Double-Cascade Events from New Physics in Icecube

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A variety of new physics models allows for neutrinos to up-scatter into heavier states. If the incident neutrino is energetic enough, the heavy neutrino may travel some distance before decaying. In this work, we consider the atmospheric neutrino flux as a source of such events. At IceCube, this would lead to a "double-bang" (DB) event topology, similar to what is predicted to occur for tau neutrinos at ultrahigh energies. The DB event topology has an extremely low background rate from coincident atmospheric cascades, making this a distinctive signature of new physics. Our results indicate that IceCube should already be able to derive new competitive constraints on models with GeV-scale sterile neutrinos using existing data.

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Introduction.—Although neutrino physics has rapidly moved into the precision era, a number of fundamental questions remain unanswered. Perhaps the most important among these is the mechanism responsible for neutrino masses. In the most naïve extension of the standard model (SM), neutrino masses and mixing can be successfully generated by adding at least two right-handed neutrinos (N_R), with small Yukawa couplings Y_ν to the left-handed lepton doublets L_L and the Higgs boson ϕ. In this framework, Dirac neutrino masses are generated after electroweak (EW) symmetry breaking, as for the rest of the SM fermions. As singlets of the SM the right-handed neutrinos may also have a Majorana mass term, since it is allowed by gauge symmetry. In this case, the neutrino mass Lagrangian reads

$$\mathcal{L}^{\nu}_{\rm mass} \supset Y_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} M_R \overline{N^c_R} N_R + \text{H.c.},$$

where $\tilde{\phi} \equiv i\sigma_2\phi^*$, $N^c_R \equiv C\bar{N}^T_R$ is the charge conjugate of N_R and we have omitted flavor and mass indices. This is the well-known type I seesaw Lagrangian [1–3]. Traditionally, the type I seesaw assumed a very high Majorana mass scale M_R. For $M_R \gg v$ the light neutrino masses are proportional to $m_\nu \propto Y^\dagger_\nu M^{-1}_R Y_\nu v^2$, where v is the Higgs vacuum expectation value, while the right-handed neutrino masses would be approximately $m_N \simeq M_R + \mathcal{O}(m_\nu)$. In this framework the SM neutrino masses are naturally suppressed by the new physics scale and can be much smaller than the charged fermion masses without the need for tiny Yukawa couplings. However, such heavy neutrinos are too heavy to be produced in colliders, and the inclusion of very massive Majorana neutrinos would considerably worsen the hierarchy problem for the Higgs mass [4].

Models with lower values of m_N can lead to a more interesting phenomenology, testable at low-energy experiments, and possibly even solve some of the other problems of the SM. For example, keV neutrinos offer a very good dark matter candidate [5], while Majorana neutrinos with masses $m_N \sim \mathcal{O}(1\text{–}100)$ GeV can successfully generate the matter-antimatter asymmetry of the Universe [6–9]. While right-handed neutrinos with masses above the EW scale are subject to very tight bounds from EW observables and charged lepton flavor violating experiments [10,11], these constraints fade away for lower masses. Indeed, for right-handed neutrinos in the (keV–GeV) range, the strongest constraints come from precision measurements of meson decays [12,13], muon decays, and other EW transitions; see, e.g., Ref. [14] for a review.

In this Letter we point out that IceCube and DeepCore can be used to test models with GeV neutrinos directly. To this end, we consider events with a "double-bang" (DB) topology. A schematic illustration of the event topology can be seen in Fig. 1. In the first interaction, an atmospheric neutrino would up-scatter off a nucleus into a heavier state. This generally leaves a visible shower (or cascade) in the

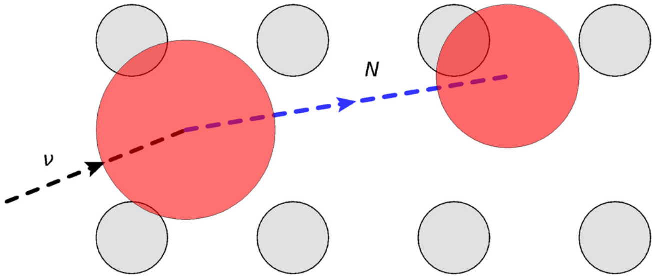

FIG. 1. Schematic illustration of a DB event in IceCube. An incoming active neutrino ν up-scatters into a heavy neutrino N, which then propagates and decays into SM particles. The small circles represent the DOMs while the large circles indicate the positions where energy was deposited.

