How opaque is the Earth to ultrahigh energy neutrinos?

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We carry out a numerical calculation of ultrahigh energy neutrino propagation through the Earth, taking into account the neutrino regeneration process in both neutral current and charged current neutrino interactions. The attenuation of neutrinos traversing the Earth (shadow effect) is determined, and the fluxes of ν-induced upward-going leptons (muon and tau) are obtained at the Earth's surface and for two configurations of the neutrino flavor in the incident neutrino flux ($\nu_\mu \rightarrow \nu_\tau$ mixing). The implications of these results are discussed in the context of the possibility of detection of ν-induced leptons in the next round of fluorescent telescopes such as the AUGER detector.

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I. INTRODUCTION

An understanding and description of the sources, accelerator mechanism, and process of diffusion of ultrahigh energy cosmic ray (UHECR) particles is still far from being achieved. Of particular interest is the search for the nature of those particles with energies above 10^{20} eV, because if they are charged particles (protons) and their sources are far extragalactic objects (beyond 100 Mpc), their energy spectrum must exhibit the Greisen-Zatsepin-Kuz'min (GZK) cutoff at $\sim 5 \times 10^{19}$ eV due to their interaction with the cosmic microwave background. However, the absence of a GZK cutoff in the experimental data "opens the door" for many scenarios and speculations about the origin and nature of these UHECR particles. Are they gamma rays or neutrinos? Or new exotic particles beyond the standard model? (For a review, see [1,2].) Even if these UHECR particles were protons, UHE neutrinos would be expected as products due to the photopion production in the proton-photon (microwave) interaction. Such neutrinos are called GZK neutrinos.

On the other hand, the first results for UHECR particles [3] are consistent with an isotropic distribution of sources. This characteristic together with the absence of a GZK cutoff are the main ingredients of the so-called top-down models. In this scenario the so-called topological defects (TDs) formed in the symmetry breaking phase transition in the early universe [4,5]; they may produce the bulk of the UHE particles with energies up to the grand unified theory (GUT) scale, typically 10^{15}–10^{16} GeV, through their collapse or decay in a volume of 100 Mpc around the Earth, where the GZK cutoff is not relevant. Leptons and hadronic jets are emitted from the decay of these supermassive X particles such as magnetic monopoles and superconducting strings. It is expected that a hadronic jet would produce even more neutrinos than nucleons. Such neutrinos are called TP neutrinos.

In addition, transient high energy phenomena such as gamma ray bursts (GRBs) may also be a source of UHE neutrinos [6] (GRB neutrinos). Both UHECRs and GRBs are distributed isotropically in the sky and the rates of GRBs are close to those of UHECRs. These similarities suggest a common origin for them.

The discovery of TeV γ-ray emission from two nearby extragalactic blazar objects MRK421 and MRK501 by the Whipple Collaboration [7,8], caused considerable interest in the study of active galactic nuclei (AGNs), which are believed to be the most powerful sources of high energy γ rays and neutrinos in the universe. Several mechanisms of acceleration of particles in these objects have been proposed and the so called AGN neutrino energy spectra were derived [9–11].

In order to test the hypothesis mentioned above, which suggests a universe filled with high and extremely high energy diffuse neutrino fluxes from AGNs and from cosmological sources as well as point sources, several neutrino telescopes are partially deployed and currently operating.

Neutrinos in the GeV energy region become detectable in underground experiments when they undergo a charged current (CC) interaction within the rock surrounding the detector and the produced muons reach the detector, Kamiokande [12], IMB [13], Baksan [14], Macro [15], or Frejus [16,17]. In the TeV up to EeV (or more) energy region, the neutrino flux is expected to be very low, and large active areas are necessary. The neutrino telescopes consist of a huge volume ($\sim$Km^3) of a transparent medium, water or ice, in which neutrinos interact via the CC and the leptons produced (muons, taus) can be seen and reconstructed through the detection of their Cherenkov light or through the shower initiated after neutrino interaction or after the lepton decays or both (double bang signature), as was suggested in [18] for the case of ν_τ at PeV energies. Nowadays, there are in operation the Lake Baikal detector [19], the Antarctic Muon and Neutrino Detector Array (AMANDA) detector [20], and RICE [21] at the South Pole, and the discontinued Deep Underground Muon and Neutrino Detector (DUMAND) project [22] in the Pacific Ocean. There are also two underwater telescopes Antares and Nestor [23], both in the Mediterranean, and an underice telescope ICECUBE [24] at the South Pole, all in construction or advanced planning. A complete and up to date review of these topics can be found in [25].

In addition there are projects to use ground level fluorescence telescopes to detect neutrinos in the EeV or higher energy region through the upward-going ν-induced leptons in the Earth, because a fraction of these charged leptons can emerge from the Earth. In this case the atmosphere is used as a Cherenkov medium. The τ decays also induce an atmospheric shower. The electromagnetic component of this upward-going shower produces light due to the nitrogen fluorescence. Both the Cherenkov and fluorescence radiations can be detected by fluorescence telescopes, like the existing HiRes detector, the next Pierre Auger telescope [26], and the Telescope Array [27] (both under construction). The main goal of this paper is the study of the neutrino component of UHE cosmic rays and their ν-induced upward-going leptons leaving the Earth and the rates expected at the AUGER fluorescence telescope.

