Cosmic PeV Neutrinos and the Sources of Ultrahigh Energy Protons

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The IceCube experiment recently announced the first detection of multi-PeV neutrinos, which cannot easily be explained by atmospheric or cosmogenic fluxes. We examine whether these neutrinos originate from the same sources as ultrahigh-energy cosmic rays. We find that producing the requisite neutrino flux through photopion production in the source leads to a proton flux at the level of cosmic-ray data at $\sim 10^{18}$ eV in a constrained scenario where neutrinos only arise from $\pi^+$ decays. In more general cases the proton yield is much lower, requiring a dominant class of accelerator that allows cosmic rays to escape without significant losses.

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Introduction.— High-energy astrophysical neutrinos have much to tell us about the most extreme environments in the Universe; however, finding them is a difficult endeavor [1–3]. Colossal detectors are required, such as IceCube [4], that can observe the tracks of muons produced in charged-current $\nu_\mu/\bar{\nu}_\mu$ scattering or showers (cascades) induced by various channels (as we discuss later). The recent observation of two PeV-energy shower events by IceCube may represent the discovery of such neutrinos [5], as atmospheric PeV neutrino fluxes are low [6,7]. The most likely astrophysical mechanism is photoproduction by protons on a photon background, $p \gamma \rightarrow N \pi$, leading to neutrinos via pion decays.

An example of this process is the suppression of ultrahigh-energy cosmic-ray (UHECR) proton fluxes at $\gtrsim 10^{19.5}$ eV due to the cosmic microwave background (CMB), the GZK effect [8,9]. The measured UHECR spectrum displays a downturn near this energy [10,13]. However, the $\gtrsim 10^{18}$ eV neutrinos resulting from the decays of pions produced [14,17] are too energetic to explain the IceCube events, while the flux of lower-energy neutrinos from decays of neutrons is too small.

The cosmic infrared/optical background allows for photoproduction by lower-energy protons in propagation, leading to lower-energy neutrinos [18–20]. However, Fermi measurements of gamma-ray absorption in blazar spectra now indicate a low level of the $\lesssim 10$ eV diffuse photons [21] needed to photoproduce with $\lesssim 10^{17}$ eV protons to yield $\sim 10^{15}$ eV pionic neutrinos. Moreover, unless magnetic fields lead to sufficient synchrotron losses in the subsequent cascades to suppress gamma rays, a PeV neutrino flux cannot be produced at the required level that respects the isotropic gamma-ray background [22]. This suggests that, if the neutrino flux is cosmic, it likely arises from within some class of sources.

Our goal is to determine whether the IceCube PeV neutrinos share a common origin with UHECRs in the $\sim 10^{18}$ eV range where the composition is inferred to be light [23,25]. The UHECR protons observed at Earth must have been able to retain sufficient energy upon leaving their acceleration sites [26]. However, the magnetic fields required to contain the particles during the acceleration process can lead to severe adiabatic losses if they cannot be promptly escaped.

If this is to be achieved through photohadronic interactions producing neutrons that later decay to protons outside the source, then there must be an accompanying flux of pionic neutrinos (for this reason, IceCube limits disfavor gamma-ray bursts [27–30]). We use the neutrino flux implied by the IceCube events (for an assumed source spectrum, evolution with redshift, flavor ratios, and neutrino oscillations) to normalize the outgoing proton spectrum to determine whether this is the mechanism operating in ultrahigh-energy sources.

Neutrinos and IceCube.— We begin by constructing a source neutrino spectrum that results in fluxes at Earth that yield shower rates that peak at the IceCube energy range using a smoothly-broken power law (with $E$ in GeV) as

$$\frac{dN}{dE} = f_0 \left[ \left( \frac{E}{E_0} \right)^\alpha + \left( \frac{E}{E_0} \right)^\beta \right]^{1/\eta},$$

(1)

![Image](image-url)
where the slopes are $\alpha$ and $\beta$, with $\eta = -1$ to give a smooth break at $E_\nu$. We obtain the neutrino fluxes at Earth, $\varphi_\nu(E_\nu)$, by integrating these spectra up to $z_{\text{max}} = 8$ as

$$\varphi_\nu(E_\nu) = \frac{c}{4\pi} \int_0^{z_{\text{max}}} \frac{dN_\nu}{dE_\nu} \frac{W(z)}{dE_\nu} dz/dz,$$  