detector coming from the hadronic part of the vertex. After traveling a macroscopic distance inside the instrumented ice, the heavy neutrino would decay back to SM particles. The decay will produce a second cascade if the final state involves charged particles or photons which can be detected by IceCube's digital optical modules (DOMs). Thus, the final DB topology would be two cascades (or "bangs") visibly separated, but with no visible track connecting them. A similar topology is predicted to occur in the SM from the production of a τ lepton in ν_τ charged-current (CC) scattering at PeV energies [15], and has already been searched for by the collaboration [16]. In our case, however, the heavy neutrinos will be produced from the atmospheric neutrino flux and thus produce much lower energy DBs.

To illustrate some of the new physics scenarios giving rise to low-energy DB events we consider two basic scenarios depending on the main production or decay mode of the heavy state: (i) through mixing with the light neutrinos, and (ii) through a transition magnetic moment involving the light neutrinos.

Heavy neutrino production via mixing.—The measurement of the invisible decay width of the Z implies that, if additional neutrinos below the EW scale are present, they cannot couple directly to the Z (i.e., they should be "sterile"). For simplicity, let us focus on a scenario where there is sizable mixing with only one heavy neutrino while the others are effectively decoupled. We may write the flavor states ν_α as a superposition of the mass eigenstates as

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\nu_{iL} + U_{\alpha 4}N^c_{4R}, \tag{1}$$

where U is the 4×4 unitary mixing matrix that changes between the mass and the flavor bases. For a sterile neutrino with a mass $m_N \sim \mathcal{O}(0.1\text{–}10)$ GeV, its mixing with $\nu_{e,\mu}$ is severely constrained as $|U_{\alpha 4}|^2 \lesssim 10^{-5}\text{–}10^{-8}$ $(\alpha = e,\ \mu)$ [14]. Conversely, the mixing with ν_τ is much more difficult to probe, given the technical challenges of producing and detecting tau neutrinos. For $m_N \sim \mathcal{O}(0.1-10)$ GeV the most stringent bounds are derived from the DELPHI [17] and CHARM [18] experiments. However, a mixing as large as $|U_{\tau 4}|^2 \sim 10^{-2}$ is still allowed for masses around $m_N \sim \mathcal{O}(400)$ MeV [14].

At IceCube, the atmospheric neutrino flux can be used to constrain the values of $U_{\alpha 4}$ directly. Atmospheric neutrinos are produced as a result of the cosmic rays impacting the atmosphere. At the production point, this flux is primarily composed of ν_μ and ν_e. However, for neutrinos crossing Earth a large fraction of the initial ν_μ flux will have oscillated into ν_τ by the time the neutrinos reach the detector. Therefore, here we focus on probing the mixing with ν_τ since this one is much harder to constrain by other means.

To this end, we propose to conduct a search for low-energy DB events. In each event the first cascade is produced from a neutral-current (NC) interaction with a nucleon n, as $\nu n \to N n$. This process is mediated by a Z boson and takes place via mixing between the light and heavy states. Neglecting corrections due to the mass of the heavy neutrino, the up-scattering cross section goes as $\sigma_{\nu_\tau N} \simeq \sigma_\nu^{\rm NC} \times |U_{\tau 4}|^2$, where $\sigma_\nu^{\rm NC}$ is the NC neutrino-nucleon cross section in the SM. Unless the process is quasielastic, it will generally lead to a hadronic shower in the detector. Here we compute the neutrino-nucleon deep-inelastic scattering (DIS) cross section using the parton model, imposing a lower cut on the hadronic shower of 5 GeV so it is observable [19]. In fact, throughout our whole analysis we will assume perfect detection efficiencies above threshold. Although this may be simplistic, we find it adequate to demonstrate the potential of IceCube to search for new physics with low energy DB events. Once the heavy state has been produced, its decay is controlled by kinematics and the SM interactions inherited from the mixing with the active neutrinos. The partial decay widths of a heavy neutrino can be found in Refs. [14,20] and were recomputed here. The decay channels include two-body decays into a charged lepton (active neutrino) and a charged (neutral) meson, and three body decays into charged leptons and light neutrinos. The deposited energy in the second shower is also required to be above 5 GeV. It should be noted that if the N decays into three light neutrinos the second shower will be invisible: those events do not contribute to our signal. As an example, for $m_N = 1$ GeV and $|U_{\tau 4}|^2 = 10^{-3}$, the boosted decay length (for an energy of 10 GeV) is $L_{\rm lab} \sim 20$ m.

