ON NON HADRONIC ORIGIN OF HIGH ENERGY NEUTRINOS

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Some of the non hadronic interactions, such as the $\eta$ resonance formation in the $\gamma\gamma$ interactions and the muon pair production in the $e\gamma$ interactions, are identified as possible source interactions for generating high energy neutrinos in the cosmos.

1 Introduction

At present, a main motivation for high energy neutrino astronomy ($E_\nu \geq 10^3$ GeV) is that it may identify the role of hadronic interactions taking place in cosmos. The hadronic interactions mainly include the $p\gamma$ and $pp$ interactions. These interactions produce unstable hadrons that decay into neutrinos of all three flavors. There is a formation of $\Delta$ resonance in $p\gamma$ interactions, at center-of-mass energy, $\sqrt{s} \sim m_\Delta$, that mainly decay into electron and muon neutrinos. In an astrophysical site for these interactions, the protons are considered to be accelerated up to a certain maximum energy and then interact with the photons and other protons present in the vicinity of the source and those present in the interstellar medium. Our galaxy and the earth atmosphere are two examples of such astrophysical sites.

Currently, the detectors taking data in the context of high energy neutrinos are Antarctic Muon and Neutrino Detector Array (AMANDA) at south pole and the lake Baikal array in Russia. These detectors are primarily based on muon detection and are commonly referred to as high energy neutrino telescopes. The other high energy neutrino telescope under construction is the Astronomy with a Neutrino Telescope and Abyss environmental RE-Search (ANTARES) project. These high energy neutrino telescopes (envisage to) measure the showers and the charged leptons produced mainly in the deep-inelastic neutrino-nucleon and resonant (anti electron) neutrino-electron

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scatterings occurring near or inside the high energy neutrino telescopes. The later interaction can be used to calibrate the incident neutrino energy in future high energy neutrino telescopes. The Monopole, Astrophysics and Cosmic Ray Observatory (MACRO) in Gran Sasso laboratory, Italy has also recently reported its results for the high energy neutrino searches. Given the present upper bounds on the high energy neutrino flux from AMANDA (B10) and Baikal detector, the role of semi and non hadronic interactions becomes relevant. We shall call the later interactions as purely electromagnetic ones. Examples of these include $ep$ and $\gamma\gamma$ interactions respectively.

Upper bound from the AMANDA detector rule out some of the high energy neutrino flux models based on hadronic interactions only. However, several variants of these models can still possibly be compatible with the high energy neutrino non observations. These include, for instance, the direct pion production off the $\Delta$ resonance in $p\gamma$ interactions.

The absolute high energy neutrino flux originating from the non hadronic interactions, though expected to be small relative to that from hadronic interactions, can be a good scale for future large high energy neutrino telescopes such as IceCube. This will be a guaranteed level of the high energy neutrino flux should the conventional astrophysics explanation for observed high energy photon emission from extra galactic astrophysical sources such as AGNs is correct. Here, only electromagnetic interactions are taken into account for explaining the observations. Thus, the implicit assumption of proton acceleration can be avoided. The discussion that follows is also relevant in cases where the highest energy cosmic rays, considered to be mainly protons, may not originate from the GRBs which are the likely sources of high energy gamma rays.

This contribution is organized as follows. In Section 2, we briefly discuss some essentials of purely electromagnetic interactions possibly taking place in astrophysical and cosmological sites. In Section 3, we summarize the main points.

2 Purely electromagnetic interactions

The non hadronic interactions are defined to have $e^\pm$ and $\gamma$ in the initial state, rather than $p$ and $\gamma$. Therefore, the possible interactions that may generate high energy neutrinos include

$$\gamma\gamma \rightarrow \mu^+\mu^-, \ e\gamma \rightarrow \gamma' \nu\bar{\nu}, \ e^+e^- \rightarrow \nu\bar{\nu}.$$  

For comparison, note that for $\sqrt{s} \sim m_{\Delta}$, the cross sections for these interactions are typically $\ll \mu b$. For $\sqrt{s} \geq m_{\pi^\pm}$, other channels such as $e\gamma \rightarrow e\pi^+\pi^-$

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The non hadronic interactions also include the magnetic field induced interactions such as $\gamma\gamma \rightarrow \nu\bar{\nu}$, which will be briefly commented later in this Section.

