Search capability for $\eta \to \nu_{e,\tau}\bar{\nu}_{e,\tau}$ decays in cubic-kilometer neutrino detectors

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We investigate the discovery potential of cubic-kilometer neutrino observatories such as IceCube to set stringent limits on the forbidden decays $\eta \to \nu_e\bar{\nu}_e$ and $\eta \to \nu_\tau\bar{\nu}_\tau$. The signatures for these decays are cascade events resulting from the charged-current reactions of ν_e, ν_τ, $\bar{\nu}_e$, and $\bar{\nu}_\tau$ on nuclei in such detectors. Background cascade events are mainly due to ν_e's from atmospheric μ, K^+, and K_S^0 decays and to a lesser extent from atmospheric ν_μ neutral-current interactions with nuclei. A direct upper limit for the branching ratio $\eta \to \nu_{e,\tau}\bar{\nu}_{e,\tau}$ of 6.1×10^{-4} at 90% CL can be achieved.

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I. INTRODUCTION

The observation of the decay $\eta \to \nu\bar{\nu}$ or $\pi^0 \to \nu\bar{\nu}$ would imply new and interesting physics. The η as well as the π^0 have zero spin and odd intrinsic parity, i.e. $J^P = 0^-$, and thus conservation of momentum and angular momentum require that the decay products ν and $\bar{\nu}$ possess the same helicity. This decay provides an ideal laboratory to search for the pseudoscalar (P) weak interaction, because only the P interaction allows the selection rule for the $0^+ \to 0^-$ transition for nearly massless neutrinos and antineutrinos. Other exotic effects such as the presence of a right-handed weak current through the exchange of a Z_R^0 would also allow such decays. The information derived from $\pi^0 \to \nu\bar{\nu}$ and $\eta \to \nu\bar{\nu}$ are complementary because the former is sensitive only to the isovector neutral-current (NC) interactions while the latter is sensitive to the isoscalar NC interactions [1]. Furthermore, π^0 decays involve only u- and d-quarks while η decays additionally involve the s-quark and perhaps other heavier quarks. If the Z^0 couples to a massive neutrino with the standard weak-interaction strength, the branching ratio (BR) for $\pi^0 \to \nu_\tau\bar{\nu}_\tau$ and $\eta \to \nu_\tau\bar{\nu}_\tau$ have maximum values of 5.0×10^{-10} and 1.3×10^{-11} [2], respectively, at the ν_τ mass upper limit of $m_{\nu_\tau} = 18.2$ MeV$/c^2$ [3]. It is noteworthy that BRs of $\approx 2 \times 10^{-18}$ and $\approx 2 \times 10^{-15}$ are allowed within the standard model (SM) for $\pi^0 \to \nu\bar{\nu}\gamma$ and $\eta \to \nu\bar{\nu}\gamma$, respectively [2].

II. EXISTING LIMITS

To date no exclusive limits have been set on $\eta \to \nu\bar{\nu}$ in any experiment. The Particle Data Group (PDG) [3] reports an inclusive upper limit of $\Gamma(\eta \to \text{invisible})/\Gamma(\eta \to \gamma\gamma) < 1.65 \times 10^{-3}$ from the BES-II Collaboration [4], corresponding to an upper limit on the BR for $\eta \to$ invisible of 6.0×10^{-4}. The BES-II results are inclusive results obtained by using 58×10^6 $J/\psi \to \phi\eta$ decays.

Possible $\eta \to$ invisible decay products could be light dark matter (LDM) particles or light neutralinos. These LDM particles may have an adequate relic density to account for the nonbaryonic mass of the Universe. Our estimated IceCube limits will be complementary to BES-II limits since the SM neutrinos would be a component of BES-II reported inclusive measurements. Limits on $\pi^0 \to \nu_\alpha\bar{\nu}_\alpha$ ($\alpha = \nu_e, \nu_\mu, \nu_\tau$) are more common. An experimental upper limit, $\Gamma(\pi^0 \to \nu_e\bar{\nu}_e)/\Gamma(\pi^0 \to \text{all}) < 1.7 \times 10^{-6}$ at 90% confidence level (CL), was set by Dorenbosch *et al.* [5]. The LSND Collaboration [6] has set an upper limit on the BR for $\pi^0 \to \nu_\mu\bar{\nu}_\mu$ of 1.6×10^{-6} at 90% CL. In the tau neutrino channel, Hoffman has set a limit of $\Gamma(\pi^0 \to \nu_\tau\bar{\nu}_\tau)/\Gamma(\pi^0 \to \text{all}) < 2.1 \times 10^{-6}$ at 90% CL [7]. An inclusive search for $\pi^0 \to \nu\bar{\nu}$ using $K^+ \to \pi^+\pi^0$ has set an upper limit of 2.7×10^{-7} at 90% CL [8], (see PDG for details).

