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Superheavy particle origin of IceCube PeV neutrino events

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ABSTRACT

We interpret the PeV shower events observed by the IceCube Collaboration as an *s*-channel enhancement of neutrino–quark scattering by a leptoquark that couples to the τ-flavor and light quarks. With a leptoquark mass around 0.6 TeV and a steep $1/E^{2.3}$ neutrino flux, charged-current scattering gives cascade events at ~ 1 PeV and neutral-current scattering gives cascade events at ~ 0.5 PeV. This mechanism is also consistent with the paucity of muon-track events above 100 TeV.

The IceCube (IC) experiment has reported intriguing results from a search for high-energy neutrino events with a contained vertex [1,2]. By requiring anti-coincidence with the detector edges, the background from charged-muon initiated events can be filtered out. This allows the observation of neutrinos from 4π directions in a fiducial volume of 420 Megatons. The search is sensitive to all neutrino types at energies above 50 TeV. The charged current (CC) interactions of muon-type neutrinos give a track associated with the muon. The CC of electron-type neutrinos, the CC of τ-type neutrinos with hadronic decays of the τ, and the neutral current (NC) neutrino events give showers in the detector.

In 662 days of data, the IceCube Collaboration found two spectacular shower events with electromagnetic-equivalent energy deposits in the detector of about 1.05 PeV and 1.15 PeV [1]. Both events are down-going. A follow-up analysis [2] found 26 more events with energies between 20 TeV and 300 TeV (21 showers without tracks and 7 events with tracks indicating visible muons). This rate is about twice that expected from neutrinos of charm origin from atmospheric neutrinos [3] and the energy spectrum merges well with the atmospheric neutrino data at lower energies. The overall signal is inconsistent at 4.3 σ with standard atmospheric neutrino backgrounds. Moreover, the data suggest a potential upper cutoff at ~ 2 PeV. These observations motivate consideration of a new neutrino physics component at ultra-high energies (UHE).

The following characteristics of the IC data focus our model considerations:

(i) The two PeV events are showers, which indicates electron–neutrino CC scattering, ν_τ CC production of τ-leptons that decay to hadrons, or NC events;
(ii) The two PeV events have about the same energy, within their energy uncertainties;
(iii) The two PeV events are downward;
(iv) No events are observed in a gap between 0.3 PeV and 1 PeV; we subsequently refer to this as the energy gap;
(v) Between 0.15 PeV and 0.3 PeV, there are 2 upward showers, 2 downward showers and one upward muon-track event.

The absence of events above 2 PeV could be the consequence of the decline in the neutrino flux from the cosmic acceleration mechanism of cosmic ray protons and iron [4]. It is possible that above-PeV events will be observed in future data [5]. More exciting, from a particle physics standpoint, is that there is indeed an approximate effective energy cut-off somewhat above 1 PeV. It is the consequences of this, and an associated neutrino flavor problem, that we pursue. The flavor problem is a paucity of muon-track events in comparison with shower events in the IceCube events at the highest energies. The neutrino flux ratios at the source are converted by neutrino oscillations to universal 1:1:1 composition [6]. But, no muon-track events are seen above 0.3 PeV. The track event in the 0.15 to 0.3 PeV range could be from a τ lepton that decays to a muon. As a cautionary remark, we note that the IceCube result is not inconsistent with a 1:1:1 flavor composition. The IC event selection in the current analysis is based on deposited energy, which is more favorable to cascade events than contained track events. Also, muon–neutrino events may be underrepresented because the produced muon carries away energy. Since the IC acceptance corrected exposure at ~ 1 PeV is higher for ν_e than that for ν_μ or ν_τ, it is possible that the PeV events are CC interactions of electron–neutrinos [7] and do not require new physics. Here we pursue the interesting possibility that the PeV events are the first signals of new physics, namely a third generation leptoquark.

Aside from an unexpected modification to the primary neutrino flux composition, there are several new physics possibilities that

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could explain such an energy cut-off and the observed flavor asymmetry, as we now discuss.

