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Propagation of superluminal PeV IceCube neutrinos: A high energy spectral cutoff or new constraints on Lorentz invariance violation

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The IceCube observation of cosmic neutrinos with $E_\nu > 60$ TeV, most of which are likely of extragalactic origin, allows one to severely constrain Lorentz invariance violation (LIV) in the neutrino sector, allowing for the possible existence of superluminal neutrinos. The subsequent neutrino energy loss by vacuum e^+e^- pair emission (VPE) is strongly dependent on the strength of LIV. In this paper we explore the physics and cosmology of superluminal neutrino propagation. We consider a conservative scenario for the redshift distribution of neutrino sources. Then by propagating a generic neutrino spectrum, using Monte Carlo techniques to take account of energy losses from both VPE and redshifting, we obtain the best present constraints on LIV parameters involving neutrinos. We find that $\delta_{\nu e} = \delta_\nu - \delta_e \leq 5.2 \times 10^{-21}$. Taking $\delta_e \leq 5 \times 10^{-21}$, we then obtain an upper limit on the superluminal velocity fraction for neutrinos alone of 1.0×10^{-20}. Interestingly, by taking $\delta_{\nu e} = 5.2 \times 10^{-21}$, we obtain a cutoff in the predicted neutrino spectrum above 2 PeV that is consistent with the lack of observed neutrinos at those energies, and particularly at the Glashow resonance energy of 6.3 PeV. Thus, such a cutoff could be the result of neutrinos being slightly superluminal, with δ_ν being $(0.5 \text{ to } 1.0) \times 10^{-20}$.

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I. INTRODUCTION

The possible existence of superluminal neutrinos as a consequence of Lorentz invariance violation (LIV) was brought to the attention of the physics community by their apparent observation [1]. Shortly thereafter, Cohen and Glashow [2] presented a powerful theoretical argument against the results in Ref. [1]. Their argument was based on the implication that these neutrinos would rapidly lose energy by the dominant energy loss channel of vacuum electron-positron pair emission (VPE), i.e., $\nu \to \nu e^+ e^-$. Eventually, the results in Ref. [1] were retracted [3]. (See also Ref. [4]).

The IceCube Collaboration has recently reported the observation of 37 extraterrestrial neutrinos with energy above ~60 TeV, giving a cosmic neutrino signal 5.7σ above the atmospheric background [5]. This is significant evidence for a neutrino flux of cosmic origin, above that produced by atmospheric cosmic-ray secondaries [6]. The very existence of PeV neutrinos has been used to place strong constraints on LIV in the neutrino sector [7,8].

II. COSMIC HIGH ENERGY NEUTRINOS

There are four indications that the cosmic neutrinos observed by IceCube are extragalactic in origin [7]: (1) The celestial distribution of the 37 reported cosmic events is consistent with isotropy, with no significant enhancement in the galactic plane [5], although it has been argued that a subset of these events might be of galactic origin [9]. (2) A possible cutoff in the energy spectrum of these neutrinos may be indicative of photopion production followed by pion decay [10] such as expected in AGN cores [11], GRBs [12], or intergalactic interactions [13]. (AGN jets have also been looked at, but there may be difficulties with the jet models [14]. Neutrinos from starburst galaxies are discussed in Sec. VI.) (3) The diffuse galactic neutrino flux [15] is expected to be well below that observed by Ice Cube. (4) At least one of the ~1 PeV neutrinos observed by IceCube (dubbed "Ernie") came from a direction off of the galactic plane.

An upper limit for the difference between putative superluminal neutrino and electron velocities of $\delta_{\nu e} \equiv \delta_\nu - \delta_e \leq \sim 5.6 \times 10^{-19}$ was previously derived by one of us, confirming that the observed PeV neutrinos could have reached Earth from extragalactic sources. After obtaining an upper limit on the superluminal electron velocity of $\delta_e \equiv v_e - 1 \leq \sim 5 \times 10^{-21}$, an upper limit of $\delta_\nu \equiv v_\nu - 1 \leq \sim 5.6 \times 10^{-19}$ was derived from one of the ~PeV neutrino events [7]. (Here $c = 1$ and $\delta_\nu = -\overset{\circ}{c}^{(4)}$ in the standard model extension effective field theory framework for describing the effects of LIV and CPT violation [16]). This previous limit allows for the possibility that minimally superluminal neutrinos can propagate over large distances from extragalactic sources such as active galactic nuclei (AGN) and γ-ray bursts (GRB), while undergoing energy losses by VPE.