A yet another possibility to generate high energy neutrinos in purely electromagnetic interactions is through the formation and decay of $\eta$ resonance into (charged) pions in $\gamma\gamma$ interactions ($\gamma\gamma \rightarrow \eta \rightarrow \pi^+\pi^-\pi^0$). Let us consider in some detail a simple implication of this purely electromagnetic interaction in the context of high energy photon propagation and consequent high energy neutrino generation. The cross section for this interaction is given by

$$\sigma(\gamma\gamma \rightarrow \eta \rightarrow \pi^+\pi^-\pi^0, s) = \frac{5.2\Gamma_\eta^2}{(s - m_\eta^2)^2 + \Gamma_\eta^2 m_\eta^2},$$  \hspace{1cm} (1)$$

where $\Gamma_\eta \sim 1.18$ KeV and $m_\eta \sim 547$ MeV, so that $\Gamma_\eta/m_\eta \sim 10^{-6}$. The peak cross section is $\sigma^{\text{res}}(s = m_\eta^2) \leq 3$ mb. Let us remark that $\sigma^{\text{res}}(s = m_\Delta^2) \leq 0.5$ mb, however here $\Gamma_\Delta/m_\Delta \sim 10^{-3}$. The branching ratio for the light unflavored $\eta$ meson to decay into $\pi^+, \pi^-$ and $\pi^0$ is $\sim 23\%$.

A useful quantity in the context of high energy photon propagation is the average interaction length defined by

$$l(E)^{-1} = \int_{m_\eta^2/4E}^{\infty} n_b(\epsilon) d\epsilon \int_{1}^{\epsilon} \left(1 - \frac{\mu}{2}\right) \sigma(s) d\mu, \hspace{1cm} (2)$$

with $s = 2\epsilon E(1 - \mu)$ and $\mu = \cos \theta$. The lower limit of integration for $\epsilon$ corresponds to a head on collision so that $\mu = -1$. Note that for a high energy photon with energy $E \sim \text{GeV}$, the background photon energy is $\epsilon \sim \text{GeV}$ to form the $\eta$ resonance. For definiteness, let us consider the interaction between high energy photons and the cosmic microwave background (CMB) radiation which has the following number density

$$n_b(\epsilon) = \frac{\epsilon^2}{\pi^2} \exp(\epsilon/T_b(0)) - 1. \hspace{1cm} (3)$$

Here $T_b(0) \approx 2.74$ K. The other ubiquitous photon backgrounds include the infrared and ultraviolet radiation, considered to exist in the present universe, particularly after galaxy formation epoch. For simplicity, we ignore their effects as well as the effects of a possible magnetic field present in the cosmos.

The high energy photons are considered to originate from an astrophysical or cosmological site within the present horizon length $cH^{-1}(0) \sim 3 \cdot 10^3$ Mpc (where 1 pc $\sim 3 \cdot 10^{18}$ cm), as we take $H(0) \sim 65$ km s$^{-1}$ Mpc$^{-1}$.

Substituting Eq. (1) and Eq. (3) into Eq. (2), the two integrations can be carried out easily under the narrow width assumption, such that for $\sqrt{s} \approx m_\eta$, and $\gamma \gamma \rightarrow \pi^+\pi^-$ also become available for high energy neutrino generation.
we obtain

\[ l(E) \simeq \frac{8\pi E^2}{5.2 \Gamma_{\eta} m_\eta T} \left\{ \ln \left( \frac{\exp(m^2_{\eta}/4ET)}{\exp(m^2_{\eta}/4ET - 1)} \right) \right\}^{-1}. \] (4)

For \( 4ET \simeq m^2_{\eta}, \) i.e., \( E \sim 3 \cdot 10^{11} \) GeV, we note that \( l \sim 10^4 \) Mpc > \( cH^{-1}(0). \) A such single interaction give a total of 6 neutrinos. For comparison, we display in Fig. 1 the \( l_\eta \equiv l(\gamma\gamma \to \eta \to \pi^+\pi^-\pi^0) \) along with the more familiar relevant \( l, \) namely for \( \gamma\gamma \to \mu^+\mu^- \). From the figure, we note that the Eq. (4) is a quite good approximation to obtain \( l \) in resonance and that \( l_\eta \gg l_{\mu^+\mu^-} \) for same \( E. \) In general, this observation may also have some relevance for high energy photon propagation in a dense photon background with relatively narrow background photon flux spectrum such as those arising in some astrophysical sites in the context of high energy neutrino generation.

