

Implications of ultrahigh energy neutrino flux constraints for Lorentz-invariance violating cosmogenic neutrinos

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We consider the implications of Lorentz-invariance violation (LIV) on cosmogenic neutrino observations, with particular focus on the constraints imposed on several well-developed models for ultrahigh energy cosmogenic neutrino production by recent results from the ANITA long-duration balloon payload, and RICE at the South Pole. Under a scenario proposed originally by Coleman and Glashow, each lepton family may attain maximum velocities that can exceed c , leading to energy-loss through several interaction channels during propagation. We show that future observations of cosmogenic neutrinos will provide by far the most stringent limit on LIV in the neutrino sector. We derive the implied level of LIV required to suppress observation of predicted fluxes from several mainstream cosmogenic neutrino models, and specifically those recently constrained by the ANITA and RICE experiments. We simulate via detailed Monte Carlo code the propagation of cosmogenic neutrino fluxes in the presence of LIV-induced energy losses. We show that this process produces several detectable effects in the resulting attenuated neutrino spectra, even at LIV-induced neutrino superluminality of $(u_\nu - c)/c \approx 10^{-26}$, about 13 orders of magnitude below current bounds.

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In the current Standard Model (SM) of particle physics, neutrinos are massless and unmixed, and couple to other fundamental particles only through the weak interaction. This theory is very successful at describing the gauge boson fields and their interactions, and the three generations of quarks and leptons. However, observations of neutrino oscillations imply mixed neutrinos with nonzero mass, the most compelling evidence requiring extensions to the SM. The search for a fundamental theory that can explain and predict properties of neutrinos with nonzero mass has in turn become one of the most active areas of high energy particle physics. It is thus natural to anticipate that neutrino observations may provide unique opportunities for investigation of other beyond-standard-model physics such as Lorentz-invariance violation (LIV). While a recent claim of LIV in the form of superluminal behavior in muon neutrinos [1] appears to have been spurious and due to subtle instrumental effects, the possibility that LIV can appear at very small levels in many sectors of particle physics has been seriously explored for decades. Investigation of LIV that could lead to nontachyonic

superluminal particle velocities has received renewed motivation from recent efforts to develop consistent quantum gravity theories, through exploration of the possibility that Lorentz invariance may not be an exact vacuum symmetry at high energies [2,3].

SM modifications which specifically address LIV have been developed both as a way of incorporating the low-energy effects of spontaneous CPT -violation into the SM [4], and for high-energies, via general perturbation analysis [5,6]. The former work has been generalized to a Standard Model Extension (SME), and as such it provides a comprehensive framework for analysis of almost any LIV effect in any particle sector; recent compilations of experimental constraints now give limits for hundreds of different possible LIV parameters [7,8], and particular applications to the neutrino sector, with a primary focus on low-energy phenomena, have also been developed within this framework [9], and more recently for even a fully relativistic formulation with operators of arbitrary dimension [10].

The work of Coleman and Glashow [5,6], which focused on the high-energy limit, provides some specific predictions

regarding energy-loss mechanisms for superluminal LIV charged particles. These results have been used to provide stringent constraints on LIV on both ultrahigh energy cosmic ray (UHECR) protons [5] and UHECR photons [11]. More recently, similar considerations have been extended to cosmogenic neutrinos arising in intergalactic UHECR propagation showing that LIV in the hadron sector could lead to suppression of photomeson production, and a resulting decrease in the daughter neutrino fluxes [12]. Thus detailed ultrahigh energy (UHE) cosmogenic neutrino measurements and constraints can indirectly signal very small levels of LIV in the hadronic sector.

