A Study of the Behavior of Ultra-High Energy Neutrinos

Mou Roy
Department of Physics, University of California, Riverside, California 92521-0413, USA

Neutrino Oscillations in the presence of strong gravitational fields are studied specifically for Majorana neutrinos. We look at ultra high energy neutrinos (∼ 1 PeV) emanating from Active Galactic Nuclei (AGN). The spin flavor resonant transitions of such neutrinos may occur in the vicinity of AGN due to gravitational effects and due to the presence of a large magnetic field (∼ 1 Tesla). In this scenario the matter effects (normal MSW transitions) become negligible in comparison to gravitational effects. We discuss the corresponding bound on the magnetic moment (transition magnetic moment for Majorana neutrinos). Fluxes of different flavor neutrinos are estimated and probabilities for different neutrino transitions calculated.

1. Introduction

Majorana particles are natural representations of massive neutrinos. Neutrinos in general, and in particular Majorana neutrinos can be used to probe the core of cosmological objects. Due to their small cross sections these particles can stream out unaffected from even the most violent environments such as those in Active Galactic Nuclei (AGN)\(^a\). In their trek from their source to the detector the neutrinos can undergo flavor and/or spin transitions which can obscure some of the features of the source. Because of this, and due to the recent interest in neutrino astronomy (e.g. DUMAND II, AMANDA, NESTOR, BAIKAL, etc.\(^1\)) it becomes important to understand the manner in which these transitions occur in the hope of disentangling these effects from the ones produced by the properties of the source\(^2\).

2. Neutrino Oscillations in AGN environment

To determine the effective interactions of the Majorana neutrinos in an AGN environment we start following\(^2\) from the Dirac equation in curved space including their weak and electromagnetic interactions

\[
[i e \nu^a (\partial_\mu + \omega_\mu) - m + \mu \sigma^{ab} F_{ab}] \psi = 0 \tag{1}
\]

where \(e^\nu_a\) are the tetrads, \(\gamma^a\) the usual Gamma matrices, \(m\) the mass matrix, \(\mu\) the neutrino magnetic moment, and \(\omega_\mu\) the gravitational field. Here \(\mu = J_5\), and \(J_5 = g^a \gamma^a\) is the usual weak interaction current matrix.

\(^a\)AGN are the most luminous objects in the Universe, believed to be powered by a supermassive black hole of mass \(10^4\) to \(10^{10} M_\odot\).
netic moment, $F^{ab}$ the electromagnetic field tensor, $\sigma^{ab} = \frac{1}{4}[\gamma_a, \gamma_b];$ and the spin connection is $\omega_{\mu} = \frac{1}{8}[\gamma_a, \gamma_b] e^{\nu\rho} e_{\nu\mu}$, where the semicolon denotes a covariant derivative. We used Greek indices ($\mu, \nu, \ldots$) to denote space-time directions, and Latin indices ($a, b, \ldots$) to denote directions in a local Lorentzian frame. We have studied in detail the method of extracting the effective neutrino Hamiltonian from eqn.(1) in Ref. We have allowed the possibility of rotation of the central AGN black hole using a Kerr metric (we also assume that the accreting matter generates a small perturbation of the gravitational field). The metric for a Kerr black hole contains two parameters, $r_g$, the horizon radius and $a$ the total angular momentum of the black hole per unit mass. Using the typical spherical accretion AGN model, we can compare the magnitude of the weak interaction current, $J_W \sim 10^{-33} \rho \text{eV}^{-1}$, to its gravitational counterpart $J_G \sim r_g^{-1}$. The order of matter density $\rho$ for typical cases is $10^4 - 10^4 \text{eV}$ which shows that the gravitational current part dominates the weak current part for all relevant values of $r_g$ ($10^{14}$ to $10^{20} \text{eV}^{-1}$). This causes the normal MSW effects to be negligible in this scenario.