Figure 1. The average interaction length using Eq. (4) for high energy photons propagating in cosmic microwave background photon flux as a function of incident photon energy.
In the limit $4ET \ll m_\eta^2$, we obtain

$$l(E) \simeq \frac{8\pi E^2}{5.2\Gamma m_\eta T} \exp \left( \frac{m_\eta^2}{4ET} \right), \quad (5)$$

whereas, in the opposite limit, namely when $4ET \gg m_\eta^2$, we obtain

$$l(E) \simeq \frac{8\pi E^2}{5.2\Gamma m_\eta T} \left\{ \ln \left( \frac{4ET}{m_\eta^2} \right) \right\}^{-1}. \quad (6)$$

In the two limiting cases, $l(E) \gg cH_0^{-1}$. Let us further remark that although $\sigma^{\text{res}}(s = m_\eta^2) \gg \sigma^{\text{vac}}(s = m_\Delta^2)$, however $l_\eta^{\text{res}} \gg l_\Delta^{\text{res}}$ because of rather narrow $\eta$ width.

In the presence of an external magnetic field, we note that the cross section for $\gamma\gamma \rightarrow \nu\bar{\nu}$ is significantly enhanced with respect to its value in the vacuum. However, such an enhancement is still insufficient for this process to be presently relevant for high energy neutrino generation. For comparison with $\gamma\gamma \rightarrow \mu^+\mu^-$, it is found that for $B = 10^{12}$ G, $\sigma(\gamma\gamma \rightarrow \nu\bar{\nu}) \approx 10^{-49}$ cm$^2$ for $s \gtrsim 4 m_\mu^2$. This cross section scales as $B^2$ for $B < B_c \approx 4 \cdot 10^{13}$ G.

2.1 Astrophysical sites

Presently, there exists no model to estimate the high energy neutrino flux in purely electromagnetic interactions taking place in sources of highest energy gamma rays such as the AGNs and the GRBs. To make an order of magnitude estimate, we assume that the above astrophysical sites can accelerate electrons to energies greater than the observed gamma ray energies. As these electrons undergo inverse Compton scattering, the up-scattered high energy photons are produced. The scatterings of high energy photons over the ambient photon fields present in the vicinity of the AGNs or GRBs may lead to the $\mu^+\mu^-$ final state or three-pion final state through the $\eta$ resonance.

Phenomenologically speaking, the resulting (relative) high energy neutrino flux can be parameterized as $\phi_\nu^\gamma(E_\nu) \sim P \phi_\nu^{\text{el}}(E_\nu)$, where the probability function $P$ depends on the ratio of high energy photon/electron flux associated with a specific astrophysical site to the corresponding high energy proton flux on the same site. The function $P$ certainly also depends on the ratio of neutrino production cross sections between two mechanisms. Finally it also depends on the magnetic field strength on the site, which are relevant for the acceleration of charged particles. A diffuse non hadronic high energy neutrino flux with a representative $P \sim 10^{-4} - 10^{-5}$ can in principle be measurable by future large high energy neutrino telescopes such as IceCube.
2.2 Cosmological sites

Topological defects formed in the early epochs may play some role in the latter epochs of the expanding universe. The cosmological and astrophysical aspects of topological defects are the density or metric perturbations that they may generate, particularly in the epoch of large scale structure formation in the expanding universe.

The associated particle physics aspect is the possible release of large amount of energy trapped inside these topological defects in the form of gauge bosons. These gauge bosons subsequently decay into known hadrons and leptons. Assuming that (some fraction of) the topological defects are formed in the early epochs of the expanding universe and thus contain a large amount of energy, it becomes possible to explain at least some features of the observed highest energy cosmic rays. For this scenario to work, the observed highest energy cosmic rays have to be dominantly the photons. In this (conventional) scenario, the high energy neutrino flux is generated from the decay of charged pions.

