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ABSTRACT

There may be a high-energy cutoff of neutrino events in IceCube data. In particular, IceCube does not observe either continuum events above 2 PeV, or the Standard Model Glashow-resonance events expected at 6.3 PeV. There are also no higher energy neutrino signatures in the ANITA and Auger experiments. This absence of high-energy neutrino events motivates a fundamental restriction on neutrino energies above a few PeV. We postulate a simple scenario to terminate the neutrino spectrum that is Lorentz-invariance violating, but with a limiting neutrino velocity that is always smaller than the speed of light. If the limiting velocity of the neutrino applies also to its associated charged lepton, then a significant consequence is that the two-body decay modes of the charged pion are forbidden above two times the maximum neutrino energy, while the radiative decay modes are suppressed at higher energies. Such stabilized pions may serve as cosmic ray primaries.

The fact that IceCube does not (yet) observe neutrinos with energies above about 2 PeV [1,2] invites some interesting speculation: Perhaps there are none! IceCube does observe three events in the 1–2 PeV range.[1] The expected number of continuum (meaning, non-resonant) events above 3 PeV, normalized to the three observed events in the 1–2 PeV region, is 1.5 for a neutrino flux falling as $E^{-2.0}$ [4]. (Other experiments such as Auger [5] and ANITA [6] are not necessarily expected to see any neutrinos resulting from Standard Model (SM) processes, and they do not.) Furthermore, the absence of "Glashow resonance" [7] events $\bar{\nu}_e + e^- \to W^- \to$ shower at $E_{\bar{\nu}_e} = 6.3$ PeV in the IceCube detector volume lends further credence to the cutoff hypothesis, because the effective area at the resonant energy partially cancels the falling power law ($E_\nu^{-\alpha}$) of the incident neutrino spectrum. The expected number of resonance events (at ~ 6.3 PeV) at IceCube for a neutrino flux with flavor ratios $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$ at Earth as expected from the $\pi^\pm$ production and decay chain, relative to the three observed events in the 1–2 PeV region is 1.0 for $\alpha = 2.0$ [4]. An earlier statistical study concluded that α was constrained by the absence of Glashow events in the IceCube data, to $\alpha \geq 2.3$ (also assuming a $1:1:1$ flavor ratio at Earth) [8].[2] For the steeper $\alpha = 2.3$ spectrum, the expected continuum and resonance event numbers are 1.1 and 0.9 [4]. The Poisson probability that an experiment would experience a downward fluctuation of 2.5 expected events (for $\alpha = 2.0$) to zero is $e^{-2.5} = 8.2\%$. The probability that 2.0 expected events (for $\alpha = 2.3$) would fluctuate downward to zero is $e^{-2.0} = 14\%$. These probabilities are small, but not extremely so. Our hypothesis is that these numbers are meaningfully small, and that the absence of events above a cutoff value $\gtrsim 2$ PeV is fundamental.

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[1] The two published PeV events deposited $1.041^{+0.132}_{-0.144}$ PeV and $1.141^{+0.143}_{-0.133}$ PeV of energy in photo-diode electrons (PDEs), respectively. This PDE energy is a minimum but sensible estimate for the true event energy of showers. The third event has the highest PDE energy, $2.004^{+0.236}_{-0.262}$ PeV [3].

[2] It is worthwhile to note that in *pp* collisions the nearly isotopically neutral mix of pions will create on decay a neutrino population in the ratio $N_{\nu_\mu} = N_{\bar{\nu}_\mu} = 2N_{\nu_e} = 2N_{\bar{\nu}_e}$. In contrast, photopion interactions have the isotopically asymmetric process $p\gamma \to \Delta^+ \to \pi^+ n$, $\pi^+ \to \mu^+ \nu_\mu \to e^+ \nu_e \bar{\nu}_\mu \nu_\mu$, as the dominant source of neutrinos; then, at production, $N_{\nu_\mu} = N_{\bar{\nu}_\mu} = N_{\nu_e} \gg N_{\bar{\nu}_e}$, which suppresses production of the Glashow resonance [9]. Alternatively, Glashow events can be suppressed if the pion decay chain is terminated in the source region by energy loss of the relatively long-lived muon [10].