The number of DB events from ν_τ mixing with a heavy neutrino, for two cascades taking place within a distance L, is proportional to

$$\int dE_\nu dc_\theta \mathcal{B} \frac{d\phi_{\nu_\mu}}{dE_\nu dc_\theta} P_{\mu\tau}(c_\theta, E_\nu) \frac{d\sigma_{\nu_\tau N}}{dE_\nu} P_d(L) V(L, c_\theta), \tag{2}$$

where E_ν is the incident neutrino energy and $c_\theta \equiv \cos\theta$ is the cosine of its zenith angle. The atmospheric ν_μ flux [21] is given by ϕ_{ν_μ} while $P_{\mu\tau}$ is the oscillation probability in the $\nu_\mu \to \nu_\tau$ channel, which depends on the length of the baseline traveled (inferred from the zenith angle) and the energy. Here, $P_d(L) = e^{-L/L_{\rm lab}}/L_{\rm lab}$ is the probability for the heavy state to decay after traveling a distance L, while $\mathcal{B}$ is its branching ratio into visible final states (i.e., excluding the decay into three light neutrinos). Antineutrino events will give a similar contribution to the total number of events, replacing ϕ_{ν_μ}, $\sigma_{\nu_\tau N}$, and $P_{\mu\tau}$ in Eq. (2) by their analogous expressions for antineutrinos.

In Eq. (2) we have omitted a normalization constant which depends on the number of target nuclei and the data taking period, but we explicitly include an effective volume

$V(L, c_\theta)$. In this work, this was computed using Monte Carlo integration. First, for triggering purposes we require that at least three (four) DOMs detect the first shower simultaneously, if it takes place inside (outside) DeepCore [22]. Once the trigger goes off, all the information in the detector is recorded, and we thus assume that the second shower is always observed as long as it is close enough to a DOM. Eventually, the energy of a cascade determines the distance from which it can be detected by a DOM: the longer the distance, the more energetic the cascade should be so the light can reach the DOM without being absorbed by the ice first. Here we assume that a cascade is seen by a DOM if it takes place within a distance of 36 m, since this is roughly the maximum distance between an event and a DOM inside DeepCore [22]. This is conservative, since showers with energies much above 5 GeV will typically reach a DOM from longer distances. Finally, a minimum separation is required between the two showers so they can be resolved. This ultimately depends on the time resolution of the DOMs. Following Ref. [16], IceCube can distinguish pulses separated by $T \sim 66$ ns. Thus, we require a minimum distance between the two showers of $T/c = 20$ m.

The dominant source of background for DB events is given by two coincident cascades taking place within the same time window Δt. The rate can be estimated as [23] $N_{\rm bkg} \simeq C^2_{\rm DB} (\Delta t/T)^2$, where $C^2_{\rm DB} = N_{\rm casc}(N_{\rm casc} - 1)/2$ comes from the number of possible combination of pairs, and $N_{\rm casc}$ is the number of cascade events within a time period T. The number of cascades in the DeepCore volume, with a deposited energy between 5.6 and 100 GeV, is $N_{\rm casc} \simeq 2 \times 10^4\ \mathrm{yr}^{-1}$ [24]. These include CC events with electrons, taus, or low-energy muons in the final state (which do not leave long identificable tracks), as well as NC events. A particle traveling at the speed of light traverses 1 km in $\sim 10^{-5}$ s. Thus, for a conservative time interval $\Delta t = 10^{-3}$ s, we get $N_{\rm bkg} < 10^{-11}\ \mathrm{yr}^{-1}$.

