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Explanation for the Low Flux of High Energy Astrophysical Muon Neutrinos

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Abstract

There has been some concern about the unexpected paucity of cosmic high energy muon neutrinos in detectors probing the energy region beyond 1 PeV. As a possible solution we consider the possibility that some exotic neutrino property is responsible for reducing the muon neutrino flux at high energies from distant sources; specifically, we consider: (i) neutrino decay and (ii) neutrinos being pseudo-Dirac particles. This would provide a mechanism for the reduction of high energy muon events in the IceCube detector, for example.

The most recent data from the IceCube collaboration[1] place stringent limits on the muon neutrino flux at high energies from astrophysical sources. The new limits appear to put severe bounds on models of neutrino production in GRB's and AGN's[2]. Similarly, other experiments probing the ultra-high-energy regime, such as ANITA[3] and AUGER[4] have not seen any evidence of long anticipated cosmic neutrinos. It should be noted that very recently there have been re-evaluations of the expected neutrino fluxes from GRB's, especially following the stringent upper limits from IceCube [1].

It has been pointed out [5, 6] that IceCube [1] calculation of the WB neutrino flux from the observed gamma ray flux may have been an overestimation by as much as a factor of 5. So the discrepancy may not be that dire, yet; but the possibility remains that as the bounds get tighter with future observations, the Waxman-Bahcall models [2] will be challenged. In such an eventuality, we would like to offer in this letter the possibility of other causes for the smallness of the muon neutrino flux, which arise from neutrino properties. We note that there are alternative astrophysical models (see [7, 8] and references therein) which predict a lower neutrino flux compared to the Waxman-Bahcall models [2].

In this note we would like to raise the possibility that these severe bounds are illusory because the small flux may be due to depletion of muon neutrinos which in turn is caused by neutrino properties We consider two possible scenarios. One is that neutrino decay is responsible for depletion of muon-neutrinos and the other is that neutrinos are pseudo-Dirac particles and there is leakage into the sterile components of the pseudo-Dirac particles. Both of these were considered almost ten years ago[9, 10], but the focus then was on the modification of the flavor mix from the canonical 1:1:1 as expected from conventional flavor oscillations with the known neutrino mixings[11].

In the following, we describe both possibilities. To be definite, we are considering neutrino energies in the vicinity of order of a PeV, and the distances from the sources of order of hundreds of mega-parsecs. In principle, when the distances become large enough, the cosmological red shift becomes important, and the travel distance L is limited; these effects were discussed some time ago in ref.[10, 12] and more recently in ref.[13] and ref.[14].

Of course, because of the uncertainty in predicting fluxes, we do not know precisely what amount of depletion is needed. But the scenarios we suggest below can provide a wide range of suppression ranging from none to an order of magnitude.

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Neutrino Decay:

We consider here scenarios with three light neutrinos and assume that the source distances are large enough so that two of the three mass eigenstates, specifically ν_2 and ν_3 have decayed away completely. If the neutrino masses are quasi-degenerate, that is the masses of ν_2 and ν_3 are close to that of ν_1, then the daughter neutrino, ν_1 carries most of the energy of the parent, and so contributes to the flux at that energy; in this case even though the final state is pure ν_1, there is not much depletion. So for our purpose here, the preferred mass spectrum is quasi-hierarchical, namely m_2 and m_3 much larger than m_1; in this case the daughter neutrino energy is much lower than the parent and the final ν_1 does not contribute to the flux at that energy and can be counted out. This is discussed in detail in several papers, especially clearly in ref.[15]. This means that the exponential decay factor exp $(-L/\gamma c\tau)$ is negligibly small for them. Since distances to GRB's are of order of 100's of MPc, for energies in the PeV range, $\frac{L}{\gamma c\tau} = \frac{L}{E}\left(\frac{mc^2}{c\tau}\right) \gg 1$ corresponds to $\tau/m < 10^3 sec/eV$ where τ is the rest frame lifetime. A lower bound on the lifetime follows from the BBN (Big Bang Nucleosynthesis). If the standard picture is to remain intact then all three neutrinos must be present and in equilibrium in the BBN era so that the crucial n/p ratio and the nuclear abundances as obtained in standard picture remains unaffected. This puts a lower bound of $\frac{\tau}{m}E > 1$ sec on the neutrino lifetime with $E \sim$ MeV. These considerations restrict the allowed window of lifetime in the range

$$10^{-6} sec./eV \leq \frac{\tau}{m} \leq 10^3 sec./eV \,. \tag{1}$$

As for the neutrino decay modes, we know the following. The radiative decays such as $\nu_i \to \nu_j + \gamma$ are severely constrained by their contribution to $\nu + e \to e + \nu'$ and from the current bounds on such contributions the radiative decay lifetime must satisfy [16].