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The showers due to the Glashow resonance (the W-boson) events are expected to populate multiple energy peaks [11]. The dominant one is at $E_{\rm res} = M_W^2/2m_e = 6.3$ PeV, while the others occur at $E_{\rm vis} = E_{\rm res} - E_X$, where E_X is the energy in the W decay which does not contribute to the visible shower: the hadronic decay modes $W \to q\bar{q}$ will populate the peak at 6.3 PeV, while the leptonic modes $W^- \to \bar{\nu} + \ell^-$ will lose half of their energy to the invisible neutrino. Furthermore, the muonic mode will show just a track, and no shower at all, while in the τ mode, the τ decay will produce a second invisible neutrino, leaving a visible shower with 1/4 of the energy of the initial $\bar{\nu}_e$. Thus we expect the ratio of the lower energy peaks at 1.6 and 3.2 PeV, to the higher energy peak at 6.3 PeV, to be $\text{BR}(\tau) : \text{BR}(e) : \text{BR}(\text{hadrons}) \sim 1 : 1 : 6$. It is tempting to associate the observed events at 1–2 PeV with the leptonic decay modes of the Glashow resonance [12], but this exacerbates the issue of why the more numerous resonance events at 6.3 PeV are not seen.

In this Letter we consider the possibility of a cutoff in the neutrino energy. The cutoff energy $E^\nu_{\rm max}$ could be 2 PeV, 20 PeV, or higher, with each increase in cutoff energy making the experimental determination of the cutoff statistically more difficult due to the expected falloff in the neutrino spectrum (and to some extent, due to the absence of a null resonance signal for a cutoff energy above 6.3 PeV). In what follows, we present an example of how a cutoff in the neutrino energy might arise from Lorentz-Invariance Violation (LIV), and discuss its phenomenological implications. If it happens that there is a bound on the neutrino energy, then it is possible to discriminate our proposal from standard cutoff models that do not need new physics (*e.g.*, a steeply-falling or broken power-law spectrum $\propto E_\nu^{-\alpha}$, with α exceeding 2.3).

The possibility of LIV in terms of a limiting velocity, different for each kind of particle, has been analyzed in Ref. [13]. As long as all limiting velocities are less than or equal to the limiting velocity of the photon, causality is preserved – new "lightcones" appear inside *the* lightcone. (For a discussion of superluminal neutrinos in the present context, see *e.g.* [14].) Unlike the realization of LIV of Ref. [13], in which the limiting velocity does not lead to a limiting energy, we postulate an equivalence of limiting energy and limiting velocity β_ν:

$$E^\nu_{\rm max} \equiv \frac{m_\nu}{\sqrt{1-\beta_\nu^2}} \sim \frac{m_\nu}{\sqrt{2(1-\beta_\nu)}}, \quad \text{with } \beta_\nu \equiv \frac{v_\nu}{c}. \tag{1}$$

Accordingly, the required limiting velocity to suppress $E^\nu_{\rm max}$ neutrinos is $\beta_\nu \approx 1 - 1/(2\gamma_\nu^2)$, differing from the speed of light by

$$1 - \beta_\nu \simeq 0.5 \times 10^{-28} \left(\frac{m_\nu}{10\ \text{meV}}\right)^2 \left(\frac{\text{TeV}}{E^\nu_{\rm max}}\right)^2. \tag{2}$$

It is very likely that the highest boost factors will forever remain the domain of neutrinos; even for $E^\nu_{\rm max} \geq 2$ PeV, a "boost-equivalent" proton energy is five orders of magnitude higher than has ever been observed for a proton primary.[3]

The obvious phenomenological statement is that no neutrino with energy exceeding $E^\nu_{\rm max}$ will ever be observed. In particular, so-called "guaranteed" BZ [15] neutrinos from the cosmogenic GZK [16] process will not be produced if $E_{\rm BZ}$, typically 10^{18} eV, exceeds $E^\nu_{\rm max}$. However, the $\sim$ PeV $\bar{\nu}_e$'s from the decay of cosmic ray neutrons will still be produced.