So far, the upward-going muon flux in the GeV energy region has been measured in the underground experiments Kamiokande [12], IMB [13], Baksan [14], and Macro [15]. These muons are induced in the Earth by atmospheric neutrinos with energies below 10^4 GeV and constitute the main background in the detection of extraterrestrial neutrinos [28]. A review of these topics can be found in [29]. At energies above 10^4 GeV, the Earth's diameter exceeds the interaction length of neutrinos, or, in other words, the Earth is opaque for them, especially in some directions not far from the horizontal.

However, due to the neutral current (NC) neutrino interactions, the probability for successive neutrino interaction is not negligible and they can still penetrate to give observable lepton muons (taus). This means that the (NC) neutrino interaction is a regeneration process. In addition, the possible presence of tau neutrinos in the beam due to neutrino oscillation ($\nu_\mu \to \nu_\tau$ mixing) also permits the inclusion of neutrino regeneration process in the charged current neutrino interaction, as has been suggested by Halzen and Saltzberg [30]. A spectacular consequence of this mechanism is that for energies above the PeV region the Earth is transparent to ν_τ. Then the Earth shadowing cannot be very dramatic, even at EeV energies.

To generate upward-going ν-induced leptons, we have developed a Monte Carlo program. It generates neutrino interactions inside the Earth in the direction of a chord with nadir angle between 0° to 89° and tracks them down to leptons (ν, μ, τ) at the other side of the Earth's surface. We focus the energy region above EeV, because in this region the fluorescence Auger telescope is not fully sensitive to conventional atmospheric cascades, and the effective aperture of the telescope for the detection of upward-going lepton reaches its maximum value. Consequently, the telescope can be explored as a neutrino detector through ν-induced upward-going leptons.

II. THE INPUT

Let us first briefly summarize the simulation input assumptions of lepton transport in the Earth.

A. Neutrino-nucleon interaction

If a neutrino of energy E_ν interacts via neutral currents ($\nu N \to \nu X$) the interaction produces another neutrino of energy $(1-y)E_\nu$. This mechanism of regeneration is valid for both ν_μ and ν_τ. However, if the neutrino interaction is via charged currents ($\nu N \to l X$), the interaction produces a charged lepton. In the case of ν_μ, the charged current interactions remove neutrinos from the flux, because the interaction produces a μ that has a large decay length (see Sec. II E). For the case of ν_τ, the mechanism of charged current interaction is essentially the same; the interaction produces a τ, but with the important modification that the τ has a decay length considerable shorter than the muon decay length. In addition, the τ energy loss by radiation is around ten times lower than the energy loss by muons, and in all τ decay modes there is always another ν_τ in the final state [30]. The energy of this ν_τ is on average ~ 0.3 of the τ energy. In short, for the ν_τ the CC and NC interactions are the mechanism of neutrino regeneration.

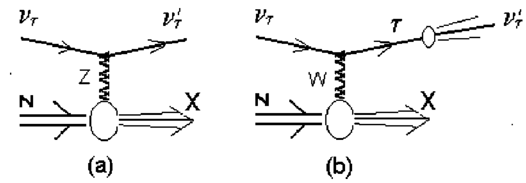

FIG. 1. ν_τ-nucleon deep inelastic scattering. (a) represents the neutral current neutrino interaction and (b) represents the charged current (CC) neutrino interaction. Both are ν_τ neutrino regeneration processes.

A schematic picture of the ν_τ-nucleon interaction is shown in Fig. 1, where (a) and (b) represent the neutral current and charged current neutrino interactions, respectively.

B. Neutrino-nucleon cross section

Calculations of the cross section for the inelastic neutrino-nucleon interaction involve some uncertainties which arise from the different parton distributions used in its determination. The discrepancies increase as the neutrino energy increases.

The structure function has been measured at values as low as 10^{-4} at the DESY *ep* collider HERA. However, extrapolation to $x \sim 10^{-8}$ is necessary. Diverse extrapolations of the structure function data at $10^{-4} < x < 10^{-8}$ differ by as much as 20% [31,32]. We adopted the CTEQ4 deep inelastic scattering (DIS) distribution [33] which is shown in Fig. 2. Recently, the neutrino cross section has been obtained based on the unified Balitskii-Fadin-Kuraev-Lipatov (BFKL) evolution equation at small x [34], and from a comparison with the CTQ4 DIS cross section discrepancies between 17% and 19% for EeV energies or above are observed.

Following Fig. 2 we can see that for energies above 10^6 GeV the differences between the neutrino and antineutrino cross sections can be neglected.

On the other hand, under the assumption that the interaction length has an exponential distribution