One such possibility is that the neutrino cross-section has a resonant enhancement at ~ 1 PeV. We note that the Glashow resonance [8] at 6.3 PeV electron–antineutrino energy is a candidate, where the hadronic decays of the produced W-boson give shower events. Even so, the Glashow resonance energy is on the high side compared to the 1 PeV of the observed shower energies. The Glashow resonance does not readily explain the energy gap noted above. Also, this interpretation requires an enhanced anti-electron–neutrino flux, possibility from decays of cosmic neutrons produced in the inelastic scatter of protons of iron on the CMB [4]. The Glashow resonance option has been considered elsewhere [9,10] and it is not the subject of our current interest.

Another resonance enhancement candidate is neutrino scattering on light quarks through via a leptoquark of mass ~ 0.5 TeV. This is the specific case that we shall pursue in some depth. In particular, we shall consider a leptoquark that couples to τ-lepton and down-quark flavors.

Alternatively, the source could be a spectral line of definite neutrino energy that could arise from the annihilations of Majorana dark matter particles (of PeV dark matter mass) to a two-neutrino final state (or Dirac dark matter annihilations to a neutrino and antineutrino) or a two-body decay of a dark matter particle to a final state with a neutrino. The dark matter decay option has been advocated in Ref. [11].

Still another scenario, that is relevant to the neutrino flavor problem, is that the most massive neutrinos may decay to the lighter neutrinos over cosmological distances [12]. This could explain the low flux of ultra UHE astrophysical muon–neutrinos. Then only the lightest mass eigenstate would survive and all events would be electron–neutrino initiated showers. The energy gap is not explained.

All of the above are conceivable new physics interpretations of the anomalous IceCube events. The dark matter scenarios allow a wide range of model freedom. The leptoquark scenario is more specifically defined and we consider its attributes as an exemplary case, but many of our arguments may apply more generally. We promote the case of a leptoquark with τ-lepton and d-quark flavor.

A crux of our argument is that the Earth is almost opaque to electron–neutrinos and muon–neutrinos. τ-neutrinos are regenerated via τ-decays, so upward neutrinos that pass through the Earth should be of τ-flavor [13]. Since τ decays to electrons or hadrons 82% of the time, the ν_τ events are dominantly characterized as showers and only 18% will give a muon-track.

Let us now compare this general expectation with the IceCube event sample. For the ensemble of events above 0.02 PeV, there are fewer events upward than downward, as would be anticipated from the absorption of electron–neutrinos and muon–neutrinos by the Earth. Moreover, all but one of the muon-track events are upward or horizontal, as expected. However, above 0.15 PeV, there is only one muon-track event (and it is upward) compared to 6 shower events (2 upward and 4 downward). Although the statistics are low, the IceCube data suggest that mainly ν_τ events are being seen above 0.15 PeV. This will be the premise of our speculation as to their origin.

For the leptoquark (LQ) model, we assume a weak-isospin LQ doublet that couples to third generation leptons (ν_τ, τ) and first and second generation quarks (u, d). Thus, the main processes of interest, because their cross-sections are resonance enhanced, are

$$\nu_\tau + q \to \text{LQ} \to \tau + q,$$

$$\nu_\tau + q \to \text{LQ} \to \nu_\tau + q$$

as illustrated in Fig. 1.

Fig. 1. Resonance processes via a leptoquark LQ in the UHE neutrino nucleon scattering. Left: the neutral current events. Right: the charged current events. The case of interest is a τ-neutrino and a τ-lepton.

We attribute the IC shower events at PeV energy to the CC reaction for which the showers are associated with the τ decays to hadrons and the hadron jet from the produced quark. The energy of the secondary neutrino from the τ decay is undetected, so the observed EM shower energy is a little less than the mass of the leptoquark. To a zero-level approximation, the shower energy deposition determines the leptoquark mass.

When the produced τ decays to a muon, giving a track, the energy of the event is lower than for the hadronic τ-decays. Likewise, in the case that the τ decays to an electron the shower energy is lower than for the τ to hadrons decay.