One may well ask to what reference frame is the limiting velocity compared? The Universe has conveniently provided us with a unique "cosmic rest frame." It is the frame where the bulk matter of the Universe is at rest (nearly the same as the rest frame of Earth). Equivalently, it is the frame in which the bulk temperature of 2.73 K is uniquely and universally defined. All other frames are to be compared to this unique Machian reference frame.

Incidentally, although particle limiting velocities will alter the behavior of the very early Universe, it is unlikely that there would be any trace of this altered behavior in the later Universe. This is because the Universe is a thermal system, so alterations would have occurred at $T \sim E^\nu_{\rm max} \gtrsim$ PeV, long before the QCD transition from quark–gluon–plasma to mesons and baryons at $\sim \Lambda_{\rm QCD} \sim$ 200 MeV, and even longer before nucleosynthesis at $\sim$ MeV.

It seems natural to impose a limiting energy or velocity on each lepton flavor. Then in association with the muon (electron) neutrino, the muon (electron) too has a limiting velocity or energy. Consequences are significant. For example, the kinematics of charged pion decay to leptons and their associated neutrinos having a common maximum energy $E^\nu_{\rm max}$ dictates that charged pions are stabilized above $\sim 2E^\nu_{\rm max}$. The pion is certainly stable at energies above $E^{\nu_\mu}_{\rm max} + E^\mu_{\rm max}$ and $E^{\nu_e}_{\rm max} + E^e_{\rm max}$, if many-body decays are ignored.[4] The pion could be stable for all practical purposes at an energy below that dictated by absolute stability, because its lifetime may be sufficiently altered by the maximum allowed lepton energies. Generally speaking, $E^{\nu_\mu}_{\rm max} \neq E^\mu_{\rm max} \neq E^{\nu_e}_{\rm max} \neq E^e_{\rm max}$, and so the track to shower ratio may be anomalous as the neutrino energy approaches a PeV.

These absolutely stable high-energy charged pions would constitute a new primary candidate for cosmic rays with energies above some stabilization energy; since pion stability will depend on $E^\mu_{\rm max}$ and $E^e_{\rm max}$ as well as on $E^{\nu_\mu}_{\rm max}$ and $E^{\nu_e}_{\rm max}$, the stabilization energy can be quite different from $E^\nu_{\rm max}$. The possibility of stable pion cosmic ray primaries adds an interesting test of our hypothesis. The common rigidity (energy/charge) of the protons and charged pions implies that (within the Galactic leaky box context) the stable pion spectrum would share the slope of the proton spectrum. On the other hand, the strong Auger limit on the photon content of ultra high energy cosmic ray showers [17] can be construed to limit any primary that showers more like a photon than like a proton. However, stable pion primaries still maintain their strong interaction cross section, and so look more like proton primaries than photon primaries. There are three attributes of a primary's scattering that determine its typical shower: the cross section, the inelasticity, and the final state multiplicity. Stable pion showers may appear proton-like in the third characteristic, the

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[3] $E^\nu_{\rm max}$ may be related to a new physics scale, such as the size of extra dimensions. It is interesting to note that a proton with boost factor equal to that of a PeV neutrino, $\frac{\text{PeV}}{m_\nu} \sim 10^{16}$, has an energy of 10^{16} GeV, comparable to the Grand Unification scale.