Here, we discuss a class of topological defects in which high energy neutrino flux generation was postulated to originate in the electromagnetic cascade rather than in charged-pion decays which result from the hadronizations of initial jets produced in the decays of GUT-scale heavy bosons. This class of sources for ultrahigh energy photons is assumed to be active before the galaxy formation epoch. This corresponds to a red shift, $z \geq 5$. Thus, for $z \geq 5$, the effects of galactic magnetic field as well as the infrared and ultraviolet photon backgrounds can be neglected. Consequently, CMB photon flux is the only important photon background. A search for high energy neutrinos can provide some useful information about the existence of this class of topological defects in the expanding universe. At high red shift, the $\gamma\gamma$ interactions between the energetic and background photons can produce muons (and charged pions) whose decay generate high energy neutrinos. Note that, at high red shift, $T_h(z) = (1 + z)T_h(0)$, whereas $n_b(z) = (1 + z)^3n_b(0)$. For $E > E_{th}(z)$, where $E_{th} = 10^{11}\text{GeV}/(1 + z)$, the $\gamma\gamma \rightarrow \mu^+\mu^-$ is most relevant for high energy neutrino generation. The $\lambda \equiv \lambda(\gamma\gamma \rightarrow \mu^+\mu^-)$ obtainable using Eq. (2) is less than the horizon length, $cH(z)^{-1}$ for $5 < z < 10$. With an invariant mass just above the threshold, the purely electromagnetic interaction $\gamma\gamma \rightarrow \mu^+\mu^-$ also has a shorter interaction length than the energy attenuation length in the electromagnetic cascade dictated by $\gamma\gamma \rightarrow e^+e^-$. Under the assumption that muons decay before interacting, the high en-
ergy neutrino flux can be calculated as

$$\phi^\gamma_\nu(E_\nu) = \int_{z_{\text{min}}}^{z_{\text{max}}} \int_{E_{\nu_{\text{min}}}}^{E_{\nu_{\text{max}}}} dz \, dE \, \phi^\gamma(z, E) \, f(z, E) \frac{dn_{\gamma\gamma \rightarrow \nu + X}}{dE_\nu}. \tag{7}$$

Here $$\phi^\gamma(z, E)$$ parameterizes the high energy photon flux from the topological defect. Typically, it is normalized by assuming that the high energy photons produced by topological defects at the high red shift are dominantly responsible for the observed high energy photon flux and/or the observed highest energy cosmic rays. The function $$f(z, E) \equiv cH(z)^{-1}/\lambda$$ gives the number of $$\gamma\gamma$$ interactions within the horizon length. The $$\frac{dn}{dE} \equiv \sigma^{-1}d\sigma/dE$$ is the neutrino-energy distribution in $$\gamma\gamma$$ interactions. The integration limits follow from the above discussion. The $$\phi^\gamma_\nu$$ peaks at $$E_\nu \simeq E_\mu/3 \simeq E_{\text{th}}/3(1 + z) \simeq 10^{11} \text{GeV}/3(1 + z)^2 \simeq 10^8 \text{GeV}$$. The $$\eta$$ resonance formation can also contribute to $$\phi^\gamma_\nu$$. It is a possibility to produce high energy neutrinos through non hadronic interactions in a cosmological setting.

The electromagnetic cascade that generate high energy neutrinos from muon decays in $$\gamma\gamma$$ interactions contains roughly equal number of photons and electrons. In Ref. [22], it was suggested that, for this class of topological defects that produce ultrahigh energy photons at the high $$z$$, the muon pair production (MPP) in $$e^-\gamma \rightarrow e^-\mu^+\mu^-$$ dominates over the triplet pair production (TPP) in $$e^-\gamma \rightarrow e^-e^+e^-$$ for $$5 \text{ m}_\mu^2 \leq s \leq 20 \text{ m}_\mu^2$$ in the electromagnetic cascade, thus enabling the MPP process to be an efficient mechanism for generating high energy neutrinos at the high $$z$$. The electrons in the final state of the above processes are considered as originating from the electromagnetic cascade generated by the ultrahigh energy photons scattering over the CMB photons present at the high red shift. This conclusion was based upon the value of the ratio $$\eta$$ defined as $$R \simeq \sigma_{\text{MPP}}/\eta_{\text{TPP}}\sigma_{\text{TPP}}$$, where $$\eta_{\text{TPP}}$$ is the inelasticity for the TPP process. The $$\eta_{\text{TPP}}$$ is basically the average fraction of the incident energy carried by the final state positron. The original estimate of Ref. [22] gives $$R \simeq 10^2$$, which favors the MPP process as the dominating high energy neutrino generating process. Namely, the electron energy attenuation length due to the TPP process is much longer than the interaction length of the MPP process because $$\sigma_{\text{MPP}} \simeq (0.1 - 1) \mu\text{b}$$. However, by an explicit calculation [23], instead it was found that $$\sigma_{\text{MPP}} < 1 \mu\text{b}$$ for $$s \geq 5 \text{ m}_\mu^2$$, thus yielding $$R < 1$$. In particular,

$$\sigma_{\text{MPP}}(s) = \begin{cases} 4 \cdot 10^{-3} \mu\text{b} & \text{for } s = 4 \text{ m}_\mu^2, \\ 1 \cdot 10^{-1} \mu\text{b} & \text{for } s = 20 \text{ m}_\mu^2. \end{cases} \tag{8}$$