III. CALCULATIONS FOR $\eta \to \nu_{e,\tau}\bar{\nu}_{e,\tau}$

Because of their enormous mass, cubic-kilometer neutrino detectors such as IceCube, offer a new opportunity to search for such exotic decays with competitive results compared to those obtained from accelerator-based experiments. IceCube, presently near completion at the South Pole, will contain 4800 digital optical modules (DOM) mounted on 80, 1-km strings. The active target consists of approximately 4.2×10^{37} ^{16}O atoms and 8.4×10^{37} H atoms. We have performed calculations using the CORSIKA Extensive Air Shower simulation code, version 6.72, to estimate the number of η mesons produced in the atmosphere [9]. The primary nucleon energy spectrum was calculated based on a sum of the power law approximations for the elemental primary energy spectra,

$$I(E) = \sum A_i \Phi_{A_i}(EA_i)^{-\gamma_A}. \quad (1)$$

The parameters Φ_{A_i} and γ_A for $i = 1, \ldots 28$ primary nuclei with mass number A_i were obtained from corresponding approximations of balloon and satellite data [10]. The resulting nucleon energy spectrum of expression (1) can

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then be written as

$$I(E) = (0.110 \pm 0.006)E^{-2.74\pm 0.02} \qquad (2)$$

in units of $(m^2 \cdot s \cdot sr \cdot TeV)^{-1}$. The simulation program was tested by comparing the simulated neutrino and antineutrino energy spectra for two zenith angles ($\theta = 0°$ and $\theta = 60°$) with the corresponding spectra of Gaisser and Honda [11].

Shown in Fig. 1 are the sum of fluxes of ν_μ and $\bar{\nu}_\mu$, above 200 GeV at zero degree (open circles) and at 60° (open squares). Also shown are the sum of fluxes of ν_e and $\bar{\nu}_e$ above 200 GeV at zero degree (solid circles) and at 60° (solid squares). These calculations, as shown in Fig. 1, agree well with those of Gaisser and Honda [11]. The $\nu_\mu(\bar{\nu}_\mu)$ rate in Fig. 1 is an order of magnitude larger than $\nu_e(\bar{\nu}_e)$ rate because pions and kaons decay mostly to $\nu_\mu(\bar{\nu}_\mu)$ and not to $\nu_e(\bar{\nu}_e)$. The largest sources of $\nu_e(\bar{\nu}_e)$ are $K^{\pm}_{e3}$ decay, i.e. $K^\pm \to \pi^0 e^\mp \nu_e$, BR = 5.08%, and K^0_{e3} decay, i.e. $K^0_L \to \pi^\pm e^\mp \nu_e$, BR = 40.55% and to a lesser extent $\mu^\pm$ decay. Because of its long lifetime most $\mu^\pm$ reach the ground before decaying. Because the atmospheric $\nu_e(\bar{\nu}_e)$ background is significantly less than the atmospheric $\nu_\mu(\bar{\nu}_\mu)$ background, we concentrate on searches for $\eta \to \nu_e(\bar{\nu}_e)$ and $\eta \to \nu_\tau(\bar{\nu}_\tau)$. Interactions of high energy atmospheric neutrinos in IceCube can be classified as events with a long muon track or as cascade events with very localized energy deposited in the detector. The muon events are due to charged-current (CC) ν_μ interaction while the cascade events are mainly from CC ν_e and to a lesser extent from NC ν_e and ν_μ. Neutrino absorption in the Earth was also taken into account using the neutrino mean free path $\lambda_\nu = 1/(N_A \rho(\theta)\sigma(E_\nu))$, where N_A is the Avogadro's number, $\rho(\theta)$ is the average density of the Earth in g/cm^3 [12] for a neutrino traversing the Earth at angle θ and σ is the ν-nucleon cross section at neutrino energy E_ν using a parton distribution functions from CTEQ6 [13].