$$\frac{dN}{dz} = \exp\left[-\frac{z}{L_{int}(E_\nu)}\right], \tag{1}$$

the neutrino penetrates a depth z before interaction given by

$$z = -L_{int} \times \ln U, \tag{2}$$

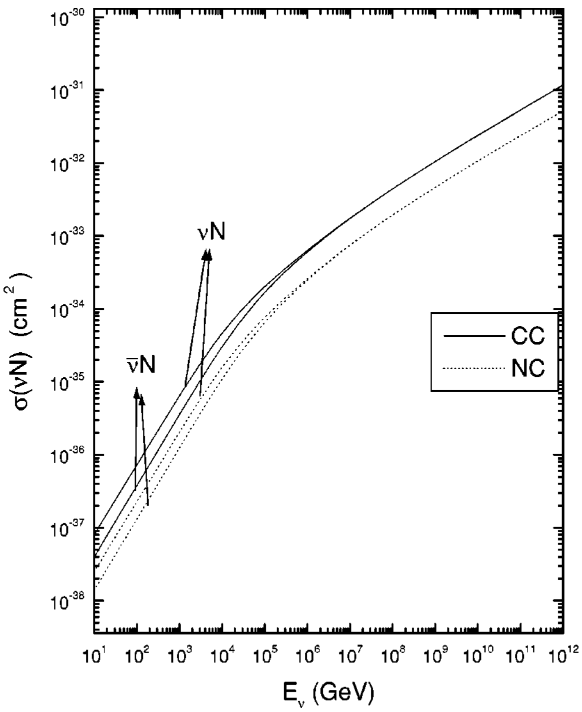

FIG. 2. CC and NC neutrino (antineutrino) nucleon cross section as a function of neutrino energy, according to the CTEQ4 DIS distribution [33].

where U is a random number in the interval [0,1], and L_{int} is the mean neutrino interaction length

$$L_{int}=\frac{1}{\sigma_{\nu N}(E_\nu)N_A}, \tag{3}$$

with $N_A=6.022\times10^{23}\ \mathrm{cm}^{-3}$ (water equivalent) the Avogadro number.

Following Fig. 2 it is found also that the probabilities of charged current and neutral current interactions are 0.667 and 0.333, respectively, and both are basically independent of energy. The neutrino energy E'_ν produced in the NC neutrino interaction or the lepton (μ or τ) energy E'_l produced in the CC neutrino interaction are related to the neutrino energy by $E'_\nu=(1-y)E_\nu$ and $E'_l=(1-y)E_\nu$, respectively. According to the CTEQ DIS distribution $\langle y\rangle\sim0.25$ in the EeV range [33,35]. A random selection of y from the $d\sigma/dy$ distribution, also taken from Refs. [33,35], is adopted in this work.

C. Ultrahigh energy neutrino sources

There are large uncertainties in the derivations of the neutrino flux from cosmological sources. On the other hand, until the last International Cosmic Ray Conference (Hamburg, August 2001) the searches for diffuse flux as well as point sources of ν_μ neutrinos by the AMANDA-II telescope [36] were negative and only upper limits had been reported in the energy region below 10^6 GeV. These experimental limits already exclude some models of AGN neutrinos.

Recently, upper limits on the ultrahigh energy electron neutrino flux from diverse sources have been reported by RICE (radio ice Cherenkov experiment) [37]. The Cherenkov radiation in the radio-wavelength region associated with ν_e-induced ice showers is detected by using a cubic array ($2.0\times10^6\ \mathrm{m}^3$) of dipole radio receivers at the South Pole and at 100–300 m depths colocated with the AMANDA experiment.

The RICE upper limits (95% confidence level) assuming an incident power law neutrino energy spectrum $dN/dE_\nu\sim E^{-\gamma}$ at EeV energies can be expressed as

$$\frac{dN}{dE_\nu}\sim7.93\times10^{-11}\left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-1.5}\ (\mathrm{GeV\,cm^2\,s\,sr})^{-1} \tag{4}$$

and

$$\frac{dN}{dE_\nu}\sim1.58\times10^{-5}\left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2.0}\ (\mathrm{GeV\,cm^2\,s\,sr})^{-1}. \tag{5}$$

From a comparison between the electronic neutrino flux model prediction and the corresponding RICE upper limits, it is possible to associate approximately the flux with spectral index 2.0 with GZK neutrinos and that with the index 1.5 with neutrinos from topological defects (TP neutrinos). On the other hand, fluxes in the energy region below EeV and with spectral index 3.5, 3.0, and 2.5 are linked with AGN neutrinos.

The RICE results are in agreement with the AGASA upper bound on the UHE ν_e flux for index 2.0 with 95% C.L. [38] obtained from ν_e-induced horizontal air showers.

D. Density profile of the Earth

If a neutrino is inside the Earth surface with a nadir angle θ_N, it travels in the Earth along a chord of length $l(\theta_N)=2R_T\cos\theta_N$, where R_T (=6371 km) is the Earth's radius. As the Earth is not a homogeneous medium the lengths of the chords are transformed to cm w.e. (centimeters of water equivalent). For instance, in this outline, the Earth's diameter ($=2\times R_T$) is equivalent to a column whose depth is 1.1×10^{10} cm w.e.

Seismological measurements of the Earth [39] provide knowledge of the Earth's density radial distribution $\rho(r)$ with good accuracy. The length of the chord for a certain nadir angle is obtained by a numerical integration:

$$l(\theta_N)=\int_0^{2R_T\cos\theta_N}\rho[r(z,\theta_N)]dz, \tag{6}$$

with the constraint condition

$$r^2=z^2+R_T^2-2zR_T\cos\theta_N. \tag{7}$$

We have determined the lengths of the chords for nadir angles in the region $0°\leq\theta_N\leq89°$ in steps of 1°, because $\theta_N=90°$ represents the horizon, where the Earth's atmosphere has a depth of $\sim3.6\times10^4$ cm w.e. Results of an analysis of neutrino propagation in the atmosphere near the horizon will be reported in a separate paper.

E. Continuous charged lepton energy loss and decay

The energy loss for EeV charged leptons is governed by radiation processes and they are bremsstrahlung, pair production, and photoproduction. The two first processes are (asymptotically) energy independent and in the very high energy region only the photoproduction processes is (weakly) energy dependent.