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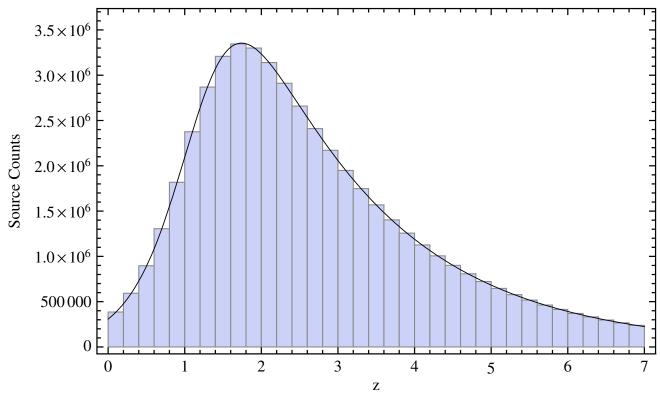

FIG. 1 (color online). Binned number of neutrinos used in our Monte Carlo runs sampled from the star formation rate distribution of Ref. [18].

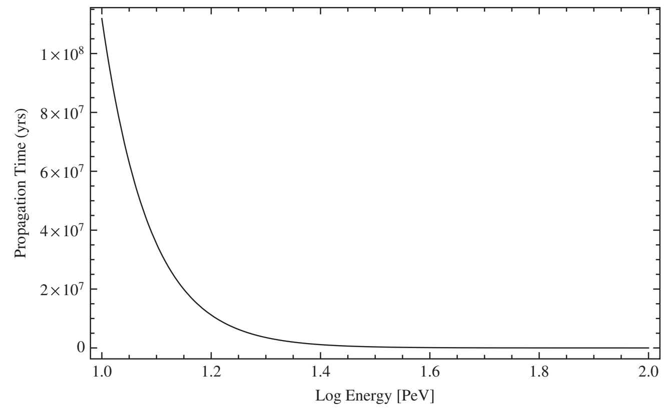

FIG. 2. Mean propagation time before decay as a function of neutrino energy for a threshold energy of 10 PeV.

Given that neutrinos detected by IceCube are extragalactic, cosmological effects should be taken into account in deriving new LIV constraints. The reasons are straightforward. As opposed to the extinction of high energy extragalactic photons through electromagnetic interactions [17], neutrinos survive from all redshifts because they only interact weakly. We thus consider here a scenario where the neutrino sources have a redshift distribution that follows that of the star formation rate [18] (see Fig. 1), as appears to be roughly the case for both active galactic nuclei and γ-ray bursts. Since the Universe is transparent to neutrinos, most of the cosmic PeV neutrinos will come from sources at redshifts between ~0.5 and ~2 [11]. Therefore neither energy losses by redshifting of neutrinos nor the cosmological ΛCDM redshift-distance relation can be neglected in our calculations.

III. NEUTRINO ENERGY LOSSES

We again note the definitions $\delta_{\nu e} = \delta_\nu - \delta_e$, $\delta_\nu = v_\nu - 1$, and $\delta_e = v_e - 1$. The v's here are to be understood to be the maximum attainable velocities of the neutrinos and electrons, respectively. (The definition of δ used here is *half* that used in Refs. [2] and [19] but is consistent with that used in Ref. [20].) For $\delta_\nu \geq \delta_e \geq 0$ and defining $\delta_{\nu e} \equiv \delta_\nu - \delta_e$, the VPE process $\nu \to \nu e^+ e^-$ is kinematically allowed provided that [19,20]

$$E_\nu \geq m_e \sqrt{2/\delta_{\nu e}}. \quad (1)$$

The decay width for the VPE process, $\nu \to \nu e^+ e^-$, is given by [2]

$$\Gamma = \frac{1}{14} \frac{G_F^2 E_\nu^5 (2\delta_{\nu e})^3}{192\pi^3} = 1.3 \times 10^{-14} E_{\mathrm{GeV}}^5 \delta_{\nu e}^3 \ \mathrm{GeV}. \quad (2)$$

The mean decay time is then just $1/\Gamma$. To obtain the numerical value of the mean decay time for VPE, we note that in units where $\hbar = 1$, 1 GeV $= 6.58 \times 10^{-25}$ s^{-1}. We adopt the mean fractional energy loss due to a single pair emission of ~0.78 from [2].