In Fig. 2 the expected sum of the ν_e and $\bar{\nu}_e$ energy spectrum from the standard K and μ decay modes is presented (open circles). Figure 2 also shows the prompt $\nu_e(\bar{\nu}_e)$s from charm decay. This contribution becomes significant by 10 TeV and dominates at high energies [14]. Also shown are neutrino energy spectra for the possible decay modes $\pi^0 \to \nu_e \bar{\nu}_e$ (solid circles) and $\eta \to \nu_e \bar{\nu}_e$ (solid squares), assuming 100% BR. The energy spectra of neutrinos from a π^0 and η SM-forbidden decays have nearly the same shape as the primary nucleon spectrum ($\gamma \simeq -2.7$) whereas the energy spectrum of neutrinos from K and μ decays is significantly steeper ($\gamma \simeq -3.58$). This is because both π^0 and η with very short lifetimes ($\tau_{\pi^0} = 8.4 \times 10^{-17}$ s and $\tau_\eta \approx 5.0 \times 10^{-19}$ s) do not interact and lose energy before decaying, while charged pions and kaons with much longer lifetimes interact substantially with the atmosphere before decaying. The corresponding integral spectra are shown in Fig. 3. The flux of background neutrinos from the lower hemisphere ($\cos\theta <$ 0) is practically equal to the flux from the upper hemisphere because neutrino absorption in the Earth is approxi-

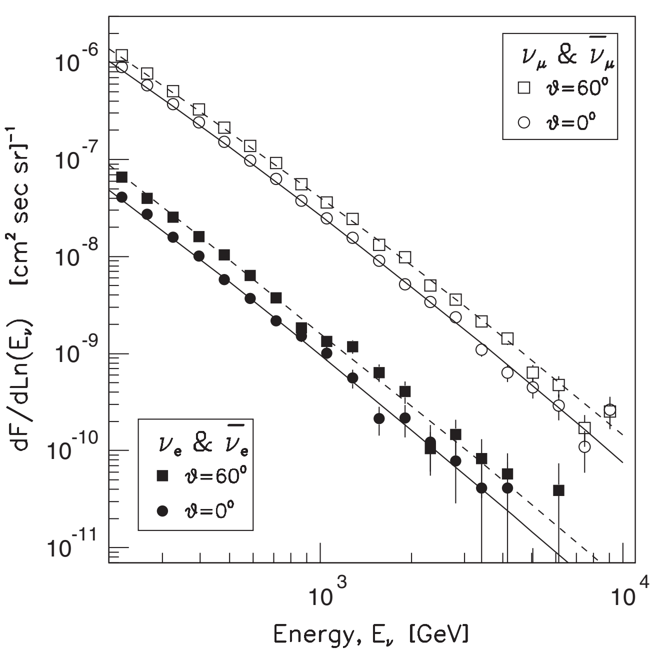

FIG. 1. Atmospheric $\nu_e(\bar{\nu}_e)$, and $\nu_\mu(\bar{\nu}_\mu)$ energy spectra for two zenith angles compared with those of Gaisser and Honda [11] shown with solid and dashed lines.

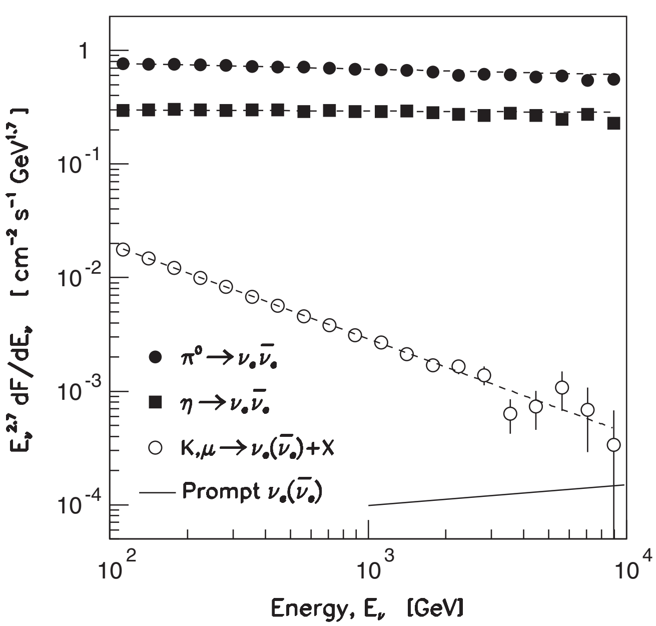

FIG. 2. The expected energy spectrum of $\nu_e(\bar{\nu}_e)$ from decays of atmospheric K and μ is shown by open circles. The solid line shows the contribution of $\nu_e(\bar{\nu}_e)$ from charm decays [14]. The $\nu_e(\bar{\nu}_e)$ energy spectra from possible decay modes $\pi^0 \to \nu_e(\bar{\nu}_e)$ (solid circles) and $\eta \to \nu_e(\bar{\nu}_e)$ (solid squares) are shown assuming a 100% BR.

