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Observability of Earth-Skimming Ultrahigh Energy Neutrinos

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Neutrinos with energies above 10^8 GeV are expected from cosmic ray interactions with the microwave background and are predicted in many speculative models. Such energetic neutrinos are difficult to detect, as they are shadowed by Earth, but rarely interact in the atmosphere. Here we propose a novel detection strategy: Earth-skimming neutrinos convert to charged leptons that escape Earth, and these leptons are detected in ground level fluorescence detectors. With the existing HiRes detector, neutrinos from some proposed sources are marginally detectable, and improvements of 2 orders of magnitude are possible at the proposed Telescope Array.

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Cosmic neutrinos with energies above 10^8 GeV, thus far unobserved, have great potential as probes of astrophysics and particle physics phenomena. They escape from dense regions of matter and point back to their sources, thereby providing a unique window into the most violent events in the Universe. Once they reach Earth, they interact with center-of-mass energies far beyond foreseeable man-made colliders and probe new physics at and beyond the weak scale.

The sources of ultrahigh energy neutrinos range from the well established to the highly speculative [1]. The cosmic ray spectrum is well measured up to the Greisen-Zatsepin-Kuz'min (GZK) cutoff [2,3] at 5×10^{10} GeV. Such cosmic rays necessarily interact with the 2.7 K cosmic microwave background through pion photoproduction $p\gamma \to n\pi^+$, producing "Greisen neutrinos" when the pions decay [2,4]. In addition to this "guaranteed" flux, far larger fluxes are predicted in models of active galactic nuclei (AGN) [5,6] and in proposed explanations of the observed cosmic rays with energies above the GZK cutoff. The latter include decays of topological defects (TDs) [7] and Z bursts [8]. Fluxes from photoproduction and some representative hypothesized sources are given in Fig. 1.

The detection of ultrahigh energy cosmic neutrinos is, however, extremely difficult, especially for those with energies above 10^8 GeV. At these energies, the neutrino interaction length is below 2000 km water equivalent in rock, and so upward-going neutrinos are typically blocked by Earth. This shadowing severely restricts rates in underground detectors such as AMANDA/IceCube [11], which are bounded by detection volumes of at most 1 km^3. At the same time, the atmosphere is nearly transparent to these neutrinos. Even for quasihorizontal neutrinos, which traverse an atmospheric depth of up to 360 m water equivalent, fewer than 1 in 10^3 convert to charged leptons. At the Pierre Auger Observatory, estimated detection rates are of the order of 0.1 to 1 event per year for Greisen neutrinos from the ground array [12,13], with similar rates for the Auger air fluorescence detectors [14].

Here we explore an alternative method for detecting ultrahigh energy neutrinos with $E_\nu > 10^8$ GeV. While upward-going neutrinos are usually blocked by Earth, those that skim Earth, traveling at low angles along chords with lengths of the order of their interaction length, are not. Some of these neutrinos will convert to charged leptons. In particular, muon and tau leptons travel up to $\mathcal{O}(10\text{ km})$ in Earth at these energies, and so a significant number of them may exit Earth and be detected by surface fluorescence detectors. A schematic picture of the events we are considering is given in Fig. 2. This method exploits both Earth as a large-volume converter and the atmosphere as a large-volume detector.

Upward-going air showers have been discussed previously [15], with an emphasis on differences between upward-going and conventional showers and the possibility of space-based detection. The question of rates was not addressed. Very recently, the detection of showers