In the neutrino sector, LIV can appear in a very large variety of forms; for example, the recent comprehensive study by Kostelecky & Mewes gives 369 possible coefficients of LIV parameters for models which are restricted to be renormalizable [10]. In general, these coefficients can be associated with both flavor-changing effects, where the velocity between neutrino mass eigenstates can differ, and flavor-blind effects, where all flavors show an LIV-induced effect. In addition, directional dependence of the particle velocity may be implied when the LIV involves a preferred inertial frame. The flavor-dependent effects may appear as a type of oscillation signal for neutrinos propagating along different pathlengths or along different directions, but need not imply superluminal LIV. Detection of an LIV-induced signal due to these effects requires a search for modulation of the neutrino signal as a function of the effective propagation distance, and such searches can be extremely sensitive since they search for differential effects. In contrast, flavor-blind effects would be responsible for producing LIV that would be unique to the entire neutrino sector, affecting each mass eigenstate in the same way, and potentially leading to superluminal states. Searches for these effects must differentiate the neutrino sector velocity against another sector such as the photon sector, and are thus much more difficult in practice.

Currently, velocity differences between different neutrino mass eigenstates are constrained to parts in 10^{-23} by MINOS [13] with accelerator-based neutrinos, and to parts in 10^{-27} by IceCube using atmospheric muon neutrinos. However, constraints on the overall velocity difference of all neutrino flavors with respect to photons are many orders of magnitude weaker than the constraints on intra-mass-eigenstate variation, and are also weak compared to constraints on many other particle sectors in the SME.

In this work we focus only on LIV which can lead to an overall LIV superluminal behavior for the neutrino sector, and we will concentrate only on isotropic effects without direction dependence. The Lagrangian density prescribed in the LIV-motivated SME leads to a modified energy-momentum relation for neutrinos [6,14]:

$$E_\nu^2 = m_\nu^2 c^4 + [1 + 2\delta_\nu(\hat{p}_\nu)]c^2 \vec{p}_\nu^2, \quad (1)$$

where E_ν , m_ν , \vec{p}_ν are the particle's energy, mass, and momentum and the parameter $\delta_\nu(\hat{p}_\nu)$, which is in general

a spin-dependent, linear combination of several SME parameters, and can be identified with the dimension-three isotropic coefficient in the SME denoted $(c_L)_{00}$, or $(c_{of})_{00}$ in the flavor-blind, oscillation-free limit [10,15].

This term effectively determines the maximum possible velocity in direction \hat{p}_ν as $u_\nu \approx c(1 + \delta_\nu)$, where we have kept only terms to first order in δ_ν . This relation implies kinematically that the velocity of a neutrino may exceed that of photons *in vacuo* in the high-energy limit. This behavior is distinct from the hypothesis of Lorentz-invariant *tachyonic* neutrinos, first proposed by Chodos *et al.* [16], which have very different phenomenology and constraints; see Ref. [17] for a recent review.

Recent work [18] has shown that LIV-induced superluminal neutrino propagation in vacuum will lead to several energy-loss mechanisms not present in SM propagation. One mechanism in particular, electron-positron pair creation, or *pair bremsstrahlung*, is efficient enough for even very small values of δ_ν , that it leads to strong constraints in any experiment where neutrinos of sufficient energy are detected after propagation over significant distances. This in turn implies that even miniscule nonzero values of δ_ν will effectively attenuate cosmogenic neutrino fluxes to undetectable levels. Detection of such effects take the form of a disappearance search, coupled with the possibility of modification of the parent neutrino spectral energy distribution. This then alleviates the need to compare the neutrinos against another particle sector to establish the propagation characteristics.

Cowsik *et al.* [19] have recently investigated the bounds on LIV in the neutrino sector that arise from atmospheric muon neutrinos observed in IceCube, using the convention $E_\nu = p_\nu c(1 + \alpha_\nu)$ for the LIV parameter, where they have neglected the neutrino mass in the high energy limit, and thus $\alpha_\nu = \delta_\nu$ as used above in the SME. At high energies in the pair bremsstrahlung process noted above, $\nu_i \rightarrow \nu'_i + e^- + e^+$, the neutrino loses about 3/4 of its energy, and thus to first order a single pair bremsstrahlung interaction during neutrino propagation may be treated as an effective neutrino decay [18,19] with characteristic decay time

$$\tau_\nu = \tau_{CG} E_{\nu, \text{GeV}}^{-5} \alpha_\nu^{-3} \text{ s}, \quad (2)$$

where $\tau_{CG} = 6.5 \times 10^{-11}$ s. For IceCube's observations of upcoming atmospheric neutrinos, by requiring that the decay time exceed the crossing time of the Earth, Cowsik *et al.* find a resulting bound of $\alpha_\nu < 10^{-13}$.