(2)

where $dz/dt = H_0 (1 + z)[\Omega_m(1 + z)^3 + \Omega_\Lambda]^{1/2}$ (with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km/s/Mpc) and $dE_\nu/dE_\nu = (1 + z)$ accounts for redshift. We set the evolution in the rate of neutrino production, $W(z) = 1$, which conservatively bounds the required neutrino emissivity, and discuss alternatives later.

Motivated by the model in [32] for an $E^{-2}$ accelerated proton spectrum, we first use a neutrino spectrum with $\alpha = -1$, $\beta = -2$, and photopion opacity $\sim 1$ for $E_\nu = 10^7$. We assign the initial flavor ratios resulting from equal numbers of $\pi^+$ and $\pi^-$, as in sources with hard photon backgrounds. Neutrinos result from $\pi^\pm$ decays, $\pi^+ \to \mu^+ \nu_\mu$, $\mu^+ \to e^+ \bar{\nu}_e \nu_\mu$, and $\pi^- \to \mu^- \bar{\nu}_\mu$, $\mu^- \to e^- \nu_e \bar{\nu}_\mu$, giving $\nu_\mu: \bar{\nu}_\mu: \nu_e = 1:2:0$ and $\bar{\nu}_e: \nu_e: \nu_\mu = 1:2:0$. We account for neutrino oscillations using mixing parameters from [33]. The lower panel of Fig. 1 shows the shapes of the arriving fluxes, broken down by flavor.

We also consider the extreme in which only $\pi^+$ are produced, as with near-threshold photoproduction due to a soft background. Muons experience higher synchrotron losses than pions in the strong magnetic fields within the acceleration region of sources [34, 35]. We use this to obtain a model with no $\bar{\nu}$ component by assuming that muons are produced, but cool and decay only to low-energy neutrinos. The initial flavor ratios are approximated as those from the $\pi^+$ decay, $\nu_\mu: \bar{\nu}_\mu: \nu_e = 0:1:0$ and $\bar{\nu}_e: \nu_e: \nu_\mu = 0:0:1$. Here, we take pion cooling to result in a break at $E_\nu = 10^7$, so that $\beta = -3$, as in the upper panel of Fig. 1. In both cases, we neglect the $\bar{\nu}_e$ flux from neutron decay, which carries much less energy and peaks at energies lower by about two orders of magnitude.

Rates of shower-like events in IceCube are principally determined by the normalized neutrino fluxes, effective volume, and cross sections for neutrino-nucleon, $\sigma_{\nu N}$ and $\sigma_{\bar{\nu} N}$, and antineutrino-electron, $\sigma_{\bar{\nu} e}$, scattering. We use the total deep-inelastic scattering cross sections from [36] for charged-current (CC) and neutral-current (NC) scattering, and the average inelasticity, $\langle y(E_\nu) \rangle$, from [37], approximating $\langle y \rangle = 0.25$ at $\gtrsim$ PeV energies.

The visible energy of the shower depends upon the interaction channel. For NC events ($\nu N \to \nu X$), $\sigma_{\nu N}$ is identical for all flavors, and $\langle y \rangle$ determines the fraction of energy imparted to a quark in the nucleon. The resulting hadronic shower results in less light than an equivalent-energy electromagnetic shower by a factor that is a function of energy $[38]$ that we assume to be $f_{\text{had}} \approx 0.9$. Thus, working in terms of the electromagnetic-equivalent shower energy $E_{\text{em}}$ (as in Fig. 2), with $q_{\nu N} \approx 0.23$, we have

$$E_{\text{em}, \nu N} = f_{\text{had}}(y) E_\nu = q_{\nu N} E_\nu.$$

(3)

For CC $\nu_e$ events ($\nu_e N \to e X$), we assume that the electron deposits its entire energy, $E_e = (1 - y) E_\nu$, into an electromagnetic shower. There is also an accompanying hadronic shower of energy $\langle y \rangle E_\nu$. We add these together to get a total effective visible energy per interaction as $E_{\text{em}, e} = (1 - y) E_\nu + f_{\text{had}}(y) E_\nu = q_e E_\nu$, with $q_e \approx 0.95$ (and similarly for $\bar{\nu}_e$).