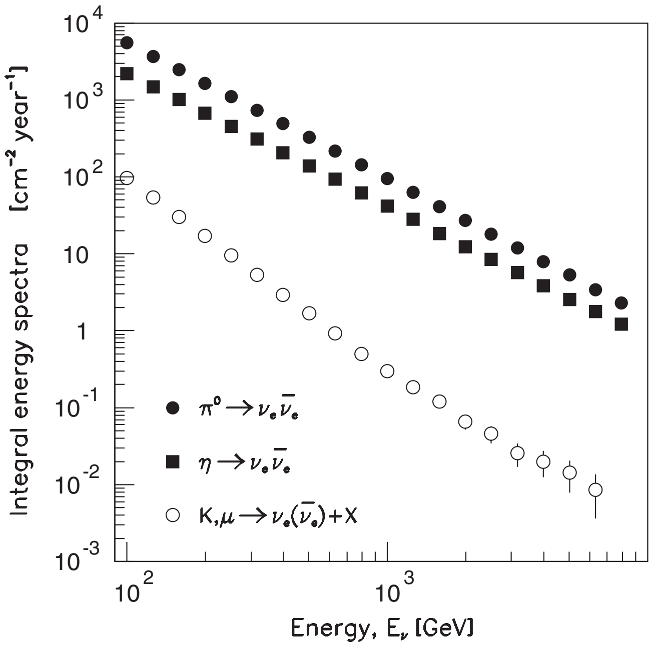

FIG. 3. ν_e integral energy spectra (see Fig. 2) in the units of $(\mathrm{cm}^2 \cdot \mathrm{year})^{-1}$.

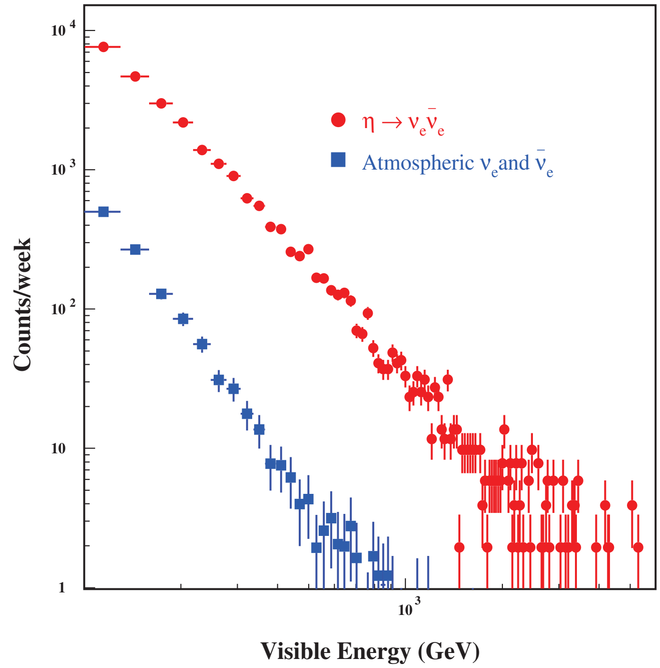

FIG. 4 (color). GEANT output for the spectrum of Fig. 3. The trigger requirement of at least 8 PMTs has been applied.

mately compensated by the larger atmosphere depth in the case of upward-going neutrinos originating from the northern hemisphere.

The flux of neutrinos induced by π^0 and η decays slightly depend on atmospheric depth in the range of 700–1000 g/cm^2. The CORSIKA generated neutrinos from π^0 and η decays with a CTEQ6 parton distribution model and the corresponding cross sections for CC and NC were calculated according to the formalism employed by Reno [13]. The expected rate of detectable ν_e events for the IceCube detector was then calculated using a GCALOR simulation MC program [15].

IV. GCALOR CALCULATIONS AND LIMITS

The 3-momenta of these events for e and τ leptons were written to a file which was then read by GEANT and electron and τ transport with their accompanying hadron, a proton in this case, were simulated. The interaction vertices were distributed uniformly throughout the detector volume. The GEANT CERENKOV code together with the input IceCube geometry with average PMT quantum efficiency as well as an ice model with appropriate absorption and scattering [16] simulated the hit PMTs. The resulting trigger efficiencies for number of hit PMTs ≥ 8 are 0.75 and 0.70 for $\eta \to \nu_{e,\tau}\bar{\nu}_{e,\tau}$ and the atmospheric background due to K and μ decays, respectively. Figure 4 shows the energy distributions of the possible signal and the background events. We also estimated the atmospheric background due to cascades from ν_μ NC interaction with nuclei as well as CC ν_μ interactions where the muon is not detected due to edge effects. These types of events have a trigger efficiency of 0.30 and contribute only at a 15% level and have been included in the atmospheric neutrino background. The atmospheric ν_τ contribution to the background are small below 10 TeV [14]. Furthermore, above a few TeV prompt $\nu_e(\bar{\nu}_e)$'s from charm decay must be taken into consideration [14]. The amount of MC data shown corresponds to one week of data taking with an 80-string IceCube detector configuration. Figure 5 shows the expected upper limits on BRs for $\pi^0 \to \nu_e\bar{\nu}_e$ and $\eta \to \nu_e\bar{\nu}_e$ decays that could be obtained from 5 years of measurements by the IceCube detector. The computations were performed at a 90% CL using the expression