The energy loss by radiation is proportional to the lepton energy and large fluctuations are expected. However, we are interested only in leptons with ultrahigh energy threshold, around 10^8 GeV or above, and this characteristic permits us to make some simplifications in the analysis of the continuous lepton energy loss processes.

The average lepton energy loss rate is

$$-\left\langle \frac{dE}{dX} \right\rangle = \alpha(E) + \beta(E) \times E; \tag{8}$$

here X is the thickness of material (we adopt units of cm w.e.). At high energy the first term of Eq. (8) [$\alpha(E) \sim 2$ MeV(cm w.e.)$^{-1}$], which represents the ionization energy loss, is negligible and only the term $\beta(E)$ that represents the loss energy due to radiative processes is considered. It has a weak dependence on the energy.

In the case of muons the weak energy dependence of β_μ is taken from Fig. 9 (solid line) of Ref. [40]. We can see that at energies around 10^8 GeV, $\beta_\mu \sim 6.0 \times 10^{-6}$ (cm w.e.)$^{-1}$. Due to the relatively long lifetimes of muons $t_\mu = 2.197 \times 10^{-6}$ s, the probability P that a muon produced with an energy E survives until an energy E_{th} is basically $P = 1$. This means that before the muon decays it either loses its energy below the energy threshold or emerges from the Earth. Under these conditions, it is possible to calculate the muon range for initial energy E up to energy E_{th} as

$$R_\mu(E) = \int_{E_{th}}^{E} \left(\left\langle \frac{dE}{dX} \right\rangle \right)^{-1} dE \sim \frac{1}{\beta_\mu} \ln\left(\frac{E}{E_{th}} \right), \tag{9}$$

and fluctuations in the muon range can be obtained by using the relation

$$R_\mu = -R_\mu(E) \times \ln(U). \tag{10}$$

A more accurate scheme to take into account the fluctuations is reported in [41], because the introduction of a cutoff y_{cut} in the fraction of the muon energy loss is necessary to avoid divergences in the radiative cross section. The method requires large computing time, especially if small values of y_{cut} are chosen. However, in the very high energy region, the choice of the value of y_{cut} is not essential, and the relationship (10) is a good approach.

For the case of the τ lepton the situation is rather different because the tau has a lifetime ($t_\tau = 2.906 \times 10^{-13}$ s) considerably shorter than the muon lifetime. In order to take into account the continuous energy loss of the tau leptons in their propagation in the Earth, the following scheme has been implemented, including the exponential decay Monte Carlo algorithm reported by the Particle Data Group [42].

First, as the tau travels in the Earth via a chord, we divided the chord into bins of width

$$\Delta z = z_{i+1} - z_i = \frac{R_\tau(E)_{decay}}{n}, \tag{11}$$

where $R_\tau(E)_{decay}$ is the average range of the tau lepton in the absence of energy loss given by

$$R_\tau(E)_{decay} = \Gamma \times c t_\tau, \tag{12}$$

where $\Gamma = E/m_\tau$ is the Lorentz gamma factor, $ct_\tau = 86.93$ μm is the tau decay length, and n is a whole number. The larger this number, the better the accuracy (we adopt $n = 20$).

Second, the average energy loss can be expressed as

$$\beta(E) = -\frac{1}{E} \left\langle \frac{\Delta E}{\Delta z} \right\rangle \cong -\frac{1}{\Delta z} \ln\left(\frac{E_i}{E_{i+1}} \right); \tag{13}$$

at energies around 10^8 GeV $\beta_\tau \sim 0.8 \times 10^{-6}$ (cm w.e.)$^{-1}$ [43]. Following Eq. (13), we can see that in the present scheme the loss of energy of the τ is considered every time it crosses the bin. As the width of the bin, Δz, is smaller than $1/\beta_\tau$, the fluctuations can be taken into account according to the following scheme. If the value of β_τ changes by an amount $\Delta \beta_\tau$, the τ radiation length R_τ should be changed by an amount ΔR_τ,

$$\frac{\Delta \beta_\tau}{\beta_\tau} = \frac{\Delta R_\tau}{R_\tau} \approx \frac{\Delta z}{R_\tau}. \tag{14}$$

A random selection of β_τ from a Gaussian distribution with mean and variance given by the relations (13) and (14), respectively, permits us to obtain the fluctuation that is adopted in this work.

Third, to generate lepton decays between z_i and z_{i+1} according to $P = \exp[-z/R_\tau(E)]$, z is obtained as

$$z = -R_\tau(E) \times \ln[r_2 + U \times (r_1 - r_2)], \tag{15}$$

with $r_1 = \exp[-z_i/R_\tau(E)]$ and $r_2 = \exp[-z_{i+1}/R_\tau(E)]$.

Fourth, if $z < \Delta z$ the tau decays; otherwise we evaluate the energy loss and the survival probability in the next bin. The process is repeated until the tau lepton decays, giving another ν_τ neutrino, or its energy decreases below the threshold. If the τ is produced near the Earth's surface it can also emerge from the Earth.

III. THE OUTPUT

Let us now summarize the simulation output. As has already been indicated, we focus on the EeV energies, because in these regions or above, the fluorescence Auger telescope is not fully sensitive to conventional atmospheric cascades, and the background associated with the downward-going particles is reduced. On the other hand, so far, the neutrino flux upper limits reported by RICE at EeV energies are basically linked to the GZK and TP neutrinos.