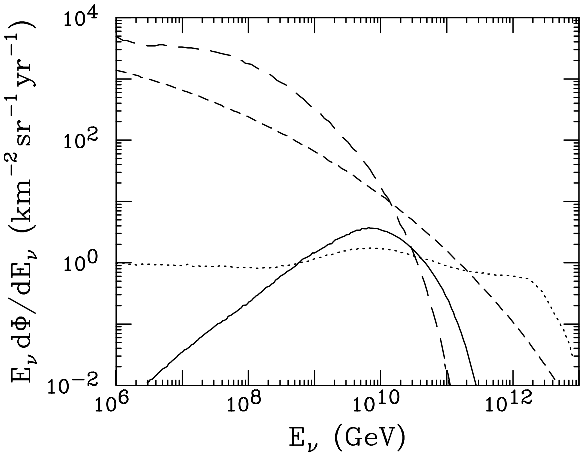

FIG. 1. Differential fluxes of muon neutrinos ($\nu_\mu + \bar{\nu}_\mu$) from Greisen photoproduction [4] (solid line), active galactic nuclei [6] (long dashed line), topological defects [9] (short dashed line), and Z bursts [10] (dotted line). For maximal $\nu_\mu - \nu_\tau$ mixing, these fluxes are divided equally between μ and τ neutrinos when they reach Earth.

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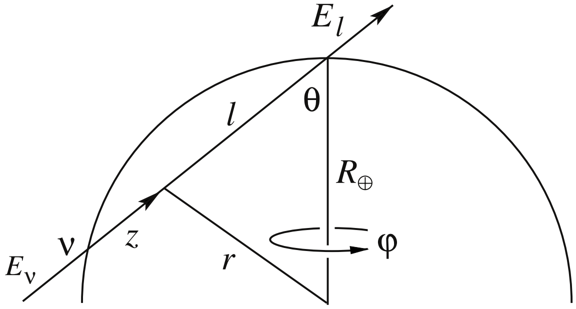

FIG. 2. A neutrino ν enters Earth with energy E_ν at nadir angle θ and azimuthal angle ϕ. It then travels for distance z before converting to a charged lepton ℓ, which exits Earth with energy E_ℓ.

from τ decays in the Auger Observatory ground array has been considered [16]. The possibility of detecting moon-skimming neutrinos through radio signals has also recently generated interest [17,18].

Given an isotropic neutrino flux Φ_ν, the resulting differential flux of charged leptons exiting Earth is

$$\frac{d\Phi_\ell(E_\ell, \cos\theta, \phi)}{dE_\ell\, d\cos\theta d\phi} = \frac{1}{2\pi}\int dE_\nu \frac{d\Phi_\nu(E_\nu)}{dE_\nu} K(E_\nu, \theta; E_\ell), \tag{1}$$

where K is the probability that a neutrino entering Earth with energy E_ν and nadir angle θ produces a lepton that exits Earth with energy E_ℓ. Such an event requires that (a) the neutrino survives for some distance z in Earth, (b) the neutrino then converts to a lepton, (c) the created lepton exits Earth before decaying, and (d) the lepton's energy and position when produced are such that it leaves Earth with energy E_ℓ.

The probability for a neutrino with energy E_ν and nadir angle θ to survive for a distance z is

$$P_a = \exp\left[-\int_0^z \frac{dz'}{L_{CC}^\nu(E_\nu, \theta, z')}\right], \tag{2}$$

where $L_{CC}^\nu(E_\nu, \theta, z) = \{\sigma_{CC}^\nu(E_\nu)\rho[r(\theta, z)]N_A\}^{-1}$ is the charged current interaction length, with $\sigma_{CC}^\nu(E_\nu)$ the interaction cross section $\sigma(\nu N \to \ell X)$ for a neutrino with energy E_ν, $\rho(r)$ is Earth's density at distance r from its center, and $N_A = 6.022 \times 10^{23}\ \mathrm{g}^{-1}$. The distance r is given by $r^2(\theta, z) = R_\oplus^2 + z^2 - 2R_\oplus z\cos\theta$, where $R_\oplus \approx 6371$ km is the radius of Earth. For $E_\nu \gtrsim 10^8$ GeV, the charged current ν and $\bar{\nu}$ cross sections are virtually identical, and we may neglect multiple charged current interactions and neutrino energy degradation from neutral current processes. Also, at these energies, the optimal nadir angle for charged lepton production is $90° - \theta \approx 1°$. Leptons produced by Earth-skimming neutrinos travel essentially horizontally.