The Glashow resonance, $\bar{\nu}_e W^+ \to X$, is important near $E_{\bar{\nu}_e} \approx 6.3$ PeV. $W$ channels yielding quarks are purely hadronic ($q_{G,q} \approx 0.9$). The $e\tau$ channels result in a neutrino carrying away most of the energy ($\langle y \rangle \approx 0.25$ [37]).

 Tau neutrino CC events ($\nu_\tau N \to \tau X$) typically have properties intermediate between CC $\nu_e$ and NC events. One difference is that a tau at PeV energies will travel $\sim 50$ m before decaying [39], with $\sim 80\%$ of decays [33] involving channels that result in a shower, although with an escaping $\nu_\tau$ carrying away energy. Decays to electrons result in an electromagnetic cascade with an outgoing $\nu_e$. Other decays involve multiple mesons, which result in a hadronic shower. Assuming all such decays to give hadronic-like cascades, including the initial cascade and assuming the two bangs to be indistinguishable for now gives $E_{\text{em}, \tau} = q_\tau E_\nu$, with $q_\tau \approx 0.9$.

The spectrum of events for each channel can be given in terms of the electromagnetic-equivalent energy as $[40, 41]

$$\frac{dN_{\text{sh}}}{dE_{\text{em}}} = 2\pi N_A \rho T V_{\text{eff}} \sigma(E_\nu) \varphi_\nu(E_\nu)/q,$$

(4)

where $N_A \rho$ is the molar density of ice. Using $2\pi$ sr, due to the

FIG. 2: Neutrino event spectra in IceCube using the shower energy, $E_{\text{em}}$, from the fluxes in the top and bottom panels of Fig. 1. Shown are: $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, and $\bar{\nu}_\mu$ charged current; all flavor ($\nu_X$, $\bar{\nu}_X$) neutral current; and $\nu_e e$ channels yielding $e$ and hadrons (included in $\bar{\nu}_e$ line) and $\tau$. Normalizations are based on two total $>\text{PeV}$ events.
attenuation of upgoing PeV neutrinos, and $V_{\text{eff}} T \approx 1 \text{ km}^3 \text{ yr}$ roughly matches the PeV IceCube exposure \cite{5}.

We integrate the total $\nu N$, $\bar{\nu} N$, and $\bar{\nu}_e e$ (with the electron density lower by $10/18$) shower yields above 1 PeV, and equate to two events (assuming that all showers above this limit would be counted). For the $\pi^\mp\mu^\pm$ flavor ratio model, we thus obtain the normalization for $dN_{\nu}/dE_{\nu}$ using Eq. (1) as $f_{0,\pi} \approx 4.9 \times 10^{-49} \text{ GeV}^{-1} \text{ cm}^{-3} \text{ s}^{-1}$, giving the total flux curve in Fig. 1. Our estimates using the $d\sigma/dy$ distributions in \cite{37} agree at the $\sim 10\%$ level. The lower panel of Fig. 2 shows the resulting shower spectrum in the detector.

Examining the importance of the Glashow resonance (see also \cite{42,43}), we note that $\bar{\nu}_e e$ scattering results in the peaks at $\sim 1.5 \text{ PeV}$ and $\sim 6 \text{ PeV}$, although the exact $d\sigma/dy$ significantly broadens the former. Since the $W$ width to hadrons is a factor of $\sim 3$ larger than to the sum of $e/\tau$, 6 PeV showers are the most likely and account for $\lesssim 1$ of the predicted events.

In our $\bar{\nu}$-less scenario where only $\pi^\pm$ are produced and muons cool to low energy prior to decaying, resonant $\bar{\nu}_e e$ events do not occur. Using the flavor ratios from the $\pi^+$ decay alone and starting again from Eq. (1) results in the shower signals in the upper panel of Fig. 2. To obtain two $>1 \text{ PeV}$ events requires $f_{0,\pi} = 1.4 \times 10^{-49} \text{ GeV}^{-1} \text{ cm}^{-3} \text{ s}^{-1}$.