Cowsik *et al.* also use similar analysis to derive a first-order estimate of the possible upper limit to α_ν that would arise from any observation of UHE cosmogenic neutrinos, by again requiring that the effective decay time be longer than the propagation time from the cosmogenic neutrino production site to Earth. However, they considered only neutrinos arising from sources within the nearest 100 Mpc. While this is the most conservative approach, it is in tension with the typical scenario presented by most UHE

cosmogenic neutrino models. In fact, in all current models for their production and propagation, only a negligible fraction of cosmogenic neutrinos observed at Earth arise from nearby sources; by far the largest contribution is from relatively high-redshift sources. To make an estimate consistent with this fact, we must first determine how to treat the neutrino propagation and possible effective decay over cosmological distances.

At a given redshift z , the propagation time for photons to the current epoch is given by the *lookback time* t_ℓ :

$$t_\ell(z) = \int_0^z \eta(z') dz', \quad (3)$$

where $\eta(z) = dt/dz = t_H[(1+z)\mathcal{E}(z')]^{-1}$ [20]. Here $t_H = H_0^{-1}$ is the Hubble time ($t_H \approx 3.09 \times 10^{17} h$ sec for $H_0 = 100h$ km s $^{-1}$ Mpc $^{-1}$, $h \sim 0.7$) and the function $\mathcal{E}(z)$ is given by [21]:

$$\mathcal{E}(z) = [\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda]^{1/2}. \quad (4)$$

Here the curvature parameter $\Omega_k = 1 - \Omega_M - \Omega_\Lambda$, where Ω_M, Ω_Λ are the matter density and cosmological constant, respectively. We consider three possible cosmologies, Einstein-de Sitter ($\Omega_M = 1, \Omega_\Lambda = 0$), a low-density, high-curvature model ($\Omega_M = 0.05, \Omega_\Lambda = 0$), and the currently favored high-lambda model ($\Omega_M = 0.3, \Omega_\Lambda = 0.7$). Figure 1 shows the lookback time for these three models, for $z > 0.03$, approximately 130 Mpc or more. The dotted line also shows the Euclidean-space approximation, $t = z t_H$. At $z > 0.1$ departure from Euclidean propagation is evident, and at $z \sim 1$ the propagation time begins to saturate asymptotically to the Hubble time, with less than

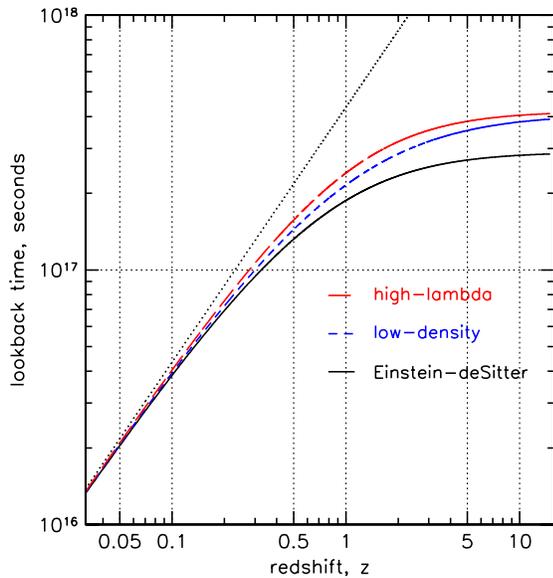


FIG. 1 (color online). Propagation time as a function of redshift z for neutrinos for 3 different cosmological models. The dotted line also indicates Euclidean propagation time.

a factor of two variation among the different cosmological models.