In the NC reaction above, the energy of the event will be about half of the CC reaction. Thus, the shower energy of the NC is an approximate measure of $\frac{1}{2}$ the leptoquark mass. The NC cross-section is about the same as the CC cross-section. The gap between the PeV events and the onset of the lower energy events should be about $\frac{1}{2}$ of the leptoquark mass, which seems consistent with what is observed.

The leptoquark can be a scalar $(J = 0)$ or a vector $(J = 1)$. A general list of leptoquark models and the experimental limits is given in the review by S. Rolli and M. Tanabashi [14] in the Particle Data Book. We show the simple scenario of a leptoquark scalar S of charge $-\frac{1}{3}$, which couples to the first generation quarks and the third generation lepton in the following form,

$$\mathcal{L}_{\text{LQ}} = f_L S^\dagger (u, d)_L \varepsilon \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L + f_R S^\dagger u_R \tau_R + \text{h.c.} \tag{1}$$

The Levi-Civita symbol ε antisymmetrizes the two $SU(2)$ doublets to match the singlet S. The couplings f_L, f_R are the leptoquark couplings to the left and right chiral quarks. In the narrow width approximation, the leptoquark resonance contribution to the neutrino cross-section has the form [15–17]

$$M_S^2\, d\sigma(\nu_\tau N \xrightarrow{\text{LQ}} \nu_\tau X) = \frac{\pi}{2} f_L^2 \text{Br}(S \to \nu_\tau d) x d_N\big(x, \mu^2\big), \tag{2}$$

$$M_S^2\, d\sigma(\nu_\tau N \xrightarrow{\text{LQ}} \tau X) = \frac{\pi}{2} f_L^2 \text{Br}(S \to \tau_{L,R} u) x d_N\big(x, \mu^2\big), \tag{3}$$

where the parton fractional momentum is $x = M_S^2/s$ with $s = 2m_N E_\nu$. The down-quark parton distribution function $d_N(x, \mu^2)$ in the target nucleon N is evaluated at the scale $\mu^2 = M_S^2$ in the leading order calculation. The inelasticity $y = (E_\nu - E')/E_\nu$ distribution is flat in the scalar leptoquark scenario; here E' denotes the outgoing energy of ν_τ or τ. The threshold energy of LQ production is $E_\nu = M_S^2/2m_N$.

The branching fractions are

$$\begin{aligned}
&\text{Br}(S \to \nu_\tau d) = f_L^2/\big(2f_L^2 + f_R^2\big), \\
&\text{Br}(S \to \tau_L u) = f_L^2/\big(2f_L^2 + f_R^2\big), \\
&\text{Br}(S \to \tau_R u) = f_R^2/\big(2f_L^2 + f_R^2\big).
\end{aligned} \tag{4}$$

They multiply the leptoquark production cross-section (see Fig. 2),

$$\sigma_{\text{LQ}}(\nu N) = \frac{\pi f_L^2}{2M_S^2} x d_N\big(x, \mu^2\big), \tag{5}$$

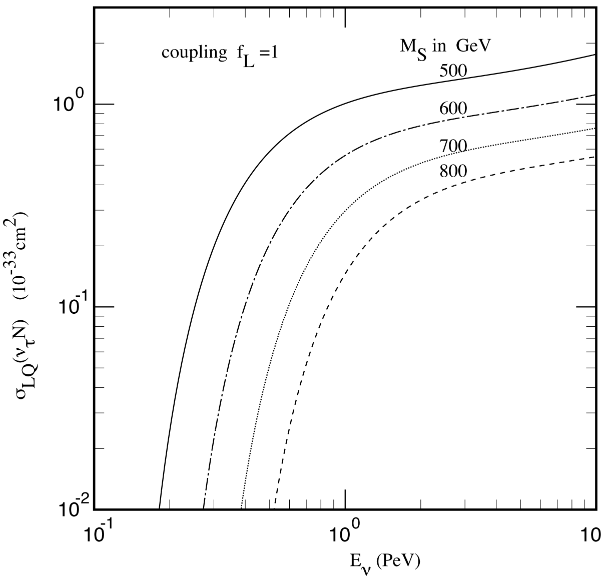

Fig. 2. LQ production cross-section in $\nu_\tau N$ scattering.