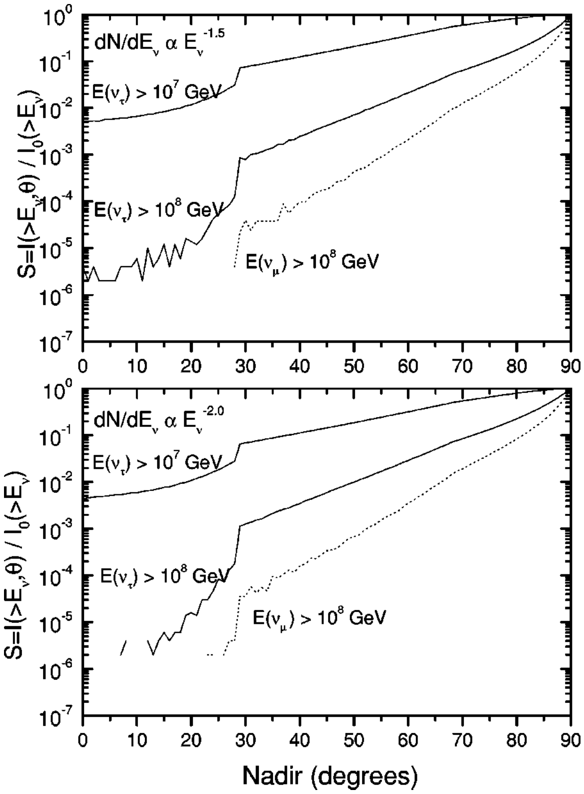

FIG. 3. Shadowing factor, defined as the relative intensity of transmitted neutrinos as a function of nadir angle for $E_\nu > 10^7 - 10^8$ GeV neutrino threshold energies. Solid lines are for ν_τ neutrinos and dotted lines are for ν_μ neutrinos. A power law neutrino spectrum is assumed with index $\gamma = 1.5$ in the upper figure and index $\gamma = 2.0$ in the lower figure [37].

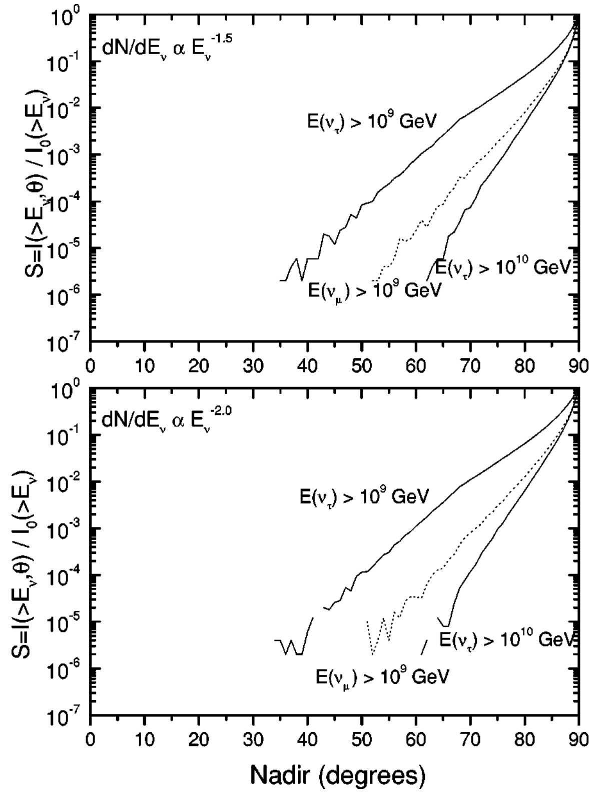

FIG. 4. Shadowing factor, defined as the relative intensity of transmitted neutrinos as a function of nadir angle for $E_\nu > 10^9 - 10^{10}$ GeV neutrino threshold energies. Solid lines are for ν_τ neutrinos and dotted lines are for ν_μ neutrinos. A power law neutrino spectrum is assumed with index $\gamma = 1.5$ in the upper figure and index $\gamma = 2.0$ in the lower figure [37].

A. Attenuation of UHE neutrino flux by the Earth

Under the assumption of isotropic neutrino fluxes at the Earth's surface, the attenuation of neutrinos traversing the Earth can be determined through a shadowing factor defined as the relative intensity of transmitted neutrinos:

$$S(>E_\nu, \theta_N) = \frac{I(>E_\nu, \theta_N)}{I_0 \ (>E_\nu)}, \tag{16}$$

where $I_0\ (>E_\nu)$ is the initial neutrino flux at the Earth's surface. The shadowing factor as a function of the nadir angle is determined for an incident neutrino spectrum such as the power law $dN/dE_\nu \sim E_\nu^{-\gamma}$ and for two different indices $\gamma = 1.5$ and $\gamma = 2.0$ as shown in Fig. 3 (upper and lower) for neutrino threshold energy $10^7 - 10^8$ GeV and Fig. 4 (upper and lower) for a threshold of $10^9 - 10^{10}$ GeV. In all cases, the solid lines are for ν_τ and the dotted lines are for ν_μ. Following these figures, it is possible to see that the relative intensity of transmitted neutrinos, especially for the case of ν_τ, is sensitive to the radial density distribution of the Earth.