A large number of studies of UHE cosmogenic neutrinos have been published since 1969 when Berezhinsky and Zatsepin [22] first described their origin as secondaries in the Greisen-Zatsepin-Kuzmin (GZK [23,24]) process by which UHE cosmic ray protons resonantly scatter off the cosmic microwave background photons. For our purposes here, we refer only to several recent results that provide estimates of cosmogenic neutrino spectra as observed at Earth, for a range of model parameters, and for sources of different redshift [20,25].

Kotera *et al.* [25] present a decomposition of the neutrino energy spectral contributions from five different redshift bins, for $z < 0.5$, $0.5 \leq z < 1.5$, $1.5 \leq z < 2.5$, $2.5 \leq z < 4$ and $z > 4$. This decomposition of the spectral contributions is also given for six different cosmogenic neutrino models. In all cases, Kotera *et al.* find that the neutrino fluxes are dominated by contributions from $z > 1.5$, well into the asymptotic region of propagation time. Thus virtually all SM cosmogenic neutrinos have similar mean propagation times to Earth, $\langle t_\nu \rangle \sim 2-4 \times 10^{17}$ s, about a factor of 20–40 higher than that assumed by Cowsik *et al.* in their estimate.

If a nonzero cosmogenic neutrino flux were observed, then solving Eq. (2) above, and requiring that the neutrino lifetime should exceed the propagation time t_ν then gives an upper bound on α_ν :

$$\alpha_\nu(E_\nu) < 4.0 \times 10^{-4} E_{\nu, \text{GeV}}^{-5/3} t_\nu^{-1/3}. \quad (5)$$

Inserting the typical value $t_\nu = 3 \times 10^{17}$ seconds, and converting energy to EeV units (1 EeV = 10^9 GeV) which are more appropriate for the cosmogenic neutrino range

$$\alpha_\nu(E_\nu) < 6 \times 10^{-25} \left(\frac{E_\nu}{1 \text{ EeV}} \right)^{-5/3}, \quad (6)$$

which, as Cowsik *et al.* note, is many orders of magnitude below the current best bound from IceCube observations of atmospheric neutrinos.

In fact this analysis is incomplete. Since the observed energy at Earth $E_{\nu, \text{obs}}$ is redshifted relative to the energy at the source, in fact $E_{\nu, \text{obs}} = E_{\nu, \text{src}}/(1+z)$. Given that the dominant redshift range for cosmogenic neutrinos is $1 < z < 4$, the bounds on α_ν are factors of 3–15 lower; we can approximate this as

$$\alpha_\nu(E_\nu) < 2 \times 10^{-25} \left(\frac{\langle z \rangle E_{\nu, \text{obs}}}{1 \text{ EeV}} \right)^{-5/3}, \quad (7)$$

where $\langle z \rangle$ is the weighted-mean z of the cosmogenic neutrinos for a given source, and $1 < \langle z \rangle < 4$ is the valid range. This somewhat overestimates the bound since the propagation does not all occur at high- z ; a more precise estimate requires integrating the energy dependence as a function of z , as we will show below, but Eq. (7) is a reasonable approximation.

Upper limits on fluxes of cosmogenic neutrinos do not of course uniquely point to new physics in order to suppress

the flux, unless the limits begin to strongly contradict other observations. For example, because the GZK process relies on well-established particle physics with lab-frame energies in the GeV range, along with the extremely well-measured cosmic microwave background radiation, the observed UHECR fluxes guarantee an associated neutrino flux, if the primary UHECRs are of a light composition, and the UHECR sources are distributed like other sources in the universe. A predominantly heavy (e.g. iron) composition for the UHECRs, such as that suggested by Auger Observatory measurements [26], will significantly suppress the cosmogenic neutrino fluxes, but only if the same UHECR composition measured for sources within the local universe applies to cosmological sources at $z > 1.5$. There is also currently some inconsistency in assuming a heavy composition for the primary UHECR, since the observed GZK cutoff would require significant tuning of the source energy spectra in order to match the cutoff, which would arise naturally for a light composition.