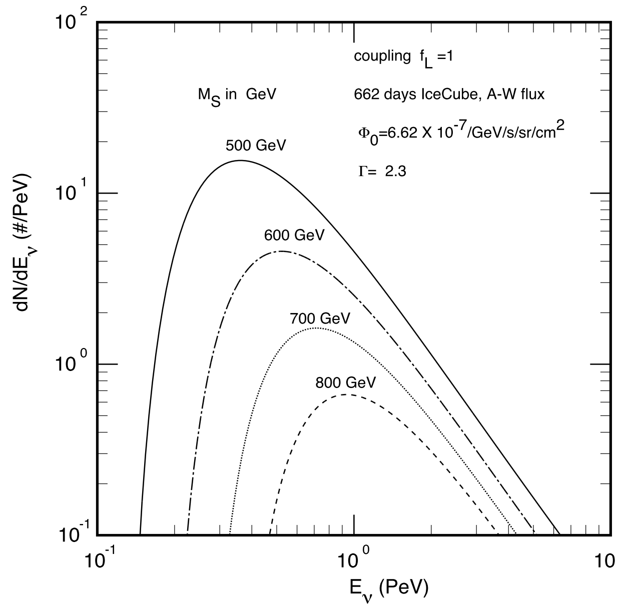

Fig. 3. Event rate distribution $d\mathcal{N}/dE_\nu$, from the LQ cross-section convoluted with the A–W flux $\Phi_\nu^{\text{A–W}}$.

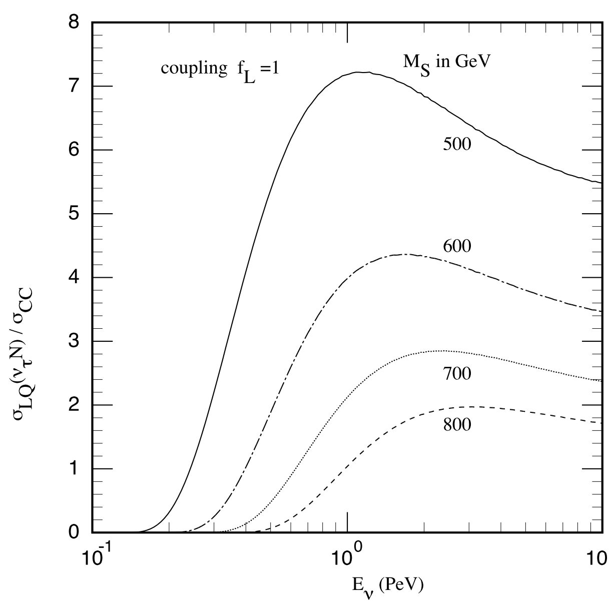

Fig. 4. Cross-section ratio of the charged current process of $\nu_\tau N$ scattering via a leptoquark resonance to the corresponding Standard Model CC process.

to produce the corresponding rates for each channel. For a vector leptoquark the cross-section is a factor of 2 larger than that of the scalar leptoquark.

The LQ width is given by

$$\Gamma_{\text{LQ}} = \frac{1}{16\pi} M_S \left(2 f_L^2 + f_R^2\right), \tag{6}$$

which is a small fraction of its mass even for a unit coupling f, so the narrow width approximation is justifiable. The partial widths of $S \to \nu_\tau + d$ and $S \to \tau_L + u$ are equal. However, f_R gives rise to the channel $S \to \tau_R + u$.

Fig. 1 shows the cross-section of scalar $\tau - q$ leptoquark production in neutrino scattering on an isospin averaged nucleon target N, taking $f_L = 1$. The CTEQ6.10 parton distributions at NLO are used in this calculation [18].