Therefore, MPP can not be a dominating process for generating high energy neutrinos. We note that the equivalent photon approximation was used in
this work to calculate the leading-order contribution to $\sigma_{MP}(s)$.

In summary, in an electromagnetic cascade generated by ultrahigh energy photons scattering over the CMB photons at the high red shift, the $\gamma\gamma \rightarrow \mu^+\mu^-$ can in principle produce high energy neutrinos, typically for $5 < z < 10$, through the muon decays. On the other hand, the process $e\gamma \rightarrow e^-\mu^+\mu^-$ occurring as the next round of interactions in the same electromagnetic cascade can not produce the high energy neutrinos.

3 Conclusions

Possibilities of high energy neutrino generations in two of the non hadronic interactions, namely $\gamma\gamma$ and $e\gamma$ reactions are briefly discussed. In the first interaction, the formation and decay of the $\eta$ resonance in addition to the muon pair production may have some implications for high energy neutrino generation. Model dependent analysis is needed to further quantify the high energy neutrino generation in non hadronic interactions.

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References

1. F. Halzen, these proceedings.
2. K. Greisen, Phys. Rev. Lett. 16, 748 (1966); G. T. Zatsepin and V. A. Kuzmin, JETP Lett. 4, 78 (1966) [Pisma Zh. Eksp. Teor. Fiz. 4, 114 (1966)].
3. H. Athar, K. Cheung, G.-L. Lin and J.-J. Tseng, arXiv:hep-ph/0112222.
4. G. Domogatsky, arXiv:astro-ph/0112440.
5. T. Montaruli [ANTARES Collaboration], arXiv:hep-ex/0201009.
6. I. F. Albuquerque, J. Lamoureux and G. F. Smoot, arXiv:hep-ph/0109174; H. Athar and G.-L. Lin, arXiv:hep-ph/0201026 and references therein.
7. M. Ambrosio [MACRO Collaboration], arXiv:astro-ph/0203181.
8. C. D. Dermer and R. Schlickeiser, Science 257, 1642 (1992).
9. See, for instance, S. T. Scully and F. W. Stecker, Astropart. Phys. 16, 271 (2002).
10. R. J. Gould and G. Schreder, Phys. Rev. Lett. 16, 252 (1966).
11. A. Zdziarski, Ap. J. 335, 786 (1988).
12. R. J. Protheroe and P. A. Johnson, Astropart. Phys. 4, 253 (1996) [erratum-ibid., 5, 215 (1996)].
13. S. Lee, Phys. Rev. D 58, 043004 (1998) and references therein.
14. M. Poppe, Int. J. Mod. Phys. A 1, 545 (1986); X. Bertou, P. Billoir, and S. Dagoret-Campagne, Astropart. Phys. 14, 121 (2000).
15. D. E. Groom et al. [Particle Data Group Collaboration], Eur. Phys. J. C 15, 1 (2000).
16. R. Shaisultanov, Phys. Rev. Lett. 80, 1586 (1998).
17. T. K. Chyi, C. W. Hwang, W. F. Kao, G. L. Lin, K. W. Ng and J. J. Tseng, Phys. Lett. B 466, 274 (1999).
18. For a review, see, R. Durrer, M. Kunz and A. Melchiorri, arXiv:astro-ph/0110348 and references therein.
19. See, for instance, G. Sigl, arXiv:hep-ph/0109202; F. Halzen and D. Hooper, arXiv:hep-ph/0110201.
20. A. Kusenko, arXiv:astro-ph/0008369.
21. P. J. Peebles, Principles Of Physical Cosmology (Princeton University Press, USA, 1993).
22. A. Kusenko and M. Postma, Phys. Rev. Lett. 86, 1430 (2001).
23. H. Athar, G.-L. Lin and J.-J. Tseng, Phys. Rev. D 64, 071302 (2001).