Despite these uncertainties, the infinitesimal level of LIV in the neutrino sector required to effectively kill the cosmogenic flux suggests that we should take this possibility seriously and consider its implications. Within the last several years, a number of experiments, including the Radio Ice Cherenkov Experiment (RICE) [27], IceCube [28], and Antarctic Impulsive Transient Antenna (ANITA) [29,30], have finally begun to constrain fluxes of cosmogenic neutrinos. Although the total model space is not yet overly restricted by these constraints, the models that are ruled out, termed *strong source evolutionary* models, are still consistent with current UHECR data. These models do come into tension with indirect bounds derived by analyzing extragalactic gamma-ray data from the Fermi satellite [31,32], but these depend on details of the secondary cascade process and UHECR source characteristics and these fluxes are thus not uniquely excluded [12]. We therefore take these model bounds as motivation to investigate what degree of LIV is required to suppress these model fluxes below the current limits, and what other observable implications this might have.

For N neutrinos of energy $E_{\nu,\text{src}}$ propagating from the cosmogenic source to Earth, the LIV-induced attenuation with propagation time is given by $dN/dt = -\lambda N$ with the decay length $\lambda = 1/\tau_{\nu}$. Then

$$\frac{dN}{dz} = \frac{dN}{dt} \frac{dt}{dz} = -\frac{\eta(z)N}{\tau_{\nu}(E_{\nu}(z))}. \quad (8)$$

Substituting for τ_{ν} , rearranging and integrating both sides

$$N(z) = N_0 \exp\left[-\frac{\alpha_{\nu}^3}{\tau_{CG}} \int_0^z dz' \eta(z') \left(\frac{E_{\nu,\text{src}}}{1+z'}\right)^5\right]. \quad (9)$$

Figure 2 shows an example of the attenuation coefficient that arises from this propagation equation, for neutrino source energies over a quite small range, from 3–7 EeV, and a value of $\alpha_{\nu} = 8 \times 10^{-26}$ (chosen at random within

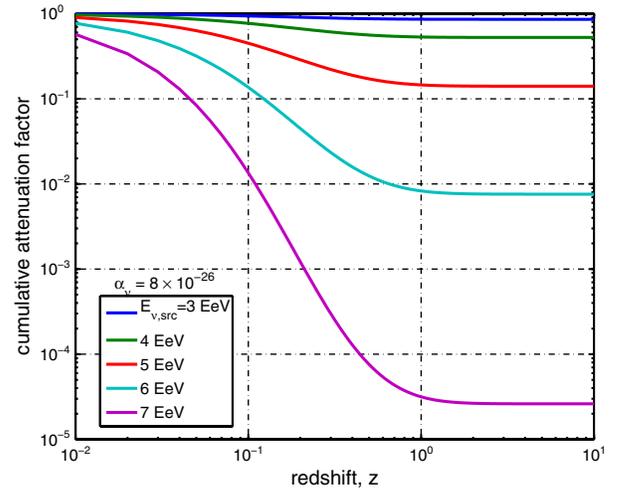


FIG. 2 (color online). The attenuation coefficient for a narrow range of source neutrino energies (e.g., un-redshifted energies) for the given value of α_{ν} , using the high-lambda cosmology and Eq. (9).

the range of interest here) for the LIV parameter. Here the redshift is that seen from the source looking out toward Earth, using the high-lambda model. It is evident that in each case the attenuation has saturated by $z \sim 1$ relative to the source, which means that any typical cosmogenic neutrino model will undergo the maximal attenuation of its beam toward Earth. We emphasize the very strong energy dependence displayed here, with attenuation for a given value of α_{ν} increasing by two orders of magnitude over an octave of energy. This will tend to have a “brick-wall” impact on neutrino model fluxes, cutting them off very rapidly above some onset energy, as we show below.