We assume for this calculation a flat ΛCDM universe with a Hubble constant of $H_0 = 67.8$ km s^{-1} Mpc^{-1}, taking $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$. Therefore, the energy loss owing to redshifting for a ΛCDM universe is given by

$$-(\partial \log E/\partial t)_{\mathrm{redshift}} = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}. \quad (3)$$

IV. CALCULATIONS OF SUPERLUMINAL NEUTRINO PROPAGATION

In order to determine the effect of VPE on putative superluminal neutrinos propagating from cosmological distances we explore a simple example using Monte Carlo techniques to take account of energy losses by both VPE and redshifting. We consider a scenario where the neutrino sources have a redshift distribution that follows that of the star formation rate [18], as appears to be roughly the case for active galactic nuclei and γ-ray bursts. We assume a source spectrum proportional to E^{-2} between 100 TeV and 100 PeV. We generate 5×10^7 events using these two distributions. Our final results are normalized to an energy flux of $E_\nu^2 (dN_\nu/dE_\nu) \simeq 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}, as is consistent with the IceCube data for both the southern and northern hemisphere for energies between 60 TeV and 2 PeV, particularly when atmospheric charm decay neutrinos [15,21] are included in the background subtraction [5].

TABLE I. Mean propagation time at the threshold energy for the threshold energies considered.

Threshold energy (PeV)	1	2	4	10	20	40
Mean propagation time (Gyr)	0.011	0.022	0.045	0.11	0.22	0.45

In our Monte Carlo runs we consider threshold energies between 1 and 40 PeV for the VPE process, corresponding to values of $\delta_{\nu e}$ between 5.2×10^{-19} and 3.3×10^{-22}. By propagating our test neutrinos including energy losses from both VPE and redshifting using a Monte Carlo code, we then obtain final neutrino spectra and compare them with the IceCube results.

V. THE ICECUBE RESULTS

The IceCube data [5] are plotted in Fig. 3. They are consistent with a spectrum given by $E_\nu^2(dN_\nu/dE_\nu) \simeq 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} up to an energy of ∼2 PeV, the energy of the so-called "Big Bird" event. No neutrino induced events have been seen above 2 PeV [22].

IceCube has not detected any neutrino induced events from the Glashow resonance effect. In this effect, electrons in the IceCube volume provide enhanced target cross sections for electron antineutrinos through the W^- resonance channel, $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ shower, at the resonance energy $E_{\bar{\nu}_e} = M_W^2/2m_e = 6.3$ PeV [23]. This enhancement leads to an increased IceCube effective area for detecting the sum of the ν_e's, i.e., ν_e's plus $\bar{\nu}_e$'s by a factor of ∼10 [6]. It is usually expected that 1/3 of the potential 6.3 PeV neutrinos would be ν_e's plus $\bar{\nu}_e$'s unless new physics is involved [24]. Thus, the enhancement in the overall effective area expected is a factor of ∼3. Taking into account the increased effective area between 2 and 6 PeV and a decrease from an assumed neutrino energy spectrum of E_ν^{-2}, we would expect about three events at the Glashow resonance provided that the number of $\bar{\nu}_e$'s is equal to the number of ν_e's. Even without considering the Glashow resonance effect, several neutrino events above 2 PeV would be expected if the E_ν^{-2} spectrum extended to higher energies. Thus, the lack of neutrinos above 2 PeV energy and at the 6.3 PeV resonance may be indications of a cutoff in the neutrino spectrum. Hopefully, the acquisition of more data will clarify this point. In the next section we consider the physics implications of both the cutoff and no-cutoff scenarios for the neutrino spectra.

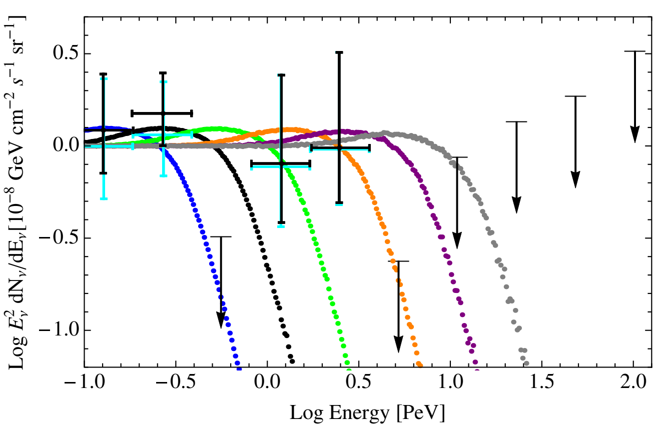

FIG. 3 (color online). Calculated neutrino spectra with VPE and redshifting compared with the IceCube data both including a subtraction of atmospheric charm ν's at the 90% C.L. (cyan) and omitting such a subtraction (black) [5]. Curves from left to right are spectra obtained with rest-frame threshold energies of 1, 2, 4, 10, 20, and 40 PeV. The corresponding values of $\delta_{\nu e}$ are given by Eq. (3).