In view of the negligible background rate, we proceed to determine the region in parameter space where at least one signal event would be expected in six years of data taking at IceCube. This is shown in Fig. 2 as a function of the mass and mixing of the heavy neutrino. The solid line shows the results using the full IceCube volume, while for the dashed line only DeepCore was considered. Our results indicate that IceCube could improve over present bounds between 1 and 2 orders of magnitude, and probe values of the mixing as small as $|U_{\tau 4}|^2 \sim 5 \times 10^{-5}$. According to these results, IceCube could test the proposed solution to the flavor anomalies in the B sector proposed in Ref. [25].

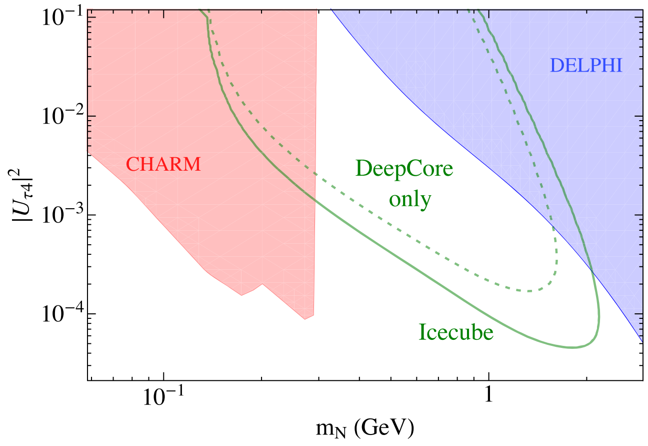

FIG. 2. Expected potential of IceCube to constrain the mixing between ν_τ and a heavy neutrino. In the region enclosed by the solid green contour, more than one DB event is expected during six years of data taking at IceCube. The dashed contour shows the most conservative result, where only the DeepCore volume is considered. The shaded regions are disfavored by CHARM [18] and DELPHI [17] at 90% and 95% C.L., respectively; see Ref. [14].

Heavy neutrino production via a transition magnetic moment.—Alternatively, the light neutrinos may interact with the heavy state N through a higher-dimensional operator. As an example, we consider a neutrino transition magnetic moment (NTMM) $\mu_{\rm tr}$:

$$\mathcal{L}_\nu \supset -\mu_{\rm tr} \bar{\nu}_{\alpha L} \sigma_{\rho\sigma} N_{4R} F^{\rho\sigma}, \tag{3}$$

where $F^{\rho\sigma}$ is the electromagnetic field strength tensor and $\sigma_{\rho\sigma} = (i/2)[\gamma_\rho, \gamma_\sigma]$. For simplicity, in this scenario we assume negligible mixing with the light neutrinos, so both the production and decay of the heavy neutrino are controlled by the magnetic moment operator. In the rest frame of N, its decay width reads $\Gamma(N \to \nu\gamma) = \mu^2_{\rm tr} M^3/(16\pi)$. For $m_N = 100$ MeV, $\mu_{\rm tr} = 10^{-8} \mu_B$ (where μ_B is the Bohr magneton), and a typical energy of 10 GeV this gives a decay length in the lab frame $L_{\rm lab} \sim 14$ m.