Muon neutrino CC scatterings ($\nu_\mu N \rightarrow \mu X$) also produce a hadronic shower; however, a defining characteristic of such events is the resulting muon. Using the normalized neutrino spectra, and accounting for the $\sim 20\%$ of tau decays that result in a muon, we find the expected number of $> \text{PeV}$ muons with contained vertices to be $\sim 1$ in both cases, in accord with a lack of IceCube muon events in this range thus far.

The cosmic-ray spectrum.— A long-standing hope is to determine the UHECR sources and ascertain the acceleration mechanism. By making a few simplifying assumptions, we relate our neutrino spectra to a proton flux with a normalization that is fixed by the IceCube data.

We assume for the $\pi^\pm\mu^\pm$ flavor ratio model that one neutron with $E_n \sim 20 E_p$ is produced corresponding to each $\pi^\pm$ pair. Since six total neutrinos result from the $\pi^\pm\mu^\pm$ decays,

$$E_p \frac{dN}{dE_{\nu}} = \frac{1}{6} E_p \frac{dN}{dE_{\bar{\nu}}},$$

with neutron decay giving a source proton spectrum in the form of Eq. (1) with $\alpha = -1, \beta = -3$, and $E_b \approx 10^{8.3}$ due to neutron interactions in the source \cite{32} as assumed above. Integrating over $10^{15} < E_p < 10^{21} \text{ eV}$, we find an emissivity $E_{p,\pi} \sim 3.8^{+5.0}_{-2.5} \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$, with uncertainties corresponding to the 68% Poisson confidence ranges \cite{44} for two detected IceCube events. Introducing a cutoff below $10^{21} \text{ eV}$ scarcely affects these energetics.

The proton flux associated with the $\pi^+$ scenario is taken to have the same spectral shape. However, (i) we must account for $f_{0,\pi} \approx 3 f_{0,\pi\mu}$; (ii) $f_{0,\pi}$ normalizes a flux from a single neutrino species, rather than the sum of six, so that the proton flux must be larger by an additional factor of six, thus giving $E_{p,\pi} \sim 6.7^{+8.8}_{-4.3} \times 10^{45} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$.

![FIG. 3: The ultrahigh-energy cosmic-ray spectrum. Shown are the proton fluxes associated with our $\pi^\pm\mu^\pm$ (dashed) and $\pi^+$ (solid) neutrino flavor models, with normalizations obtained from the IceCube neutrino observations, with 68% confidence bands based on two events. These are compared to HiRes-II \cite{10}, Auger \cite{12}, and Telescope Array \cite{13} data.](image)

To find the expected proton fluxes at Earth from these spectra, three types of energy loss must be accounted for in propagation. At energies where photopion production on the CMB occurs ($\gtrsim 10^{19.5} \text{ eV}$), $p \gamma \rightarrow N \pi$ is the dominant loss channel \cite{35}. For $E_p \gtrsim 10^{18} \text{ eV}$, and below the CMB photopion threshold, resonant pair production on background photons, $p \gamma \rightarrow p e^+ e^-$, dominates \cite{46}. This process has a large cross section, although each interaction removes only a small amount of energy. Finally, there is an energy-independent adiabatic loss term.

These can be combined via characteristic loss times \cite{47} as $\tau^{-1}_a(E_p, z) = \tau^{-1}_p(E_p, z) + \tau^{-1}_{\text{pair}}(E_p, z) + \tau^{-1}_a(z)$, giving an energy loss rate of $d\ln E_p/dt = \tau^{-1}_a(E_p, z)$. We can thus relate the injection energy at redshift $z$, $E_p' = E_p(E_p, z)$, to the detected energy, $E_p$, with

$$\frac{1}{E_p} \frac{dE_p}{dz} = \frac{1}{\tau^{-1}_a(E_p, z)}.$$

The constraints imposed by this relation can be seen in Fig. 3 of Ref. \cite{48}. Using the same $\mathcal{W}(z)$ as above, we calculate the spectrum of the arriving proton flux as

$$\varphi_p(E_p) = \frac{c}{4\pi} \int_{0}^{z_{\text{max}}} dN_{\nu} \frac{\partial E_{\nu}'}{\partial E_p} \mathcal{W}(z) dE_{\nu}',$$

with $\partial E_{\nu}'/\partial E_p$ calculated numerically from Eq. (6).