The probability for neutrino conversion to a charged lepton in the interval $[z, z + dz]$ is $dz/L_{CC}^\nu(E_\nu, \theta, z)$. However, given that detectable leptons travel nearly horizontally with path length of $\mathcal{O}(10\ \mathrm{km})$, this conversion must take place near Earth's surface where Earth's density is $\rho_s = 2.65\ \mathrm{g/cm}^3$. The conversion probability is then well approximated by

$$P_b = \frac{dz}{L_{CCs}^\nu(E_\nu)}, \tag{3}$$

where $L_{CCs}^\nu(E_\nu) = [\sigma_{CC}^\nu(E_\nu)\rho_s N_A]^{-1}$. We assume the lepton takes all of the neutrino energy. For ultrahigh energy neutrinos, the mean inelasticity parameter is $\langle 1 - E_\ell/E_\nu\rangle \approx 0.2$ [19]. We therefore expect this assumption to make only a small difference.

The survival probability P_c for a charged lepton losing energy as it moves through Earth is described by the coupled differential equations:

$$dE_\ell/dz = -(\alpha_\ell + \beta_\ell E_\ell)\rho[r(\theta, z)], \tag{4}$$

$$dP_c/dz = -P_c/(c\tau_\ell E_\ell/m_\ell), \tag{5}$$

where c is the speed of light, and m_ℓ and τ_ℓ are the lepton's rest mass and lifetime, respectively. Equation (4) parametrizes lepton energy loss through bremsstrahlung, pair production, and photonuclear interactions, under the assumption of uniform energy loss. For the energies of interest here, $\beta_\tau \approx 0.8 \times 10^{-6}\ \mathrm{cm}^2/\mathrm{g}$, $\beta_\mu \approx 6.0 \times 10^{-6}\ \mathrm{cm}^2/\mathrm{g}$ [20,21], and the effects of $\alpha_{\tau,\mu}$ are negligible. At Earth's surface, taus and muons lose a decade of energy in 11 and 1.5 km, respectively. These differential equations are easily solved for a constant density ρ_s, and the survival probability is

$$P_c = \exp\left[\frac{m_\ell}{c\tau_\ell\beta_\ell\rho_s}\left(\frac{1}{E_\nu} - \frac{1}{E_\ell}\right)\right]. \tag{6}$$

Muon lifetimes are long enough that $P_c \simeq 1$, but this factor may play a significant role for taus.

Finally, the lepton's energy and location when produced must be consistent with an exit energy E_ℓ. From Eq. (4), for constant density ρ_s and negligible α_ℓ, this condition is enforced with the delta function,

$$P_d = \delta(E_\ell - E_\nu e^{-\beta_\ell\rho_s(2R_\oplus\cos\theta - z)}). \tag{7}$$

Combining Eqs. (2), (3), (6), and (7), the kernel is then

$$K(E_\nu, \theta; E_\ell) = \int_0^{2R_\oplus\cos\theta} P_a P_b P_c P_d. \tag{8}$$

However, Eq. (8) may be further simplified, because the lepton's range in Earth is far less than the typical neutrino interaction length. The kernel is therefore dominated by the contribution from $z \approx 2R_\oplus\cos\theta$, and we may replace z with $2R_\oplus\cos\theta$ in P_a. The only remaining z dependence is in P_d. Using $\int dz\, \delta[h(z)] = |dh/dz|_{h=0}^{-1}$, the z integration yields

$$K(E_\nu, \theta; E_\ell) \approx \frac{1}{L_{CCs}^\nu(E_\nu)} e^{-\int_0^{2R_\oplus\cos\theta}\{dz'/[L_{CC}^\nu(E_\nu, \theta, z')]\}} \times \exp\left[\frac{m_\ell}{c\tau_\ell\beta_\ell\rho_s}\left(\frac{1}{E_\nu} - \frac{1}{E_\ell}\right)\right]\frac{1}{E_\ell\beta_\ell\rho_s}. \tag{9}$$

In our calculations, we use the kernel of Eq. (9) with the Preliminary Earth density profile [22]. Our cross section evaluation closely follows Refs. [19,23]; details will be presented elsewhere [24].