$$\tau_i/m_i \;\; > 10^{17} \; sec./eV. \tag{2}$$

The three-body invisible decay mode

$$\nu_i \to \nu_j \; + \nu\bar{\nu} \tag{3}$$

is constrained by BBN and the deviation of the invisible width of Z from the expected value (with three neutrinos) in SM [17]; and is given by

$$\tau_i/m_i > 10^{28} sec./eV \tag{4}$$

The kinds of decay models possible are quite restricted. Models where the coupling is chirality conserving (e.g. into a light vector boson or into a scalar boson with a derivative coupling), would by $SU(2)_L \times U(1)$ symmetry lead to flavor changing decays of charged leptons at the same strength. The severe bounds on flavor changing decays of μ and τ into invisible two body modes lead to limits on lifetimes of ν_2 and ν_3 of order of $\tau > 10^{20}$ sec [18], and so such decays are ruled out. Hence, the only neutrino decay modes which can be relevant for the short lifetimes of interest here are helicity changing decays into a neutrino and a light boson, as discussed in ref.[9, 16]. The current limits on the lifetimes of the three mass eigenstates are as follows. The most stringent is on that of ν_1, from the observation of neutrinos from SN1987A as being about $\tau_1/m_1 > 10^5 s/eV$[19]. The limits on the other two mass eigenstates are: $\tau_2/m_2 > 10^{-4} s/eV$ from the solar neutrino observations[15, 20] and $\tau_3/m_3 > 10^{-10} s/eV$ from the atmospheric neutrino observations[21]. Obviously, the limits on the lifetimes of ν_2 and ν_3 are quite weak.

In the picture adopted here, all the neutrinos originating from GRBs reach the earth as pure ν_1 whose flavour content is $\nu_e : \nu_\mu : \nu_\tau = |U_{e1}|^2 : |U_{\mu 1}|^2 : |U_{\tau 1}|^2$ as observed long ago[22]. If we insert the current best fit values [23] for the Maki-Nakagawa-Sakata-Pontecorvo (MNSP) [24] neutrino mixing matrix elements, we find that $|U_{\mu 1}|^2$ ranges between 0.1 and 0.3 with a central value of about 0.16. [The unknown value of the CP violating phase δ in the MNSP mixing matrix determines the precise value]. This is a suppression beyond the factor of two due to the standard flavor oscillations. Thus, a suppression of the muon neutrino flux by an order of magnitude is easily achieved. Since the value of $|U_{e1}|^2$ is between 0.65 and 0.72, the ν_e flux is not affected much by the decays of ν_2 and ν_3 . We note that the flux ratio of ν_e to ν_μ is between 2.5 and 8 with a central value of about 4, depending on the value of the phase δ. We have discussed the most favorable scenario for ν_μ flux reduction by assuming (i) normal hierarchy, because in the inverted hierarchy the decay of ν_1 has strong limits from SN1987a so only ν_2 can decay into ν_3 but in that case we do not achieve any suppression of ν_μ and (ii) hierarchial masses, namely $m_2, m_3 \gg m_1$; otherwise if the masses are degenerate, the energy of the decaying and daughter neutrino are the same and even though the flavor ratio ν_e/ν_μ is large there is not much suppression of ν_μ flux because of enhancement of the ν_1 flux from the decay.

The invisible decays $\nu_{2,3} \to \nu_1 + J$ arise naturally in Majoron models with J identified with the massless Majoron arising from the spontaneous breaking of total lepton number or some combination of L_i, $i = e, \mu, \tau$. These models fall in two main categories: triplet majoron models [25] with a low scale lepton number violation and singlet models [26] with lepton number typ-