Neutrinos with a NTMM could scatter off both electrons and nuclei in the IceCube detector. However, for the range of energies and masses considered in this work, the largest effect comes from scattering on nuclei. In the DIS regime, the cross section for the scattering $\nu n \to N n$ via the operator in Eq. (3) reads [26]

$$\frac{d^2\sigma_{\nu n \to N n}}{dx dy} \simeq 16\pi\alpha\mu^2_{\rm tr} \left(\frac{1-y}{y}\right) \sum_i e^2_i f_i(x), \tag{4}$$

where α is the fine structure constant, $f_i(x)$ is the parton distribution function for the parton i, x is the parton momentum fraction, and e^2_i is its electric charge. Here, $y \equiv 1 - E_N/E_\nu = E_r/E_\nu$, where E_N is the energy of the outgoing heavy neutrino and E_r is the deposited energy. In Eq. (4) we have ignored the impact of the heavy neutrino mass in the cross section, which will be negligible in the region of interest. However, energy and momentum conservation requires

$$E_r^2 - W^2 - [m_N^2 - W^2 - 2xE_\nu m_n - x^2 m_n^2 + 2E_r(xm_n + E_\nu)]^2/4E_\nu^2 > 0, \tag{5}$$

where W^2 is the invariant mass squared of the outgoing hadronic system and m_n is the nucleon mass. Using Eqs. (4) and (5) we can estimate the number of DB events in IceCube using a similar expression to Eq. (2). A 5 GeV lower cut is also imposed on the deposited energy for each shower. Assuming that the decay only takes place via NTMM, the branching ratio to visible final states in this scenario is $\mathcal{B} = 1$.

Before presenting our results, let us discuss first the current constraints on NTMM. Previous measurements of the neutrino-electron elastic scattering cross section can be translated into a bound on NTMM. The corresponding cross section reads

$$\frac{d\sigma_{\nu e\to Ne}}{dE_r} = \mu_{\rm tr}^2 \alpha \left[\frac{1}{E_r} - \frac{m_N^2}{2E_\nu E_r m_e}\left(1 - \frac{E_r}{2E_\nu} + \frac{m_e}{2E_\nu}\right) - \frac{1}{E_\nu} + \frac{m_N^4(E_r - m_e)}{8E_\nu^2 E_r^2 m_e^2}\right], \tag{6}$$

where m_e is the electron mass. Moreover, for given E_ν and E_r, the maximum m_N allowed by kinematics is

$$m_{N,\max}^2 = 2[E_\nu\sqrt{E_r(E_r + 2m_e)} - E_r(E_\nu + m_e)]. \tag{7}$$

Several experiments can be used to derive constraints from their measurement of neutrino-electron scattering. DONUT derived a constraint on the ν_τ magnetic moment, $\mu_\tau < 3.9 \times 10^{-7}\mu_B$ at 90% C.L. [27]. For NOMAD [28], Primakoff conversion $\nu_\mu + X \to \nu_s + X(+\gamma)$ (where X is a nucleus) constrains NTMM [29]. Recently, the Borexino collaboration reported the limit $\mu_\nu < 2.8 \times 10^{-11}\mu_B$ at 90% C.L. [30], valid for all neutrino flavors. For CHARM-II we have derived an approximate limit on the magnetic moment of ν_μ requiring the NTMM cross section in Eq. (6) to be below the reported precision on the measurement of the neutrino-electron cross section (Bounds on NTMM from neutrino-nucleus scattering are less competitive. For example, using NuTeV data [31] we find an approximate bound $\mu_{\rm tr} \lesssim 10^{-4}\mu_B$.), assuming $\langle E_\nu\rangle \sim 24$ and $\langle E_r\rangle \sim 5$ GeV.

The ALEPH constraint on the branching ratio $\mathrm{BR}(Z \to \nu N \to \nu\nu\gamma) < 2.7 \times 10^{-5}$ [32] translates into the bound $|U_{\alpha 4}|^2(\mu_{\rm tr}/\mu_B)^2 < 1.9 \times 10^{-16}$ [33], $\alpha \equiv e,\ \mu,\ \tau$. Saturating the bound from direct searches on the mixing $|U_{\tau 4}|^2$ gives the strongest possible constraint from ALEPH data, which is competitive in the mass region $m_N \gtrsim 5$–10 GeV.

Additional bounds on $\mu_{\rm tr}$ can also be derived from cosmology. In the SM, neutrino decoupling takes places at temperatures $T \sim 2$ MeV. However, the additional interaction between photons and neutrinos induced by a magnetic moment may lead to a delayed neutrino decoupling. This imposes an upper bound on $\mu_{\rm tr}$ (see, e.g., Ref. [34] for analogous active limits).