Muons and taus may be detected in fluorescence detectors either directly or indirectly through their decay products. We have evaluated rates for all of these possibilities [24]; here we concentrate on the most promising signal from electromagnetic energy in τ-decay showers. The recent discovery of near-maximal $\nu_\mu - \nu_\tau$ mixing [25] implies that, even at the high energies of interest here, $\nu_\mu{:}\nu_\tau = 1{:}1$ at Earth's surface. We assume also that tau decay initiates an electromagnetic shower with probability $B_{\mathrm{EM}} = 80\%$ and a typical energy, averaged over all τ-decay modes weighted by a branching fraction, of $E_{\mathrm{EM}} = \frac{1}{3}E_\tau$. At energies of the order of 10^{10} GeV, the typical shower length is ~10 km in the low atmosphere.

We follow the analysis of Ref. [26] to estimate the effective aperture for τ-decay induced showers. The signal from an electromagnetic shower must compete with the average noise from the night sky. By considering the signal to background ratio in individual photomultiplier tubes, the energy required for an electromagnetic shower to be detected was found to be

$$E_{\mathrm{EM}} = E_d R_p^{3/2} e^{R_p/\lambda_R}, \tag{10}$$

where R_p is the shower's impact parameter in kilometers, and $\lambda_R \approx 18$ km is the Rayleigh scattering length [26]. E_d is an energy characteristic of the detector. In particular, $E_d \propto \sqrt{\Delta\theta/D^2} \propto \sqrt{d/D^3}$, where $\Delta\theta = d/D$ is the angular acceptance of each photomultiplier tube, and d and D are the diameters of the photomultiplier tubes and mirror aperture, respectively. For Fly's Eye, requiring a 4σ triggering threshold, the value $E_d = 10^8$ GeV was verified to reproduce the experimental data well [26]. For HiRes, D has been increased from 1.575 to 2.0 m and d reduced from 14.4 to 3.5 cm [27]; we therefore take $E_d \approx 3.2 \times 10^7$ GeV. For each module of the proposed Telescope Array, and requiring a 4σ signal, E_d has been estimated to be roughly 4×10^5 GeV [28]. Finally, the fluorescence detectors of the Auger Observatory [29] will also be sensitive to Earth-skimming events; we expect their sensitivity to lie somewhere between that of HiRes and Telescope Array.

Following Ref. [26], we assume that showers are detected if and only if initiated within distance R_p of the detector. We also make use of the fact that, at these energies, all τ leptons exit Earth horizontally. Apertures for Earth-skimming taus for each of the three detectors discussed above are given in Fig. 3. In each case, the aperture rises with energy until time dilation causes taus to decay too late to be detected. The HiRes aperture peaks at 2000 km^2 sr near 3×10^{10} GeV. With increased sensitivity, however, the aperture peak rises and moves to lower energies, significantly enhancing detection rates.

Given the kernel function $K(E_\nu, \theta; E_\tau)$ and effective apertures $(A\Omega)_{\mathrm{eff}}(E_\tau)$, the number of tau leptons detected is $N_\tau = \int dE_\nu\, dE_\tau\, d\cos\theta\, d\phi \cos\theta \frac{d\Phi_\nu}{dE_\nu} K(A\Omega)_{\mathrm{eff}} TD$, where $d\Phi_\nu(E_\nu)/dE_\nu$ is the differential flux originating from a given neutrino source, T is the time an experiment runs, and D is the duty cycle. To account for the requirement of clear moonless nights for fluorescence detection, we take $D = 10\%$, corresponding to an observing period of 3×10^6 s per year.