We note also that the fact that there is a neutrino in the final state of this interaction, carrying on average 1/4 of the energy, means that the spectrum will not be simply attenuated above the cutoff energy, but that there should also be a pile-up of lower energy neutrinos just at the edge of the effective LIV cutoff for a given values of α_{ν} . Both the brick-wall and pile-up effects are confirmed by an analysis from Bi *et al.* (2011) [33], where much lower energy neutrinos are considered, over galactic propagation scales.

To determine the impact of both the energy-dependent attenuation and the potential final-state neutrino pileup on an UHE neutrino spectrum at earth, we use the publicly available cosmic-ray propagation code CRPropa 2.0 [34] to simulate one-dimensional proton trajectories and then propagate the resulting neutrinos ourselves. We simulate protons from cosmic monoenergetic point sources out to $z = 3$. Using the energy and redshift of each neutrino produced along the trajectory, we allow it to interact via pair bremsstrahlung along its path to earth. We subtract the cumulative attenuation factors determined by Eq. (9) from unity to obtain the energy-dependent probability density functions used to find the redshift of each neutrino interaction. Multiple interactions are allowed from each initial

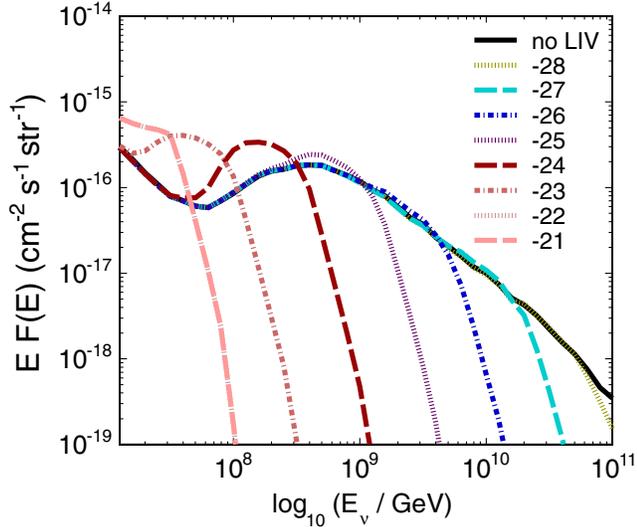


FIG. 3 (color online). Example of LIV effects on a strong-source-model cosmogenic neutrino spectrum. Black line: unattenuated cosmogenic neutrino spectrum generated by our modified CRpropa code, here with parameters chosen to give a spectral shape commensurate with that of typical strong-source cosmogenic neutrino models. The different lines indicated in the legend show the value of $\log_{10}(\alpha_\nu)$ that yields the modified spectrum shown. In each case both the brick-wall cutoff at a given energy, and an enhancement or pile-up effect just below that energy, appear in the LIV-modified spectra.

neutrino. Using the resulting collection of spectra from monoenergetic point sources, we follow the prescription for typical strong-source evolutionary models to calculate the neutrino spectra for an arbitrary injection spectrum and redshift evolution. We do not yet incorporate possible energy-dependence of the LIV parameter α_ν , although such dependence may be expected from quantum gravity considerations [2]; in any case such effects would increase the sensitivity of our results to the level of LIV.

For the final-state outgoing neutrino, we assume the pair bremsstrahlung process as a mean inelasticity such that the final state neutrino's energy is 1/4 of the initial energy. We would normally integrate over the inelasticity distribution, but such distributions are not given in the current models. In general we have found that, at least for neutrino deep-inelastic scattering inelasticity distributions, using the mean value as a proxy for a full integral is an acceptable approximation to first order. Figure 3 shows an example of these results, here applied to a cosmogenic neutrino model at varying levels of α_ν , ranging from 10^{-27} to 10^{-21} . Both the brick-wall and pile-up effects are evident, and the turnover energy of the brick-wall in each case reflects the value of α_ν present.