3. Probabilities of Allowed Transitions and Neutrino Flux Modifications.

In the adiabatic limit it is easy to quantitatively describe the gravitational effect in AGN environment by looking at the transition and survival probabilities $b$. The condition for resonances to induce an appreciable transition probability gives a bound on the neutrino magnetic moment $\mu$ (transition magnetic moment). For a study of the probabilities it is reasonable to choose a specific value of $\mu$ which would ensure neutrino transitions for all the energy and $\Delta m^2$ values of interest. We have chosen $\mu_t = 10^{-13} \mu_B$. The probabilities for a specific energy and $\Delta m^2$ remains approximately constant with $(r, \theta)$. However transition probability increases with energy and decreases with $\Delta m^2$ (reverse behavior for the survival probability). For simplicity we have limited ourselves to only two neutrino mixing.

The high energy neutrino detectors are sensitive to a wide range of neutrino parameters and will be able to test a variety of models of neutrino production in AGN for neutrino energies over 1 TeV. Matter effects are negligible in the AGN environment, but gravity-induced resonances could cause a decrease of the neutrino flux of any given flavor independent of the value of $\Delta m^2$ chosen. This effect could cause an oscillation to $\tau$ neutrinos generating a significant

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\textsuperscript{b}The procedure is essentially the same as the one used in describing the MSW resonances.

\textsuperscript{c}$\Delta m^2 = m_1^2 - m_2^2$

\textsuperscript{d}For $E = 1 \text{TeV}$ and $\Delta m^2 = 10^{-6} \text{eV}^2$, $\mu_{\min} \sim 10^{-13} - 10^{-14} \mu_B$.

\textsuperscript{e}There is negligible $\tau$ neutrino production in the AGN environment according to all standard models.
flux of $\tau$ neutrinos to which planned experiments will be sensitive in the PeV range. Around this energy we find that the muon neutrino flux decreases by about 50\% for the range of values of $\Delta m^2$ considered. This effect would decrease the number of upward moving muons beyond energy 1 PeV by a factor of 2. However if we consider oscillation between muon and electron neutrinos the flux reduction is about 25\% at this energy.

5. Conclusions

We found that ultra high energy Majorana neutrinos will be strongly affected by gravitational and electromagnetic effects provided $\Delta m^2 > 10^{-10}$eV$^2$ and that the transition magnetic moment satisfies $\mu_t > 10^{-13}\mu_B$. Gravitational oscillations are the dominant mechanism for the flavor/spin oscillation of such neutrinos emanating from AGN causing a significant muon neutrino decrease and increase of the corresponding $\tau$ neutrino flux, to which future neutrino telescopes will be sensitive. In the case of solar neutrinos the presence of more than two flavors can significantly alter the predicted fluxes. However for the present situation where the experimental information on the AGN neutrino flux is quite limited, it is sufficient to determine the various effects and their strengths by using a two flavor mixing description as we have done in our analysis.

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[1] R.J.Wilkes, in Proc.Slac.Summer Institute 1994 edited by Jennifer Chan and Lilian De Porcel; H.W.Sobel, Nucl.Phys.\textbf{B} (Proc Suppl) \textbf{19}, 444 (1991); S.Barwick \textit{et.al.}, J.Phys.G: Nucl.Part.Phys.\textbf{18}, 225 (1992).
[2] D.Piriz, M.Roy and J.Wudka, Phys.Rev.\textbf{D54}, 1587 (1996); M.Roy and J.Wudka, UCRHEP-T174, submitted to Phys.Rev.\textbf{D}.
[3] R.J.Protheroe and D.Kazanas, Ap.J.\textbf{265}, 620 (1983); D.Kazanas and D.C.Ellison, Ap.J.\textbf{304}, 178 (1986).
[4] J.G.Learned and S.Pakvasa, Astropart. Physics \textbf{3}, 267 (1995); R.Gandhi, \textit{et.al.}, \texttt{hep-ph/9601270} (unpublished), report number AZPH-TH-96-12.

\footnote{This is due to the fact that unlike tau neutrinos, the initial ($\nu_e + \bar{\nu}_e$) flux in AGN is not negligible, but is half of the initial ($\nu_\mu + \bar{\nu}_\mu$) flux.}