VI. CONCLUSIONS AND DISCUSSION

The results of our calculations show that there is a high-energy drop off in the propagated neutrino spectrum resulting from the opening of the VPE channel above threshold. Furthermore, the redshifting effect pushes the cutoff in the energy spectrum below the nonredshifted rest-frame threshold energy. As discussed before, we assume that the neutrino production rate follows the star formation rate in redshift space. This rate peaks at a redshift between 1 and 2. The neutrinos emitted during this past era of enhanced stellar and galactic activity are then redshifted by a factor of 2–3. The redshifting effect dominates the shape of the resulting spectra regardless of threshold energy. This is because the mean propagation time at the threshold energy is very short compared with the total travel time with the exception of rest-energy thresholds greater than 10 PeV as follows from equations (1)–(3) (see Table I). Furthermore, the mean propagation time is also short for *all* energies greater than the threshold, with the exception of only those very near threshold, as illustrated in Fig. 2 for a rest-energy threshold of 10 PeV. In the case of rest-energy thresholds greater than 10 PeV, the particles very near threshold will simply redshift below it without decay. This has little impact on their final observed energies at $z = 0$.

Our calculated neutrino spectra follow our assumed E^{-2} power-law form below ∼0.2 of the redshifted VPE threshold, have a small pileup effect up to the redshifted threshold energy, and have a sharp high energy cutoff at higher energies, as shown in Fig. 3. The pileup is caused by the propagation of the higher energy neutrinos in energy space down to energies within a factor of ∼5 below the threshold. This is indicative of the fact that fractional energy loss from the last allowed neutrino decay before the VPE process ceases is 0.78 [2]. The pileup effect is similar to that of energy propagation for ultrahigh energy protons near the Greisen, Zatsepin, and Kuz'min photomeson production threshold [25].

Our results yield the best constraints LIV in the neutrino sector to date, *viz.*, $\delta_{\nu e} = \delta_\nu - \delta_e \leq 5.2 \times 10^{-21}$. This is because our results for our rest-frame threshold energy cases below 10 PeV as shown in Fig. 3 are inconsistent with the IceCube data. Our result for a 10 PeV nonredshifted threshold, corresponding to $\delta_{\nu e} = 5.2 \times 10^{-21}$, is just consistent with the IceCube results, giving a cutoff effect above 2 PeV. We note that the present best upper limit on δ_e is 5×10^{-21} [7]. Thus for the conservative case of no-LIV effect, e.g., if one assumes a cutoff in the intrinsic neutrino spectrum of the sources or one assumes a steeper assumed PeV neutrino spectrum proportional to $E_\nu^{-2.3}$ [5,24], we find the new constraint on superluminal neutrino velocity, $\delta_\nu = \delta_{\nu e} + \delta_e \leq 1.0 \times 10^{-20}$. However, the steeper spectrum scenario has been placed into question [26].

Interestingly, for an E_ν^{-2} power-law neutrino spectrum, we find the possibility that the apparent cutoff in the observed spectrum above ∼2 PeV can conceivably be an effect of Lorentz invariance violation (see Fig. 3). (Another suggestion involving LIV effects of *subluminal* neutrinos has recently been discussed [27].) A hard E_ν^{-2} spectrum has been proposed to be produced in starburst galaxies [28]. The IceCube flux is below the upper limit of 2×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} obtained by one of us for the neutrino flux from starburst galaxies [29], allowing for this possibility. The power-law source spectrum option opens the possibility that a high energy cutoff in such a hard E_ν^{-2} power-law neutrino spectrum could be caused by a small violation of Lorentz invariance, with neutrinos being very slightly superluminal, with δ_ν being $(0.5 \text{ to } 1.0) \times 10^{-20}$, taking $0 \leq \delta_e \leq 0.5 \times 10^{-20}$. As has been pointed out previously for ultrahigh energy neutrinos [30], one test for the cutoff scenario would be the nonobservation of the "cosmogenic" neutrinos from photopion production interactions of ultrahigh energy cosmic rays with the cosmic background radiation [31], since all cosmological neutrinos above ∼2 PeV would be affected by the VPE process. Such a nonobservation would have implications for γ-ray constraints on ultrahigh energy cosmic ray origin and composition models, perhaps implying the ultrahigh energy cosmic rays are mainly heavy nuclei [32].

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