\mu}(E_\nu)$, $\mathcal{A}(E_{sh})$ and $d\sigma^{Tot}_{\nu N}(E_\nu, y)/dy$ represent the initial muon neutrino flux that arrives to the Earth, the acceptance of the PAO and the differential $\nu_\mu N$ total cross section, respectively. For the case of muon antineutrinos we applied a similar equation.

The astrophysical and exotic models that were explored in this work are shown in figure 1. We employed Halzen's (AGN-Hal95) [4], Protheroe's (AGN-Pro96) [5] and Mannheim's models (AGN-Man95A, AGN-Man95B) [6] to describe the diffuse flux of muon neutrinos from active galactic nuclei (AGN). The second AGN spectrum was multiplied by 0.25 according to reference [7]. We also worked with the Waxman and Bahcall's diffuse flux from gamma ray bursts [8], and with two spectra for ν_μ neutrinos from the GZK cut off due to Engel *et al.* (GZK-Eng01A and GZK-Eng01B), with different cosmological evolution for the cosmic ray sources [9]. Two Sigl's models of topological defects (TD-Sig00A, TD-Sig00B) [10] and one proposed by Protheroe and Stanev *et al.* (TD-Sta96) [11] were also included in this paper.

We estimated the total $\nu_\mu(\bar{\nu}_\mu)N$ cross sections at leading order with the quark-parton model. The latest parton distribution functions from CTEQ were used in this evaluation (in particular, the set CTEQ6-L1) [12] in combination with the Double Logarithmic Approximation [13]. Here, N is an isoscalar target.

The acceptance of the Cherenkov array of the PAO to horizontal air showers (with zenith angles between 75° and 90°) was calculated by P. Billoir in reference [14] up to shower energies of 10^{10} GeV. As it was the case in [3], we had to extrapolate Billoir's acceptance to higher energies in order to evaluate the rates given in (1) with $E_\nu^{max} = 10^{11}$ (10^{12}) GeV. A graph of the acceptance of the PAO, $\mathcal{A}(E_{sh})$, as a function of E_{sh}, is presented in figure 2a.



(a) (b)

Figure 2. (a) Acceptance of the Cherenkov array of the Pierre Auger Observatory to horizontal air showers as a function of the energy of the cascade (E_{sh}). (b) Differential rates of detectable air showers at the PAO produced by ultrahigh energy muon neutrinos and antineutrinos from different spectra as a function of the energy E_ν. We used $E_\nu^{max} = 10^{11}$ GeV and $E_{sh}^{min} = 10^8$ GeV.

3. Results and discussions

The final rates of detectable muon neutrinos at the PAO are shown in table 1. From there, we can see that these values are small but not negligible, except for the GRB model. If $E_{sh}^{min} = 10^8$ GeV and $E_\nu^{max} = 10^{11}$ GeV, the higher detectable rates come from some AGN and TD models, while the lower ones belong to the GZK and the GRB fluxes. However, the detection of the diffuse ν_μ flux from TD's and AGN's could be also as difficult as for the GZK models under the TD-Sta96 and the AGN-Man95A scenarios. The situation is worst when E_{sh}^{min} is increased to 10^9 GeV because the detectable rates become smaller. In addition, the Halzen's AGN model, which predicts neutrinos with a maximum energy of 10^9 GeV (assuming that AGN's accelerates cosmic rays up to 5×10^{19} GeV), gives no events.

In figure 2b, we show the number of detectable events in one year produced by neutrinos with different energies E_ν from some specific models and using $E_\nu^{max} = 10^{11}$ GeV and with $E_{sh}^{min} = 10^8$ GeV. In this graph, we observe the different energy intervals in the primary ν_μ spectra that are relevant for the production of detectable events in several cosmic scenarios. For the GRB spectrum and the Protheroe's model of AGN muon neutrinos, almost 99% of the events are produced by ν_μ neutrinos with energy in the interval $1 \times 10^8 - 7 \times 10^9$ GeV, respectively. In contrast, the relevant energy region in the Sigl's fluxes of TD neutrinos extends from 10^8 up to $E_\nu^{max} = 10^{11}$ GeV.

