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 $\eta \to \nu_\tau \bar{\nu}_e$ and $\eta \to \nu_e \bar{\nu}_\tau$. The signatures for these decays are cascade events resulting from the charged-current reactions of $\nu_\tau, \nu_e, \bar{\nu}_e$ and $\bar{\nu}_\tau$ on nuclei in such detectors. Background cascade events are mainly due to $\nu_\tau$’s from atmospheric $\mu, K^-$, and $K^0_S$ decays and to a lesser extent from atmospheric $\nu_\mu$ neutral current interactions with nuclei. A direct upper limit for the branching ratio $\eta \to \nu_{e,\tau} \bar{\nu}_{e,\tau}$ of $6.1 \times 10^{-4}$ 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 $\eta$ as well as the $\pi^0$ 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 $\nu$ 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, $\pi^0$ decays involve only u- and d-quarks while $\eta$ decays additionally involve the s-quark and perhaps other heavier quarks. If the $Z_\alpha^0$ 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 $5.0 \times 10^{-10}$ and $1.3 \times 10^{-11}$ [2], respectively at the $\nu_\tau$ mass upper limit of $m_{\nu_\tau} = 18.2$ MeV/c$^2$ [3]. It is noteworthy that BRs of $\approx 2 \times 10^{-14}$ and $\approx 2 \times 10^{-15}$ are allowed within the Standard Model (SM) for $\pi^0 \to \nu \bar{\nu}_{\gamma\gamma}$ and $\eta \to \nu \bar{\nu}_{\gamma\gamma}$, 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) [5] reports an inclusive upper limit of $\Gamma(\eta \to invisible)/\Gamma(\eta \to \gamma\gamma) < 1.65 \times 10^{-3}$ from the BES-II Collaboration [6], corresponding to an upper limit on the BR for $\eta \to invisible$ of $6.0 \times 10^{-4}$. The BES-II results are inclusive results obtained by using $58 \times 10^6 J/\psi \to \phi \eta$ 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 non-baryonic 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 $\pi^0 \to \nu_\alpha \bar{\nu}_\alpha$ ($\alpha = \nu_\tau, \nu_\mu, \nu_\nu$) are more common. An experimental upper limit, $\Gamma(\pi^0 \to \nu_\nu \bar{\nu}_\nu)/\Gamma(\pi^0 \to all) < 1.7 \times 10^{-6}$ at 90% confidence level (CL), was set by Dorenbosch et al. [9]. The LSND Collaboration [2] has set an upper limit on the BR for $\pi^0 \to \nu_\mu \bar{\nu}_\mu$ of $1.6 \times 10^{-6}$ at 90% CL. In the tau neutrino channel, Hoffman has set a limit of $\Gamma(\pi^0 \to \nu_\tau \bar{\nu}_\tau)/\Gamma(\pi^0 \to all) < 2.1 \times 10^{-6}$ 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 $2.7 \times 10^{-7}$ at 90% CL [8], (see PDG for detail).

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 $4.2 \times 10^{37}$ $^{16}O$ atoms and $8.4 \times 10^{37}$ $^{1}H$ atoms. We have performed calculations using the CORSIKA Extensive Air Shower simulation code, version 6.72, to estimate the number of $\eta$ mesons produced in the atmosphere [10]. The primary nucleon energy spectrum was calculated based on a sum of the power law approximations for the elemental primary energy spectra,

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

The parameters $\Phi_{A_i}$ and $\gamma_{A_i}$ for $i = 1, \ldots 28$ primary nuclei with mass number $A_i$ were obtained from corresponding approximations of balloon and satellite data.
The resulting nucleon energy spectrum of expression (1) can then be written as:

$$I(E) = (0.110 \pm 0.006) E^{-2.74 \pm 0.02}$$  \tag{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 \(\theta = 60^\circ\)) with the corresponding spectra of Gaisser and Honda \[11\].