The superdense Earth's core appears in the neutrino shadowing factor. This suggests that the ν_τ attenuation by the Earth can be used to obtain the incident neutrino spectrum. Once the spectrum is known, it is possible to do a type of "neutrino tomography" of the Earth and to know, for example, the fine structure of the central Earth's core better. The determination of the Earth's internal density through astrophysical observation of energetic neutrinos as well as the location of neutrino sources by core occultation have been proposed in several papers [44–47].

The behavior of the neutrino attenuation also permits us to know the relative flavor composition in the neutrino beam and can be a signature to obtain evidence of the neutrino oscillation in cosmological neutrinos and to obtain the oscillation parameters. It is observed too that the attenuation of ν_τ is very sensitive to the neutrino threshold energy; the attenuation increases as the energy increases. For an energy threshold above 10^9 GeV the central Earth's core is opaque for them. While the central Earth's core is already opaque for ν_μ at 10^7 GeV, in this case, the neutrino regeneration process is due only to the NC interaction ($\sim$33%) and that is translated into a very hard attenuation.

B. ν-induced upward-going leptons

The ν-induced upward-going leptons have been determined by using the RICE upper limits for ν_e neutrinos with an incident spectrum like a power law with indices $\gamma = 1.5$ and $\gamma = 2.0$. Under the assumption that the dominant mechanism for neutrino production is the hadron decay, the relative populations of neutrino flavors will be $\nu_\mu : \nu_e = 2:1$.

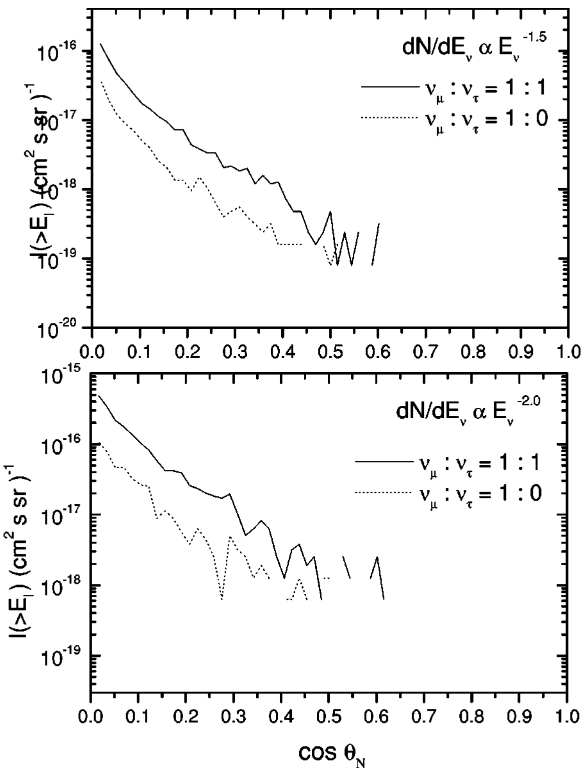

FIG. 5. Upper limits of ν-induced lepton integral flux ($E_l > 10^8$ GeV) as a function of the cosine of the nadir angle. Solid lines are for $\nu_\mu:\nu_\tau = 1:1$ and dotted lines are for $\nu_\mu:\nu_\tau = 1:0$, both at the Earth's surface. A power law neutrino spectrum is assumed with index $\gamma = 1.5$ (upper figure) and index $\gamma = 2.0$ (lower figure).

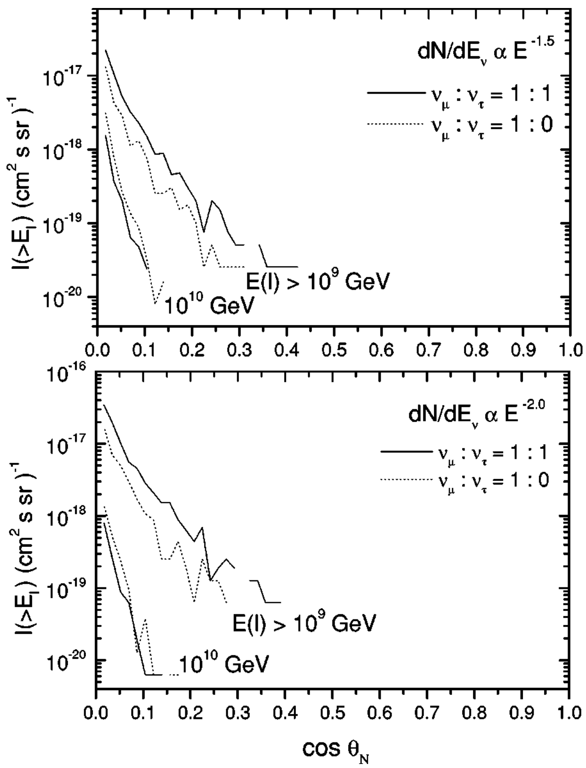

FIG. 6. Upper limits of ν-induced lepton integral flux ($E_l > 10^9$ GeV and 10^{10} GeV) as a function of the cosine of the nadir angle. Solid lines are for $\nu_\mu:\nu_\tau = 1:1$ and dotted lines are for $\nu_\mu:\nu_\tau = 1:0$, both at the Earth's surface. A power law neutrino spectrum is assumed with index $\gamma = 1.5$ (upper figure) and index $\gamma = 2.0$ (lower figure).