In Fig. 3, we present the expected cosmic-ray proton spectra that result from normalizing our neutrino spectra to IceCube

\cite{37}. The upper panel of Fig. 2 shows the resulting shower spectrum in the detector.
via Eqs. (6) & (7). We note that residing near the upper edges of the bands would cause tension with a lack of observed PeV muon events. We have also checked, using CRPropa [49], that the cosmonic gamma-ray fluxes are safely below the Fermi isotropic background [50] and associated constraints [51–55].

**Discussion and conclusions.**— If cosmic rays in the $10^{18}$ eV range are truly extragalactic protons, the steepness of the UHECR spectrum implies that their cosmic energy density is much larger than at the highest measured energies. If their escapes from acceleration regions were facilitated by photo-production of neutrons, then there must also be a substantial flux of neutrinos from pion decays. The simplified model that we have used captures the general flavor of the neutrino flux needed to explain the IceCube PeV events as a basis for comparison with cosmic-ray protons.

In Fig. 3 we see that the cosmic-ray spectrum resulting from our neutrino flux with $\pm^2$ flavor ratios is quite close to measurements in the $10^{18}$ eV range. At $\gtrsim 10^{19}$ eV, the origin of the received flux is unclear, with a heavy-nuclear composition inferred by Auger [25], in contrast to HiRes [24], and the possible influence of Cen A as a local source (see [56]). If we take the Auger results at face value and assume that nuclei make up the difference, similar to the model of [57], a transition in composition at $\sim 10^{18.5}$ eV results, although we have not addressed this or the associated neutrino fluxes in detail.

The restrictions on this scenario include a need for acceleration in the presence of a fairly soft photon background to result in near-threshold photoproduction. Also, a magnetic field of $\sim 1–10$ kG (depending on the $\Gamma$ factor of the emission) is used to cool muons, although such fields may occur near jet launching regions [58] or in the accretion disk, as in AGN core models [59, 60]. Removing the no-$\nu$ requirement would reduce the proton flux by $\sim 3$; even so, it is not obvious that the complete set of conditions can be fulfilled.

We also see in Fig. 3 that the cosmic-ray proton flux associated with a neutrino flux arising from $\pm^2$ and $\mu^\pm$ decays is significantly lower than the data (and the $\nu/\bar{\nu}$ ratio could even be larger [61]). This implies that, if the requisite neutrinos are made through this photopion process, the resulting protons are not sufficient to explain the cosmic-ray measurements. This necessitates a dominant class of accelerator that allows for proton escape without significant losses.

IceCube may well be then informing us of the workings of a class of accelerators distinct from those providing cosmic rays. Dividing our inferred neutrino emissivity into sources yields an average of $\sim 4 \times 10^{43}$ erg s$^{-1}$ (100 Gpc$^{-3}$/n) for a space density $n$. These are values similar to those of AGN. The neutrino flux is accompanied by roughly two to six times this energy in gamma rays, which will quickly cascade in or near the source, and should be discussed in terms of concrete models (e.g., [62–64]). Our use of flat evolution is similar to that of intermediate-luminosity quasars (e.g., [65]). Stronger source evolution, such as from bright quasars or the cosmic star formation rate [66], would result in relatively more neutrino flux at lower energies. This reduces the normalization and steepens the spectrum of the cosmic-ray fluxes.

Altering the cutoffs or slopes used would not greatly change these basic points. Moreover, if the events turn out to be an unlikely fluctuation of background, the lower inferred neutrino flux would strengthen the conclusion that photopion interactions are not involved in freeing cosmic-ray protons from their sources. If not, improved data may better inform us of an aspect of the extreme universe that is not evident from studies of cosmic rays alone.

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