Shown in Fig. 1 are the sum of fluxes of \(\nu_\mu\) 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 \(\nu_e\) 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 Kaon decays, i.e. \(K^\pm \rightarrow \pi^0 e^\mp \nu_e\), \(BR = 5.08\%\), and \(K_{e3}^0\) decay, i.e. \(K_{e3}^0 \rightarrow \pi^0 e^\pm \nu_e\), \(BR = 40.55\%\) and to a lesser extent \(\mu^\pm\) decay. Due to its long lifetime most \(\mu^\pm\) reach the ground before decaying. Because the atmospheric \(\nu_\mu(\bar{\nu}_\mu)\) background is significantly less than the atmospheric \(\nu_e(\bar{\nu}_e)\) background, we concentrate on searches for \(\eta \rightarrow \nu_e(\bar{\nu}_e)\) and \(\eta \rightarrow \nu_\mu(\bar{\nu}_\mu)\). 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) \(\nu_\mu\) interaction while the cascade events are mainly from CC \(\nu_e\) and to a lesser extent from NC \(\nu_\mu\) and \(\nu_\mu\). 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 \(\theta\) and \(\sigma\) is the \(\nu\)-nucleon cross section at neutrino energy \(E_\nu\) using a parton distribution functions from CTEQ6 \[13\].
The trigger requirement of at least 8 PMTs has been applied.

In Fig. 2 the expected sum of the $\nu_e$ and $\bar{\nu}_e$ energy spectrum from the standard K and $\mu$ decay modes is presented (open circles). Fig. 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 [16]. Also shown are neutrino energy spectra for the possible decay modes $\pi^0 \rightarrow \nu_e\bar{\nu}_e$ (solid circles) and $\eta \rightarrow \nu_e\bar{\nu}_e$ (solid squares), assuming 100% BR. The energy spectra of neutrinos from a $\pi^0$ and $\eta$ 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 $\mu$ decays is significantly steeper ($\gamma \simeq -3.58$). This is because both $\pi^0$ and $\eta$ with very short lifetimes ($\tau_{\pi^0} = 8.4 \times 10^{-17}$ s and $\tau_{\eta} \approx 5.0 \times 10^{-15}$ 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 approximately compensated by the larger atmospheric depth in the case of upward-going neutrinos originating from the northern hemisphere.

The flux of neutrinos induced by $\pi^0$ and $\eta$ decays slightly depend on atmospheric depth in the range of 700-1000 g/cm$^2$. The CORSIKA generated neutrinos from $\pi^0$ and $\eta$ 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 $\nu_e$ events for the IceCube detector was then calculated using a GCALOR simulation MC program [14].

IV. GCALOR CALCULATIONS AND LIMITS

The 3-momenta of these events for $e$ and $\tau$ leptons were written to a file which was then read by GEANT and electron and $\tau$ 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 [15] simulated the hit PMTs. The resulting trigger efficiencies for number of hit PMTs $\geq 8$ are 0.75 and 0.70 for $\eta \rightarrow \nu_e\bar{\nu}_e$ and and atmospheric background due to cascades from the atmospheric neutrino background. The atmospheric $\nu_e$ contribution to the background are small below 10 TeV [16]. Furthermore, above a few TeV prompt $\nu_e(\bar{\nu}_e)$s from charm decay must be taken into consideration [17]. The amount of MC data shown corresponds to one week of data taking with an 80-string IceCube detector configuration. Fig. 5 shows the expected upper limits on BRs for $\pi^0 \rightarrow \nu_e\bar{\nu}_e$ and $\eta \rightarrow \nu_e\bar{\nu}_e$ decays that could be obtained from 5 years of measurements by the IceCube detector. The computations were performed at a 90%
where $\ln k = \frac{\ln(E/E_\nu)}{2} > \pm 2.75 \pm 0.05$. Table I shows these uncertainties for the primary flux and the neutrino production cross sections using the reported values of reference [17].

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

### V. SUMMARY

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

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### Table I: Uncertainties associated with primary flux and neutrino production cross sections.

| $E_\nu$ (GeV) | $10^{-3}$ | $10^{-4}$ | $10^{-5}$ |
|--------------|----------|----------|----------|
| Primary Flux  | 0.10     | 0.11     | 0.14     |
| $\sigma_\nu$ | 0.15     | 0.15     | 0.15     |
| Overall      | 0.18     | 0.19     | 0.21     |

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

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