Our results for the NTMM scenario are shown in Fig. 3. The shaded regions are disfavored by past experiments as outlined above. These, however, fade away for heavy neutrino masses above the maximum value allowed by kinematics in each case, given by Eq. (5). [To derive $m_{N,\max}$ for Borexino, DONUT, and CHARM-II, we have used the following typical values of $(\langle E_\nu\rangle, \langle E_r\rangle)$: (420, 230 keV), (100, 20 GeV), and (24, 5 GeV), respectively.] The solid contours, on the other hand, indicate the regions where more than one DB event would be expected at IceCube, for six years of data taking. The left panel shows the results for a NTMM between N and ν_τ. Our results indicate that IceCube has the potential to improve more than 2 orders of magnitude over current constraints for NTMM, for $m_N \sim 1$ MeV–1 GeV. The right panel, on the other hand, shows the results for a NTMM between N and ν_μ. In this case, the computation of the number of events is identical as for $\nu_\tau - N$ transitions, replacing the oscillation probability

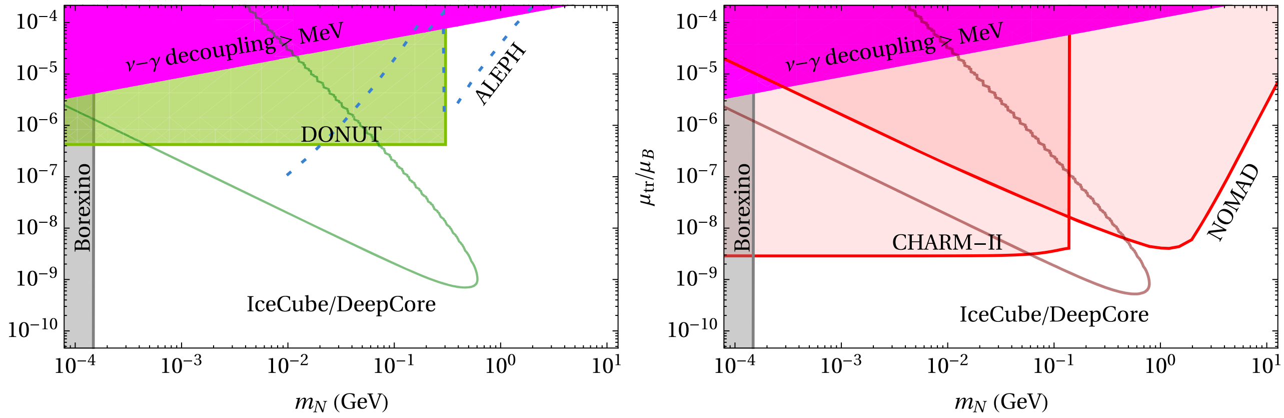

FIG. 3. Expected potential to constrain magnetic moments leading to the transitions $\nu_\tau - N$ (left panel) and $\nu_\mu - N$ (right panel) at IceCube. In the region enclosed by the solid contours, at least one DB event would be expected at IceCube, for a data taking period of six years. The shaded regions are disfavored by previous experiments; see text for details.

$P_{\mu\tau}$ by $P_{\mu\mu}$ in Eq. (2). Even though current constraints are stronger for ν_μ, we also find that IceCube could significantly improve over present bounds.

Conclusions.—In this Letter, we have studied the potential of the IceCube detector to look for new physics using low-energy DB events. The collaboration has already performed searches for events with this topology at ultrahigh energies, which are expected in the SM from the CC interactions of PeV tau neutrinos. In this work we have shown how very simple new physics scenarios with GeV-scale right-handed neutrinos would lead to a similar topology, with two low-energy cascades that could be spatially resolved in the detector. We find that IceCube may be able to improve by orders of magnitude the current constraints on the two scenarios considered here. A DB search may also be sensitive to nonminimal dark matter models, such as the one proposed in Ref. [35].

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