[4] Unless the unknown mechanism that realizes our postulate suppresses higher-order radiative decays, the pion will decay via 3-body processes like $\pi^+ \to \gamma\ell^+\nu$ and $\pi^0 e^+\nu_e$, and possibly via 4-body processes like $3\ell + \nu$ and $3\nu + \ell$ (where kinematics allow at most one ℓ to be a muon with the others electrons), and $\pi^0\gamma e^+\nu_e$ and $\gamma\gamma\ell\nu_\ell$. Here we give sufficient energy conditions to ensure $\pi^\pm$ stability; in the cases with two final state leptons, the sufficiency condition is calculated with the two leptons having identical three-momentum in the direction of the parent $\pi^\pm$. The necessary conditions on the $\pi^\pm$ energy, not yet available, will be lower than the sufficiency conditions given herein. Sufficient critical $\pi^\pm$ energies for the 3-body modes are $(\frac{m^2_{\pi^\pm}}{m^2_\ell})(E^\nu_{\rm max} + E^\ell_{\rm max})$ and $(\frac{m^2_{\pi^\pm} - m^2_{\pi^0}}{m^2_e})(E^{\nu_e}_{\rm max} + E^e_{\rm max})$, respectively (with $\ell = \mu$ kinematically forbidden for the final state containing a π^0). On the face of it, the sufficient energy assigned to the mode $\pi^+ \to \gamma\ell^+\nu$ has a dangerous prefactor, $(\frac{m^2_{\pi^\pm}}{m^2_e}) \sim 0.8 \times 10^5$; clearly, the lower, necessary energy that bounds this mode needs to be calculated. The sufficient $\pi^\pm$ energy above which the purely leptonic 4-body decay modes are disallowed are $2E^e_{\rm max} + E^\ell_{\rm max} + E^{\nu_\ell}_{\rm max}$ and $2E^{\nu_\alpha}_{\rm max} + E^\ell_{\rm max} + E^{\nu_\ell}_{\rm max}$, respectively; while the sufficient energies to disallow the 4-body semi-leptonic modes, obtained by setting the lepton pair to rest in the parent $\pi^\pm$-frame, are the same as the results for the 3-body modes. We note that since the 3-body modes are special cases of the semi-leptonic 4-body modes (with one 4-body photon energy set to zero), they cannot, and here do not, have a higher requirement on the parent energy.

final state multiplicity, but they deviate from protons on the first two attributes: the pion cross section at high energy is smaller by about 2/3 than the proton cross section, and the pions' Feynman x_F distribution, a measure of the primary particle elasticity per interaction, is harder than that of the proton [18]. For the pion, $\frac{d\sigma}{dx_F} \propto (1 - x_F)$, with a mean elasticity of $\langle x_F \rangle = 1/3$, while for the proton the cross section goes as $\propto (1 - x_F)^3$, with a mean elasticity $\langle x_F \rangle = 1/5$. The proton primary will lose 99% of its energy after 2.9 interactions on average, whereas the stable pion will lose 99% of its energy only after 4.2 interactions. Thus the shower development is delayed in the case of a pion primary relative to the proton primary. A more quantitative study is required to determine whether or not pion-primaries are viable, useful high-energy cosmic ray candidates. It is important to note, however, that within this scenario the stable $\pi^{\pm}$'s contribute to the total power budget and thereby reduce the power budget of proton sources (*e.g.*, the complete GZK chain reaction proceeds only via π^0 decay).

In summary, we have explored the hypothesis that there may be an upper limit $E^{\nu}_{\max}$ on the neutrino energy. Such an energy limit implies broken Lorentz invariance, since arbitrarily large boosts relative to the cosmic rest frame become untenable for the energy-bounded neutrino. IceCube data, statistically weak at present, suggests that this upper limit may have already been encountered, at a few PeV.

Of course, Ockham's razor favors the absence of the baroque scenario presented here. The simplest means to raise the search limit for $E^{\nu}_{\max}$ (and reduce the motivation for our speculation) is to observe neutrinos with energies extending to higher and higher values. However, if the absence of observed neutrinos above some energy persists, it would be evidence that Nature is more whimsical than William of Ockham.

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