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Influence of the regeneration by neutral currents in the observable flux of upward-going muons induced by astrophysical neutrinos

J. C. Arteaga-Velázquez, A. Zepeda
Department of Physics, Cinvestav, Apartado Postal 14-740, 07000, Mexico, DF, Mexico.
Presenter: A. Zepeda (zepeda@fis.cinvestav.mx), mex-zepeda-A-abs3-he22-poster

The telescopes of astrophysical high-energy neutrinos based on the Cherenkov technique are very different from the conventional telescopes in that the first ones look down, to the interior of the Earth. These Cherenkov detectors are designed to observe the upward-going muons produced by muon neutrinos that traverse through our planet, when they interact weakly with matter around the detector. In order to interpret the data from upward-going muons it is important to understand how the neutrino flux is modified when it travels through the Earth. Besides absorption, the neutrino flux can be altered by other mechanisms, for example, regeneration by means of neutral currents. In this work we explore the effect of the regeneration through neutral currents in the propagation of neutrinos and its influence on the observable flux of upward-going muons for different astrophysical and exotic models of high-energy neutrinos.

1. Introduction

The detection of extraterrestrial high-energy neutrinos will open a new window to the farthest and most energetic phenomena in the universe. So far, these elusive particles have escaped from observation but it is thought that with the next generation of 1 km^3 Cherenkov detectors, like Icecube, the first detection of very high-energy neutrinos from outer space could be achieved [1]. The neutrino telescopes based on the Cherenkov technique look in the direction of the Earth and use our planet as a filter for neutrinos and as an extension of the detector [2]. They are designed to observe the upward-going muons produced by muon neutrinos in charged current interactions with the rock under the detector [3].

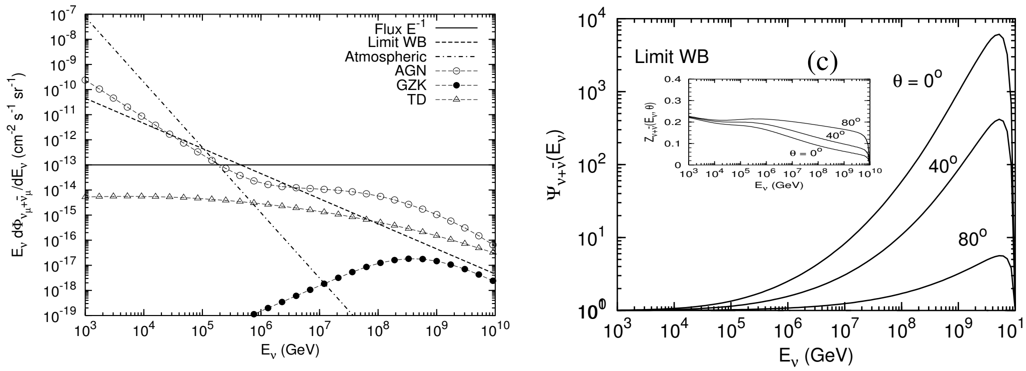
In its transit through the Earth, the neutrino flux is modified mainly by absorption due to $\nu_\mu N$ interactions, where N is a nucleon from the medium. However, there are secondary mechanisms, such as regeneration by means of neutral currents, that alter the shape of the neutrino flux and hence the rate of detectable upward-going muons. Therefore, those processes must be studied in order to understand properly the data from Cherenkov detectors. In this article, we will be concerned with the role of the regeneration by neutral currents in the propagation of muon neutrinos through the Earth and with its contribution to the detectable flux of upward-going muons from different sources.

2. Regeneration by means of neutral currents

At high energies, neutrinos which undergo charged current (CC) interactions are removed from the initial flux, but those which interact through neutral currents (NC) only degrade their energy, that is, present regeneration [4]. This phenomenon is possible because at high energies the final lepton tends to conserve the direction of the initial neutrino [5], and because in each $\nu_\mu N$ collision the neutrino, in average, loses a small fraction y of its initial energy (For $E_\nu = 10^6 - 10^{10}$ GeV, $\langle y \rangle = 0.3 - 0.2$ [6]).