$$\mathrm{BR} \leq \frac{\sqrt{I_{\mathrm{Bkgr}} + (\Delta_{\mathrm{sys}})^2}}{I_\nu(\pi^0, \eta \to \nu\bar{\nu})}. \tag{3}$$

Where I_{Bkgr} is the number of background events from K, π, μ and prompt charm decays. Δ_{sys} is the systematic uncertainty in the number of background events, and $I_\nu(\pi^0, \eta \to \nu\bar{\nu})$ is the estimated number of η decay events assuming 100% BR. Note in the above expression and the figure, the systematic uncertainties are mainly from two sources, the primary cosmic ray flux and cross sections. These uncertainties are energy dependent and a full analysis of them would include uncertainties in flux calculations and uncertainties associated with particle production cross sections. We estimated these uncertainties based on the energy-dependent flux uncertainties reported by Agrawal, *et al.* [17] and those reported by Derome [18]. Uncertainties for the neutrino production cross sections

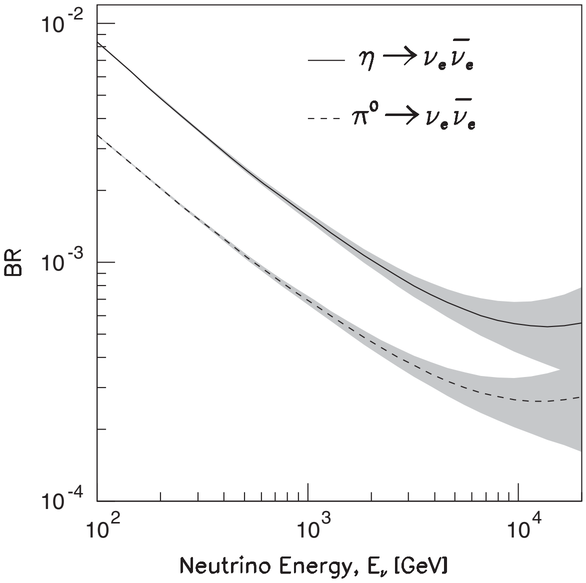

FIG. 5. Measurable upper limits (lines) for the BR of π^0, $\eta \to \nu_e \bar{\nu}_e$ decays versus neutrino energy for 5 years operating live time of the IceCube detector. The shaded areas show the statistical uncertainties.

reported by the two references is 15%. The relative primary nucleon flux systematic error is due to uncertainties in Eq. (2) and I_{Bkgr} simulations and can be approximated by

$$\frac{\Delta I}{I} = \sqrt{0.1^2 + \left(0.02 \ln\left(\frac{E_\nu k}{1000\,\mathrm{GeV}}\right)\right)^2}, \quad (4)$$

where $\ln k = \langle \ln(E/E_\nu) \rangle \simeq 2.75 \pm 0.05$. Table I shows these uncertainties for the primary flux and the neutrino production cross sections using the reported values of Ref. [17].

TABLE I. Uncertainties associated with primary flux and neutrino production cross sections.

E_ν (GeV)	10^2	10^3	10^4
Primary Flux	0.10	0.11	0.14
σ_ν	0.15	0.15	0.15
Overall	0.18	0.19	0.21

Uncertainties in Table I are the most conservative estimates that contribute to the limits on $\eta \to \nu_{e,\tau} \bar{\nu}_{e,\tau}$. As shown in Fig. 5, the most stringent limits are obtained from neutrinos above ≈ 9 TeV.

V. SUMMARY

In summary, we have investigated the IceCube discovery potential for setting stringent limits on the $\eta \to \nu_e \bar{\nu}_e$ and $\eta \to \nu_\tau \bar{\nu}_\tau$. Our studies show that a direct upper limit of 6.1×10^{-4} at 90% CL at neutrino energies above 9 TeV for both η decay to two e neutrinos or two τ neutrinos can be obtained. This limit is complementary to the limit set by the inclusive $\eta \to$ nothing measurements of Ref. [4].

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