Based on the magnitude of these rates, we can realize that the Pierre Auger observatory will have to use complementary channels to search for cosmic neutrinos, besides that which involves ν_μ interactions in the atmosphere. One of these channels could be the additional search of $\nu_e N$ interactions, again by looking for horizontal air showers [3]. Astrophysical models produce only ν_e and ν_μ neutrinos with the following proportions $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ at the source [15], but in scenarios with neutrino oscillations, there appears also a ν_τ flux from astrophysical sources produced by $\nu_\mu \leftrightarrow \nu_\tau$ oscillations that occurs in the space when neutrinos travel to the Earth [15]. The detection of tau neutrinos is another channel that could be explored in the PAO [2]. When traveling to the detector, ν_τ neutrinos that arrives near the horizontal direction or skimming the Earth may interact by charged currents with the rock around the observatory, i.e., with the rock in the mountains and inside the ground, producing taus. Thus, a ν_τ could be also detectable if the tau escapes from

Table 1. Detectable rate of extraterrestrial muon neutrinos and antineutrinos at the Pierre Auger Observatory with the Cherenkov array at ultrahigh energies under different cosmic scenarios and with $E_{\nu}^{max} = 10^{11}$ (10^{12}) GeV.

Model E_{sh}^{min}(GeV)		AGN-Man95B	AGN-Man95A	AGN-Pro96 × 25 %	AGN-Hal95	GRB-WB98
10^8		4.53	0.28	1.31	3.69	1.63×10^{-4}
10^9		1.73	0.11	0.21	0	1.68×10^{-5}
Model E_{sh}^{min}(GeV)		TD-Sig00B	TD-Sig00A	TD-Sta96	GZK-Eng00B	GZK-Eng00A
10^8		2.81 (2.99)	1.44 (1.61)	0.28 (0.42)	0.27	0.10
10^9		1.63 (1.80)	0.94 (1.10)	0.21 (0.34)	0.15	0.063

the rock and decays in the atmosphere producing an observable air shower [2]. With all the above windows the probability of detection of UHEv sources would be higher than by observing muon neutrinos alone.

4. Conclusions

The Pierre Auger observatory will be able to detect some ultrahigh energy muon neutrinos from outer space according to some AGN and TD models. However, there are also pessimistic AGN and TD scenarios which predicts a low rate of detectable muon neutrinos at the observatory. On the other hand, the background signal of muon neutrinos from the GZK cut off and the diffuse ν_μ flux from GRB's will be very difficult to detect with the Pierre Auger observatory. From these results, it can be concluded that It will be important to complement the cosmic neutrino search by using other channels, for instance, looking for horizontal air showers induced by ν_e's and ν_τ's interactions in the atmosphere and by tau decays, which could be produced by ν_τ's interacting with the rock in the mountains near the detector or, for neutrinos skimming the Earth, in the ground surrounding the observatory.

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References

[1] J. Abraham *et al.* (Pierre Auger collaboration), Nucl. Instr. and Meth. **A523**, 50 (2004).
[2] X. Bertou *et al.*, Astropart. Phys. **17**, 183 (2002).
[3] R. Gandhi *et al.*, Phys. Rev. **58D**, 093009-1 (1998).
[4] F. Halzen, electronic archive: astro-ph/0301143.
[5] R. J. Protheroe, electronic archive: astro-ph/979607165.
[6] K. Mannheim, Astropart. Phys. **3**, 295 (1995).
[7] R. J. Protheroe, electronic archive: astro-ph/9809144.
[8] E. Waxman and J. Bahcall, Phys. Rev. **59D**, 023002 (1998).
[9] R. Engel, D. Seckel and Todov Stanev, Phys.Rev. **D64**, 093010 (2001).
[10] G. Sigl, electronic archive: astro-ph/0008364.
[11] R. J. Protheroe and T. Stanev, Phys. Rev. Lett. **77**, 3708 (1996).
[12] J. Pumplin *et al.*, JHEP **07**, 012 (2002).
[13] L. V. Gribov, E. M. Levin, M. G. Ryskin, Phys. Rep. **100**, 1 (1983); D. W. McHay, J. P. Ralston, Nucl.Phys. Proc.Suppl. **18**, number 3, 86 (1991).
[14] Pierre Billoir, Pierre Auger technical note GAP-1997-049, http://www.auger.org.
[15] S. I. Dutta, M.H. Reno, I. Sarcevic, Phys. Rev. **62D**, 123001-1 (2000).