It is known that the most plausible explanation for the anomalies in the lepton ratios produced by atmospheric neutrinos and observed by underground experiments is the oscillation of muon neutrinos to tau neutrinos [48]. The probability of neutrino oscillation $P_{\nu_\mu \to \nu_\tau}$ traveling through the Earth (path $\leqslant 2\times R_T$) is expected to be less than 10^{-3}.

However, the probability of oscillation can be very large ($\simeq 1$) for extragalactic UHE neutrinos, traveling from their sources to the Earth. A more realistic inclusion of this effect in the simulation requires a more precise determination of the oscillation parameters and is the main goal of long baseline accelerator experiments. The effect of the oscillation must be a modification in the neutrino flavor composition at the Earth's surface. We assume the two cases $\nu_\mu:\nu_\tau = 1:0$, $1:1$.

If a ν-induced upward-going charged lepton (μ or τ) emerges from the Earth, the last neutrino interaction in the Earth was via the CC interaction. Figure 5 shows the upper limit of the ν-induced lepton integral flux ($E_l > 10^8$ GeV) as a function of the cosine of the nadir angle. The calculations are for two cases, $\nu_\mu:\nu_\tau = 1:1$ (solid lines) and $\nu_\mu:\nu_\tau = 1:0$ (dotted lines), both at the Earth's surface. The effect of the neutrino regeneration process is evident due to the NC and CC interactions, because the lepton flux for $\nu_\mu:\nu_\tau = 1:1$ is larger than the lepton flux for $\nu_\mu:\nu_\tau = 1:0$.

However, at nadir angles close to but below the horizon the thickness of the chords is compatible with the neutrino interaction length. If a ν_μ interacts in this region via the NC it can emerge from the Earth without becoming a muon, while a ν_τ neutrino can emerge from the Earth without becoming a tau even if the interaction is via the CC. The effect is a reduction of the difference between the fluxes with $\nu_\mu:\nu_\tau = 1:1$ and $\nu_\mu:\nu_\tau = 1:0$. The effect increases with the charged lepton threshold as is shown in Fig. 6. In this case the flux for $\nu_\mu:\nu_\tau = 1:0$ is larger than the flux for $\nu_\mu:\nu_\tau = 1:1$.

C. Event rates

In addition to knowledge of the ν-induced lepton fluxes, an estimate of event rates requires knowledge of the effective aperture of the telescope for their detection. Due to the low fluxes expected, telescopes with very large apertures are required to gather even modest statistics. Nowadays the high resolution (HiRes) Fly's Eye fluorescence detector is in operation. The effective aperture for almost horizontal UHE τ leptons through their decay to induced showers has been reported [49].

As has already been commented, there is also a more ambitious project (AUGER project) in progress to study cosmic rays with energy above 10^{19} eV. It will use hybrid techniques: a surface array to measure the lateral distribution of the air showers at the ground, and a fluorescence detector to measure the longitudinal development of the shower.

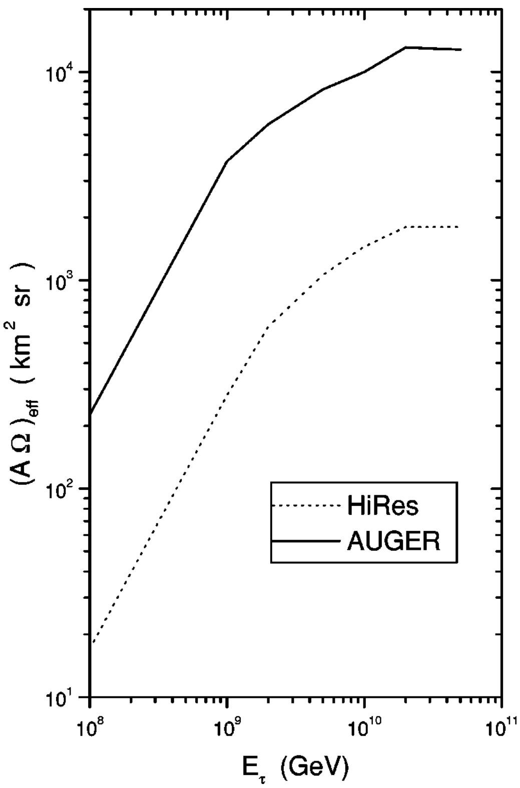

FIG. 7. Energy dependence of the effective aperture $(A\Omega)_{eff}$ for ν_τ-induced upward-going taus through their decay to induced electromagnetic showers.

The configuration of the AUGER fluorescence detector is such that the aperture is expected to be more than ten times greater than the HiRes telescope. The result is obtained from a comparison of expected event rates between the HiRes and AUGER telescopes reported in [1,50]. Figure 7 shows a comparison of the energy dependence of the effective aperture $(A\Omega)_{eff}$ of the HiRes and AUGER telescopes for neutrino-induced τ leptons and detected through their decay to an electromagnetic shower.

By using the simulation output of the ν-induced lepton flux expressed as

$$F(E_\tau,\cos\theta_N)=\frac{d\phi_\tau(E_\tau,\cos\theta_N)}{d\cos\theta_N dE_\tau}, \tag{17}$$

the rate is calculated as

$$\text{rate}=2\pi TD\int_1^0 \cos\theta_N d\cos\theta_N \times\int_{E_\tau}^{\infty} dE_\tau F(E_\tau,\cos\theta_N)(A\Omega)_{eff}. \tag{18}$$

We assume for the rate calculation a year ($T=3.15\times10^7$ s) running with duty cycle of 10% ($D=0.1$), because dark (moonless) nights are necessary to operate the fluorescence detectors.