Returning to the strong-source-evolution models currently constrained by ANITA & RICE, Fig. 4 shows the fluxes for three of these models, all of which are constrained above the 90% confidence level; also plotted are the ANITA and RICE limit curves. Energy flux (or intensity)

units (particle energy \times flux) are used here to avoid the spectral distortions that accompany less physically-motivated units such as $E^2 F(E)$ which are also often used in reporting neutrino limits. In the normalization used here, models which just match the differential limit curve for a decade of energy produce about 2 detectable events; in these three cases, the expected number was between 4–6 events for ANITA for all three models. For RICE, we estimate that the highest model of Barger *et al.* would produce of order 12 events; the higher-energy models will produce 2–3 events in RICE.

The event totals produced by an LIV-modified spectrum are determined for ANITA using ANITA event-sensitivity integrals based on our system Monte Carlos [35]; estimating these event totals for RICE was outside the scope of our effort, but it is evident based on Fig. 4 that the constraints from RICE from the Barger *et al.* model could be a factor of three better for that case at least. Table I gives the hypothetical *lower limits* on α_ν for each of the three cosmogenic neutrino models—lower limits here because they are the minimum values required to suppress these fluxes below the experimental detection levels for RICE and ANITA-II. Not surprisingly the model with the highest energy predictions has the highest sensitivity to the LIV parameter. In all cases, even extremely small values of LIV, far below existing limits in the flavor-blind case, would be adequate to make these cosmogenic fluxes essentially undetectable, accounting for the non-observation of these fluxes.

It is an interesting coincidence that the level of LIV required to produce a flavor-blind superluminal effect that would effectively suppress cosmogenic fluxes is comparable to the current best limits on velocity differences *between* mass eigenstates, as noted in the introduction. Of course there are other potential causes for suppression

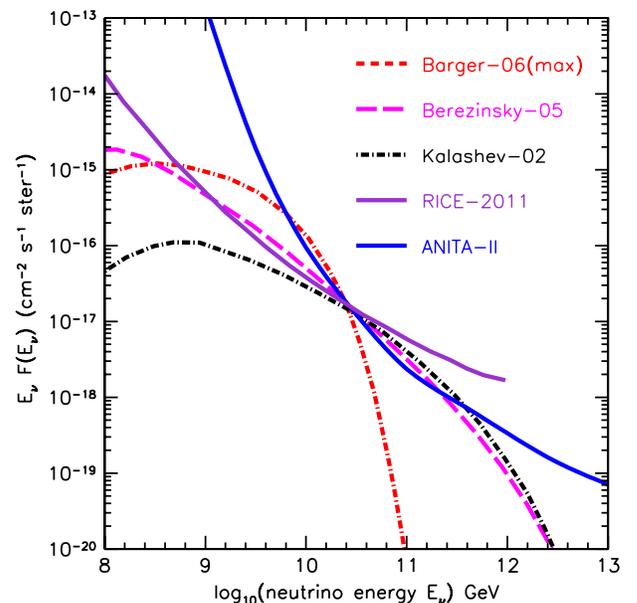


FIG. 4 (color online). ANITA-II and RICE limits and three strong-source-evolution model fluxes addressed here.