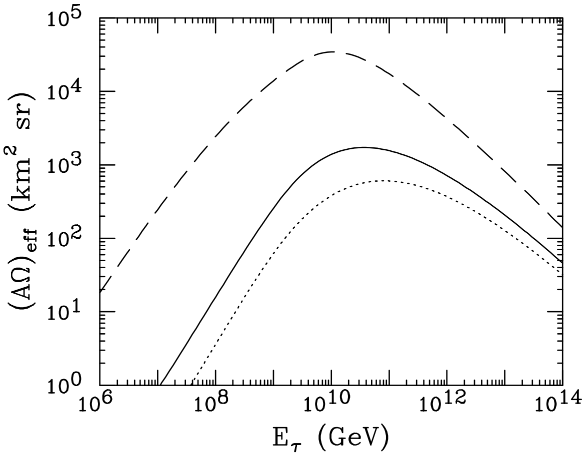

FIG. 3. Effective aperture estimates for the detection of Earth-skimming τ leptons through their decays to electromagnetic showers for Fly's Eye (dotted line), HiRes (one site) (solid line), and Telescope Array (one site) (dashed line).

Event rates for the four neutrino sources given in Fig. 1, binned by tau energy, are summarized in Table I. (Note that these rates are suppressed relative to those presented in an earlier version of this paper.) We assume 2 and 11 detectors for HiRes and Telescope Array, respectively; some reduction from overlapping fields of view may be expected. For HiRes, we find that neutrinos from AGN and TDs are marginally detectable. For Telescope Array, these rates are enhanced by more than 2 orders of magnitude—several Greisen neutrinos per year can be detected, and tens to hundreds of AGN and TD neutrinos are possible. Note that the rates may be significantly enhanced by including multibang events, which we have neglected, and also if the τ energy loss, dominated by uncertain photonuclear interactions, is less than our conservative assumption.

Hundreds or even tens of events will shed light on many aspects of ultrahigh energy astrophysics. The energy spectrum of detected events varies from source to source, as is evident in Table I. With many events, the source energy spectrum may be determined by deconvolving the observed spectrum with the kernel function. Note also that these rates may be improved with detectors that cover the sky densely very near the horizon or by filters optimized for nearly horizontal events. Placement of detectors in valleys, which effectively enhances the conversion volume, may also improve detection rates.

Earth-skimming neutrinos also open up other possibilities for detection. Cherenkov radiation provides an alternative signal for showers initiated by τ decay. Conventional air shower arrays, which deploy a large number of modules over a horizontal area, are not optimally adapted to Earth-skimming events. It is interesting to contemplate "vertical" arrays, for example, on the side of a mountain,

TABLE I. Expected number of ν_τ-induced electromagnetic showers detected by atmospheric fluorescence. Three years of running with duty cycle $D = 10\%$ is assumed.

Detector	E_τ (GeV)	Greisen	AGN	TD	Z burst
Fly's Eye	10^8-10^9	0.0039	0.051	0.0098	0.000 28
	10^9-10^{10}	0.0021	0.027	0.012	0.0015
	$10^{10}-10^{11}$	0.000 82	0.0011	0.0030	0.0014
	$10^{11}-10^{12}$	···	···	0.000 18	0.000 42
	$10^{12}-10^{13}$	···	···	···	···
	Total	0.0068	0.079	0.025	0.0036
HiRes	10^8-10^9	0.0033	0.43	0.083	0.0024
	10^9-10^{10}	0.017	0.22	0.094	0.012
	$10^{10}-10^{11}$	0.0055	0.0077	0.020	0.0092
	$10^{11}-10^{12}$	···	···	0.000 86	0.0019
	$10^{12}-10^{13}$	···	···	···	0.000 11
	Total	0.026	0.66	0.20	0.026
Telescope Array	10^8-10^9	1.4	230	41	1.0
	10^9-10^{10}	3.2	50	20	2.3
	$10^{10}-10^{11}$	0.62	0.93	2.2	0.93
	$10^{11}-10^{12}$	···	···	0.045	0.094
	$10^{12}-10^{13}$	···	···	0.000 35	0.0033
	Total	5.2	280	63	4.3

that would intercept Earth-skimming showers originating from a very large surrounding area. Earth-skimming events may also be detected from space, as in the OWL/Airwatch proposal [30].

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