Neglecting $\nu_\mu e$ interactions, the transport equation that applies to a muon neutrino flux that traverse through the Earth (in absence of ν oscillations and muon decay) is [4]

$$\frac{d\Phi_{\nu_\mu}(E_\nu,\tau)}{d\tau} = -\Phi_{\nu_\mu}(E_\nu,\tau) N_A \sigma_{\nu N}^{Tot}(E_\nu) + \int_{E_\nu}^{E_\nu^{max}} \Phi_{\nu_\mu}(E'_\nu,\tau) N_A \frac{d\sigma_{\nu N}^{NC}(E'_\nu, E_\nu)}{dE_\nu} dE'_\nu. \quad (1)$$



(a) (b)

Figure 1. (a) Astrophysical and exotic fluxes of high-energy muon neutrinos. See text for description. In (b) and (c) we can see the regeneration and the Z_ν factor, respectively, for the Waxman-Bahcall bound as a function of the energy E_ν for three different nadir angles.

A similar equation applies for muon antineutrinos. In the above equation, θ is the nadir angle of observation, $\tau(\theta)$; the column depth of matter found by a neutrino along the θ direction after traversing a given distance inside the Earth; N_A, the Avogadro's number; $\sigma_{\nu N}^{Tot}$, the total $\nu_\mu N$ cross section; $d\sigma_{\nu N}^{NC}(E'_\nu, E_\nu)/dE_\nu$, the differential one for the corresponding neutral current process, and $\Phi_{\nu_\mu}(E_\nu, \tau)$ represents the flux of muon neutrinos at $\tau(\theta)$. The first term on the right-hand side of relation (1) is associated with absorption and the second one, with regeneration. The effect of absorption and regeneration in $\Phi_{\nu_\mu}(E_\nu, \tau)$ can be factorized using the following expression [7]:

$$\Phi_{\nu_\mu}(E_\nu, \tau(\theta)) = \Phi^0_{\nu_\mu}(E_\nu) e^{-\tau(\theta)/\mathcal{L}_{\nu N}^{Tot}(E_\nu)} \Psi(E_\nu, \tau(\theta)), \quad (2)$$

where $\Phi^0_{\nu_\mu}(E_\nu)$ is the initial flux that arrives to the Earth surface and $\mathcal{L}_{\nu N}^{Tot}(E_\nu) = 1/N_A \sigma_{\nu N}^{Tot}(E_\nu)$, the total $\nu_\mu N$ interaction length of a muon neutrino with energy E_ν. The effect of the regeneration is put inside $\Psi(E_\nu, \tau)$, which has become known as the regeneration factor and satisfies $\Psi(E_\nu, \tau) \geq 1$. The factor $\Psi(E_\nu, \tau)$ is ruled by the following integro-differential equation [7]:

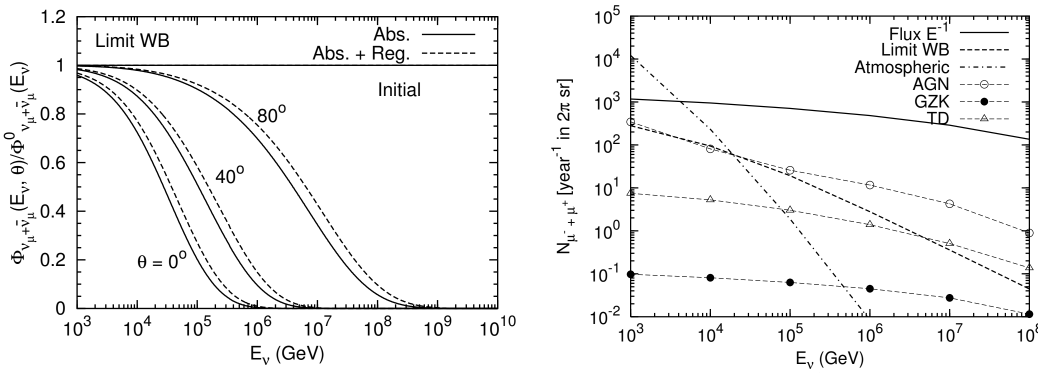
$$\frac{d\Psi(E_\nu, \tau)}{d\tau} = N_A \int_{E_\nu}^{E_\nu^{max}} dE'_\nu \frac{d\sigma_{\nu N}^{NC}(E'_\nu, E_\nu)}{dE_\nu} \frac{\Phi^0_{\nu_\mu}(E'_\nu)}{\Phi^0_{\nu_\mu}(E_\nu)} e^{-N_A[\sigma_{\nu N}^{Tot}(E'_\nu) - \sigma_{\nu N}^{Tot}(E_\nu)]\tau} \Psi(E'_\nu, \tau), \quad (3)$$

with the initial condition $\Psi(E_\nu, 0) = 1$. We solved numerically this equation for $E_\nu^{max} = 10^{10}$ GeV and different initial neutrino fluxes in order to find $\Phi_{\nu_\mu}(E_\nu, \tau)$ in each case.

Here, we considered the models displayed in graph 1a. In that figure, three different spectra of the form E^{-n} are shown, with spectral index $n = 1$ [8], 2 (Waxman-Bahcall limit [9]) and 3.6 (angle-averaged atmospheric neutrinos [6, 10], named Atmospheric in the figure). We also present the Mannheim's model for the AGN diffuse flux of muon neutrinos [11], that from Engel *et al.* for the spectra of GZK muon neutrinos [12] and a Sigl's model associated with topological defects (TD) [13].

On the other hand, the rate of detectable upward-going muons above a given threshold, E_μ^{min}, in a Cherenkov detector of effective area $A = 1\,\mathrm{km}^2$ was estimated through the relation [6]

$$N_{\mu^-}(E_\mu^{min}) = 2\pi A \int_0^1 d\cos\theta \int_{E_\mu^{min}}^{E_\nu^{max}} dE_\nu \Phi_{\nu_\mu}(E_\nu, \tau_f(\theta)) \times N_A \sigma_{\nu N}^{CC}(E_\nu) \langle R_\mu(E_\nu, E_\mu^{min}) \rangle. \quad (4)$$



(a) (b)

Figure 2. (a) Final flux of neutrinos, after traversing the Earth, compared with its corresponding initial flux for various nadir angles. The results with $\Psi_{\nu+\bar{\nu}}$ equal to and different from one are shown in the graph. In the first case only absorption is involved (Abs.) and, in the second one, regeneration is included (Abs. + Reg.). (b) Annual rate of detectable upward-going muons and antimuons in a 1 km^3 Cherenkov detector from several astrophysical and exotic sources of high-energy muon neutrinos.

In this expression, $\langle R_\mu(E_\nu, E_\mu^{min})\rangle$ represents the average range of a muon in standard rock and $\tau_f(\theta)$, the total column depth of matter along the θ direction inside the Earth. The $\nu_\mu N$ cross section was calculated at leading order in the framework of the Standard Model using the quark-parton model and considering N as an isoscalar nucleon. We also employed the CTEQ6-L1 [14] and Double Logarithmic Approximation [15] to describe the parton distributions of the nucleon. The interior of the Earth was described with the Preliminary Earth Model, which we took from [6]. Finally, in order to evaluate the average range of a muon in standard rock we used MUM v1.4 [16] and studied the propagation of 10^5 muons in this medium.

