Observability of Earth-skimming Ultra-high 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 the Earth, but rarely interact in the atmosphere. Here we propose a novel detection strategy: Earth-skimming neutrinos convert to charged leptons that escape the 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 two orders of magnitude are possible at the proposed Telescope Array.

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

The detection of ultra-high 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 the Earth. This shadowing severely restricts rates in underground detectors such as AMANDA/IceCube \cite{7}, 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 quasi-horizontal 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 order 0.1 to 1 event per year for Greisen neutrinos from the ground array \cite{8,9}, with similar rates for the Auger air fluorescence detectors \cite{10}.

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

Upward-going air showers have been discussed previously \cite{11}, 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 from $\tau$ decays in the Auger Observatory ground array

![FIG. 1. Differential fluxes of muon neutrinos ($\nu_\mu + \bar{\nu}_\mu$) from Greisen photoproduction \cite{3} (solid), active galactic nuclei \cite{4} (long dashed), topological defects \cite{5} (short dashed), and Z-bursts \cite{6} (dotted). For maximal $\nu_\mu - \nu_\tau$ mixing, these fluxes are divided equally between $\mu$ and $\tau$ neutrinos when they reach the Earth.](image-url)
has been considered [10]. 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 the Earth is

$$dΦ_ℓ(E_ℓ, θ, φ)/dE_ℓ dθ dφ = 1/(2π)\int dE_ν dΦ_ν(E_ν)/dE_ν K(E_ν; θ; E_ℓ),$$

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

$$P_a = \exp\left[-\int_0^z dz' L_{CC}^ν(E_ν, θ, z')\right],$$

where $L_{CC}^ν(E_ν, θ, z) = [σ_{CC}^ν(E_ν)ρ(r(θ, z))N_α]^{-1}$ is the charged current interaction length, with $σ_{CC}^ν(E_ν)$ the interaction cross section $σ(νN \rightarrow ℓX)$ for a neutrino with energy $E_ν$, $ρ(r)$ the Earth’s density at distance $r$ from its center, and $N_α = 6.022 \times 10^{23}$ g$^{-1}$. The distance $r$ is given by $r^2(θ, z) = R_⊕^2 + z^2 - 2R_⊕z\cos θ$, where $R_⊕ = 6371$ km is the radius of the Earth. For $E_ν \gtrsim 10^8$ GeV, the charged current $ν$ and $ν$ 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 $90° - θ ≈ 1°$. 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 $dz/L_{CC}^ν(E_ν, θ, z)$. However, even that detectable leptons travel nearly horizontally with path length of $O(10$ km), this conversion must take place near the Earth’s surface where the Earth’s density is $ρ_s = 2.65$ g/cm$^3$. The conversion probability is then well-approximated by

$$P_b = dz/L_{CC}^{ν→s}(E_ν),$$

where $L_{CC}^{ν→s}(E_ν) = [σ_{CC}^{ν→s}(E_ν)/ρ_s N_α]^{-1}$. We assume the lepton takes all of the neutrino energy. For ultra-high energy neutrinos, the mean inelasticity parameter is $(1 - E_ℓ/E_ν) \approx 0.2$ [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 the Earth is described by the coupled differential equations

$$dE_ℓ/dz = -(α_ℓ + β_ℓE_ℓ)\rho(r(θ, z)),$$

$$dP_ℓ/dz = -P_ℓ/\left(cτ_ℓE_ℓ/m_ℓ\right),$$

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

$$P_c = \exp\left[\frac{m_ℓ}{cτ_ℓβ_ℓρ_s}\left(\frac{1}{E_ν} - \frac{1}{E_ℓ}\right)\right].$$

Muon lifetimes are long enough that $P_c ≈ 1$, 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. [3], for constant density $ρ_s$ and negligible $α_ℓ$, this condition is enforced with the delta function

$$P_a = δ\left(E_ℓ - E_ν e^{-β_ℓρ_s(2R_⊕\cos θ - z)}\right).$$

Combining Eqs. (2), (3), (8), and (9), the kernel is then

$$K(E_ν, θ; E_ℓ) = \int_0^{2R_⊕\cos θ} dθ' P_a P_b P_c.$$

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 $z = 2R_⊕\cos θ$, and we may replace $z$ with $2R_⊕\cos θ$ in $P_a$. The only remaining $z$-dependence is in $P_d$. Using $\int dz δ(h(z)) = |dh/dz|_h=0$, the $h$ integration yields

$$K(E_ν, θ; E_ℓ) ≈ \frac{1}{L_{CC}^{ν→s}(E_ν)} e^{-\int_0^{2R_⊕\cos θ} dθ'/L_{CC}^{ν→s}(E_ν, θ', z')}
\times \exp\left[\frac{m_ℓ}{cτ_ℓβ_ℓρ_s}\left(\frac{1}{E_ν} - \frac{1}{E_ℓ}\right)\right] \frac{1}{E_ℓ/β_ℓρ_s}.\]
In our calculations, we use the kernel of Eq. (1) with the Preliminary Earth density profile [22]. Our cross section evaluation closely follows Refs. [14,23]; 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 $\tau$-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 the Earth’s surface. We assume also that tau decay initiates an electromagnetic shower with probability $B_{EM} = 80\%$ and a typical energy, averaged over all $\tau$ decay modes weighted by branching fraction, of $E_{EM} = \frac{4}{3}E_\tau$. At energies of order $10^{10}$ GeV, the typical shower length is $\sim 10$ km in the low atmosphere.

We follow the analysis of Ref. [26] to estimate the effective aperture for $\tau$-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

$$E_{EM} = E_dR_p^{3/2}e^{R_p/\lambda_R},$$

where $R_p$ is the shower’s impact parameter in km, and $\lambda_R \approx 18$ km is the Rayleigh scattering length [24]. $E_d$ is an energy characteristic of the detector. In particular, $E_d \propto \sqrt{\Delta \theta/D^2} \propto \sqrt{d/D}$, 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 $4\sigma$ triggering threshold, the value $E_d = 10^8$ GeV was verified to reproduce the experimental data well [27]. For HiRes, $D$ has been increased from 1.575 m to 2.0 m and $d$ reduced from 14.4 cm 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 $4\sigma$ signal, $E_d$ has been estimated to be roughly $4 \times 10^7$ 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. [24], 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 $\tau$ leptons exit the 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 tau decay too late to be detected. The HiRes aperture peaks at 2000 km$^2$ sr near $3 \times 10^{10}$ 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 ($A\Omega_{eff}(E_\nu)$), the number of tau leptons detected is $N_\tau = \int dE_\nu dE_\tau d\cos \theta d\phi d\frac{d\Phi_\nu}{dE_\nu}K(A\Omega_{eff}T D$, 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 $T = 10\%$, corresponding to an observing period of $3 \times 10^6$ s per year.

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 two 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 multi-bang events, which we have neglected, and also if the $\tau$ energy loss, dominated by uncertain photo-nuclear interactions, is less than our conservative assumption.

Hundreds or even tens of events will shed light on many aspects of ultra-high energy astrophysics. The energy spectrum of detected events varies from source to source, as 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. Cerenkov 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, say on the side of a mountain, 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].

Acknowledgements. We thank F. Halzen for helpful discussions and for bringing Ref. [16] to our attention, and A. Kusenko and T. Weiler for helpful correspondence. JLF also thanks E. Kearns, J. Rosner, and C. Walter for conversations about future experiments. This work was supported in part by the U. S. Department of Energy under cooperative research agreement DF–FC02–94ER40818.

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