As a benchmark of the neutrino flux, we adopt for illustration the A–W [19] form with a steep power index $\Gamma = 2.3$ based on the optimal fitting with the minimal deviation from IceCube UHE neutrino data.

$$\Phi_\nu^{\text{A–W}} = \Phi_0 \left(\frac{E_\nu}{1\ \text{GeV}}\right)^{-\Gamma},$$
$$\Phi_0 = 6.62 \times 10^{-7}\ /\text{GeV/cm}^2/\text{s/sr} \tag{7}$$

for each neutrino-type. We estimate the expected event number at IceCube by

$$\mathcal{N} = nt\Omega \int dE_\nu \sigma_{\text{LQ}} \cdot [\text{Br}] \cdot \Phi_\nu^{\text{A–W}}(E_\nu),$$

where we take the time of exposure $t = 662$ days, the effective target nucleons number in IceCube $n = 6 \times 10^{38}$, and the solid angle of the full 4π coverage ($\Omega = 4\pi$). The event distribution $d\mathcal{N}/dE_\nu$ is given in Fig. 3. Below we tabulate the LQ event rates in three E_ν bins, for two LQ masses M_S.

M_S (GeV)	< 1 PeV	1–2 PeV	> 2 PeV
500	8.2	2.3	1.8
600	2.6	1.4	1.1

(8)

At a neutrino energy of ~ 1 PeV a few events are predicted for LQ mass ~ 0.5 TeV, in rough accord with the two shower events observed by IceCube.

Because the cosmic neutrino flux is unknown, we also show the ratio of the CC τ-cross-section with the LQ resonance to the Standard Model CC τ-cross-section in Fig. 4. This figure demonstrates the enhancement of τ events by the LQ scenario without assumptions about the flux.

The LQ model illustrations above are for the coupling choice $f_L = 1$; the LQ cross-section scales with the value of f_L^2. According to Fig. 3, with $f_L = 1$, an LQ mass of 600 GeV would lead to 1 to 2 cascade events with reconstructed neutrino energies of order 1 PeV; the number of LQ events above 1 PeV falls rapidly with energy due to the convolution with the assumed $E^{-2.3}$ flux.

It is appropriate to ask whether the LHC can probe the LQ coupling and LQ mass that could account for the IceCube PeV cascade events. The LQ production cross-sections at LHC are calculated in Refs. [20,21]. Based on its pair production, the CMS/LHC search at

7 TeV [22] for a scalar τ-type LQ puts a constraint $M_S \gtrsim 525$ GeV. Single LQ production at the LHC can occur through the subprocesses

$$gu \to \bar{\tau} S, \qquad gd \to \bar{\nu}_\tau S.$$

The down-type LQ, S, subsequently decays into τu or $\nu_\tau d$. The resulting final states are $\bar{\tau}\tau u$, or $\bar{\tau}\nu_\tau d$, or $\bar{\nu}_\tau \nu_\tau d$, etc. Rather distinctively, these subprocesses give events of a $\bar{\tau}\tau$ pair plus a jet or a monojet and missing energy with or without a τ. A dedicated search at LHC14 for the single LQ production signals is of great interest to confirm or deny the proposed LQ explanation of the PeV IceCube cascade events.

In summary, we have interpreted the UHE neutrino events observed in the IceCube experiment in the framework of a resonance enhancement by a leptoquark that couples to the τ-lepton and to the down-type quark. The characteristic features of the events that are reproduced by the model are (i) a cross-section enhancement above atmospheric neutrino expectations, (ii) dominance of shower events over track events above 100 TeV, interpreted as dominance of ν_τ processes, (iii) an energy gap between 0.3 PeV and 1 PeV where no events were recorded, attributed to NC showers at lower energies and ν_τ CC showers at PeV energies. A leptoquark mass in the vicinity of 0.6 TeV is inferred. The next release of data, accumulated in IceCube since 2012, should further test the leptoquark explanation of the PeV events.

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