3. Results and discussions

In order to illustrate our results, we present in figure 1b the regeneration factor for the Waxman-Bahcall bound as a function of θ and E_ν. The regeneration factor, in general, increases with the angle θ and, therefore, with the total column depth $\tau_f(\theta)$. Moreover, it exhibits a maximum at high energies, in particular, near E_ν^{max}. The value of $\Psi(E_\nu, \tau)$ depends on the specific model, too. In the case of the power law spectra, it grows up as the spectral index n decreases, behavior that was already pointed out by Nicolaidis *et al.* [4].

From graph 1b, it can be observed that the value of the regeneration factor is bigger for large column depths and very high energies. But, before any conclusion about the importance of the regeneration in the flux of neutrinos through the Earth can be drawn it must be remembered that the contribution of the regeneration to the final flux compete with the effect of attenuation. For all the models that were analysed, the attenuation always dominates over the regeneration effects, as can be seen, for instance, in figure 2a, since $\Phi_{\nu_\mu}(E_\nu, \tau_f(\theta))/\Phi^0_{\nu_\mu}(E_\nu) < 1$, except for the GZK model where $\Phi_{\nu_\mu}(E_\nu, \tau_f(\theta))/\Phi^0_{\nu_\mu}(E_\nu) \geq 1$ at low energies. Then, it results that the effective attenuation length $\Lambda_\nu(E_\nu, \tau)$ defined through $\Phi_{\nu_\mu}(E_\nu, \tau) = \Phi^0_{\nu_\mu}(E_\nu)\exp[-\tau(\theta)/\Lambda_\nu(E_\nu, \tau)]$ in [17], in order to describe the combined influence of absorption plus regeneration in the neutrino flux, becomes negative and takes an infinity value when $\Phi_{\nu_\mu}(E_\nu, \tau_f) = \Phi^0_{\nu_\mu}(E_\nu)$.

The regeneration factor can be also be expressed in terms of the Z_ν factor introduced by Naumov and Perrone in reference [17] in the following way: $\Psi_\nu(E_\nu, \theta) = \exp[Z_\nu(E_\nu, \theta)\tau/\mathcal{L}^{Tot}_{\nu N}(E_\nu)]$. This $Z_\nu(E_\nu, \theta)$ factor has information about the competition between regeneration and absorption in the neutrino flux when traveling across the Earth. In graph 1c, the Z_ν factor of the Waxman-Bahcall limit is shown for three different nadir angles. We can observe that the value of the Z_ν factor is less than one. This implies that absorption is more important than regeneration. In addition, we can see that the Z_ν factor increases when the observation angle becomes closer to the horizontal direction. These characteristics of the Z_ν factor were also observed for the other models, but the first one for the GZK flux. In this case, at low energies it results that $Z_\nu \geq 1$, which means that the regeneration effects are more important than those from attenuation.

Now, the rates of detectable events with absorption and regeneration are shown in figure 2b as a function of the threshold energy at the detector. According to our evaluations, the contribution from regeneration to the $N_{\mu^-+\mu^+}(E_\mu^{min})$ flux is less than 16 %. The biggest contributions are observed in the case of the E^{-1} spectrum, the GZK model and the Sigl's flux from topological defects. We also see that, from all the E^{-n} spectra, the enhancement of the $N_{\mu^-+\mu^+}(E_\mu^{min})$ rates due to regeneration effects is smaller for those fluxes with higher spectral indexes, n.

4. Conclusions

The regeneration by means of neutral currents recycles neutrinos which undergo a neutral current $\nu_\mu N$ interaction during their propagation through the Earth. This effect is flux dependent. An increase on the amount of matter traversed by the neutrinos results in a bigger regeneration factor, although, it is not enough to compensate the effect of the attenuation. Only at low energies the first one could balance or overcome the decrease of absorption specifically for fluxes which behave like the GZK spectra. The final enhancement of the number of detectable upward-going muons due to regeneration is modest, less than 16 % for the analysed models, but it should be incorporated for a detailed description of the problem.

5. Acknowledgements. We acknowledge partial support from CONACyT.

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