TABLE I. First column: expected numbers of events N_ν for ANITA-II & RICE from three strong-source-evolution cosmogenic neutrino models; these models are all excluded at $>90\%$ confidence from these experiments. Second column: values for the level of Lorentz invariance violation that would lead to the non-observation of these models. The high-lambda cosmological model was employed for this calculation.

| <i>Model & references</i> | ANITA/RICE predicted N_ν | lower limit on LIV α_ν |
|----------------------------------|------------------------------|---------------------------------|
| Barger <i>et al.</i> 2006 [36] | | |
| ANITA-II | 3.5 | 2×10^{-27} |
| RICE2011 | 12 | 2×10^{-25} |
| Berezinsky 2005 [31] | | |
| ANITA-II | 5.1 | 3×10^{-28} |
| RICE2011 | 3.4 | 2×10^{-27} |
| Kalashov <i>et al.</i> 2002 [37] | | |
| ANITA-II | 5.6 | 2×10^{-28} |
| RICE2011 | 2.9 | 10^{-28} |

of the cosmogenic neutrino flux, and thus detection of the cosmogenic neutrinos is clearly a more interesting outcome for both neutrino astrophysics and for the resulting constraints on LIV phenomena. We can thus estimate the strength of the upper bound on LIV for a hypothetical detection of cosmogenic neutrinos for the sensitivity predicted for ANITA-III, due to fly in 2013, under the assumption of near-zero background, as has been the case for the first two ANITA flights. We have developed full Monte Carlo simulations of the sensitivity of the ANITA-III payload currently in fabrication, and based on the planned improvements we estimate about a factor of three increase in total neutrino event rate for a typical 30-day flight compared to ANITA-II. Under this outcome, with a clear detection of several neutrino events, a conservative constraint on the LIV parameter from ANITA-III would be $\alpha_\nu \lesssim 10^{-26}$, which is consistent with equation (7) above for $\langle z \rangle \sim 2$ and $E_{\nu, \text{obs}} \sim 3$ EeV. Similar constraints would obtain for future detection of several unambiguous neutrino candidates in RICE, or the future ARA experiment now in early construction [38], or for the recently fully-instrumented IceCube experiment. Thus a detection of cosmogenic neutrinos will move the flavor-blind constraints to values very close to those that currently obtain between the mass eigenstates.

As noted above, a specific prediction of such LIV effects is the very steep dropoff with energy once a threshold is reached. Thus, large-scale experiments such as IceCube [28], Askaryan Radio Array (ARA) [38], and others that have extended low-energy sensitivity to cosmogenic

neutrino models as compared to ANITA, may be able to detect such sharp cutoffs in neutrino energy spectra, signaling the onset of LIV at these extremely small levels. Thus our results modify somewhat the conclusion of Cowsik *et al.*: a clear detection of cosmogenic neutrinos *with no unexpected spectral features* would provide exceedingly tight constraints on LIV in the neutrino sector. However, if enough neutrinos were measured to indicate the very sharp energy-spectral cutoff predicted here, it would rather unambiguously indicate the presence of neutrino LIV; no other proposed process that we know of can produce such a sharp spectral cutoff in UHE neutrinos. These results emphasize the need for a broad-spectral approach toward searches for the cosmogenic neutrinos; this particular effect will turn on first at the highest energies, and might not be apparent in a cosmogenic neutrino detector whose spectral reach did not extend beyond 10 EeV or more.

We conclude by observing that, although a relatively large value of α_ν could completely attenuate the cosmogenic neutrino fluxes below any detectable level for any experiment, the results of this would not escape some other possible detection channels. Specifically, the pair bremsstrahlung process will lead to electromagnetic cascades in intergalactic space, redistributing the neutrino energy into an observable gamma-ray background. For example, in many models, the photo-hadronic cascades that UHECRs undergo in the GZK process lead to rough equipartition in energy between EeV cosmogenic neutrinos, and GeV cosmogenic gamma-rays. In the presence of complete LIV-induced attenuation of the cosmogenic neutrinos, the cosmogenic gamma-ray fluxes would be doubled to first order. Thus constraints on such a process can be obtained through careful analysis of the extragalactic gamma-ray background, such as that measured by Fermi, in direct analogy to what has already been done to constrain the integrated intensity of the cosmogenic neutrino production [32]. Such constraints may in fact be more robust than those on GZK-interaction cascades, since LIV-induced neutrino cascades are much less influenced by uncertainties in magnetic fields in the UHECR source environment.

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