In Table I we show the event rates thus obtained for several sets of $\nu_\mu:\nu_\tau$ and lepton energies. The rates have been calculated by using the RICE upper limits of the UHE neutrino flux. According to RICE, these upper limits are some 2–3 orders of magnitude above the model predictions.

IV. CONCLUSIONS

In this paper we examined some aspects of the propagation of UHE neutrinos in the Earth through a Monte Carlo simulation. Special attention is given to the inclusion of two different flavor compositions in the incident neutrino flux, due to the possible neutrino oscillation ($\nu_\mu\to\nu_\tau$ mixing). The aim of this study is to obtain the expected UHE ν-induced upward-going charged lepton flux (emerging from the Earth), taking into account explicitly the NC and CC neutrino interactions as neutrino regeneration processes (see Fig. 1) and their expected rates by using the fluorescent HiRes and AUGER telescopes.

The shadowing factor defined as the relative intensity of transmitted neutrinos is obtained for ν_μ and ν_τ as a function of nadir angle. The results are shown in Fig. 3 and Fig. 4. We can see that the shadowing factor has a strong dependence on the neutrino threshold energy. At PeV energies the Earth is transparent to ν_τ [30] since the τ produced in a CC ν_τ interaction always decay back into ν_τ before losing significant energy. However, the energy loss by radiation processes is proportional to the τ energy, and for energies above 10^7 GeV the τ energy loss can be very significant (below the threshold) especially when the propagation is in a high density medium such as the Earth's core. Exactly in this area the absorption of ν_τ is larger, as is shown in Fig. 3. These results suggest that the ν_τ neutrino attenuation can be used to obtain the incident neutrino spectrum. The calculations have been made using an algorithm implemented in order to take into account the continuous energy loss for τ leptons (see Sec. II E).

Using the incident upper limits of UHE neutrino flux from

TABLE I. Upper limits of annual event rates for neutrino-induced UHE upward-going leptons expected at the AUGER fluorescence detectors, taking into account a power law neutrino incident (RICE) spectrum with indices $\gamma=1.5$ and $\gamma=2.0$ and two sets of $\nu_\mu:\nu_\tau$.

	$\nu_\mu:\nu_\tau=1:1$		$\nu_\mu:\nu_\tau=1:0$	
E_l (GeV)	$dN/dE_\nu\sim E_\nu^{-1.5}$	$dN/dE_\nu\sim E_\nu^{-2.0}$	$dN/dE_\nu\sim E_\nu^{-1.5}$	$dN/dE_\nu\sim E_\nu^{-2.0}$
$>10^9$	30.81	49.04	14.38	21.36
$>10^{10}$	2.16	1.28	4.04	2.33

Ref. [37] we obtain the integrated ν-induced upward-going charged leptons as a function of the cosine of the nadir angle. The charged lepton flux emerging from the Earth depends on the slope of the incident neutrino flux as well as on the incident neutrino flavor ratio. It is clear that the above results are in part due to the neutrino regeneration processes that for the case of ν_τ are from both CC and NC interactions. The effect at nadir angles near the horizon is a reduction of the emergent tau lepton flux, because the ν_τ regeneration process competes with the process of ν_τ neutrino conversion to τ leaving the Earth. The effect is larger for high lepton energy threshold (above 10^{10} GeV). In this case the ν_μ-induced muon flux ($\nu_\mu:\nu_\tau=1:0$) leaving the Earth becomes dominant over the lepton flux ($\nu_\mu:\nu_\tau=1:1$) (see Fig. 6). The effect can also be observed in the expected event rates (see Table I). We point out that the RICE neutrino flux upper limits used in the calculation (input) are some 2–3 orders of magnitude above model predictions.

In short, the effect of the inclusion of the charged current neutrino interaction as a regenerative neutrino process reduces the rates of τ leptons in the range of 10^{10} GeV or above. Even so, the expected ν-induced upward-going leptons still give significant event rates, capable of being observed in the next round of fluorescence telescopes like the AUGER project.

We believe that the original question, ''How opaque is the Earth to UHE neutrinos?,'' has been answered at least in part and can be improved with a better understanding of neutrino physics. In this way, the neutrino attenuation in the Earth appears to be an excellent signature to obtain evidence of neutrino oscillations of cosmological origin in the very high energy region. Future investigations already begun with BAIKAL's and AMANDA's pioneer work will tell us more about the nature of neutrino particles and their cosmological sources. Theoretical developments as well as experimental data are called for.

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[1] J.W. Cronin, Nucl. Phys. B (Proc. Suppl.) **97**, 3 (2001).
[2] A.V. Olinto, Nucl. Phys. B (Proc. Suppl.) **97**, 66 (2001).
[3] M. Takeda *et al.*, Phys. Rev. Lett. **81**, 1163 (1998).
[4] P. Battachargee and G. Sigl, Phys. Rep. **327**, 109 (2000).
[5] D.J.H. Chung, E.W. Kolb, and A. Riotto, Phys. Rev. D **60**, 063504 (1999).
[6] E. Waxman and J. Bahcall, Phys. Rev. Lett. **78**, 2292 (1997).
[7] M. Puch *et al.*, Nature (London) **160**, 477 (1992).
[8] J. Quinn *et al.*, Astrophys. J. Lett. **456**, L83 (1996).
[9] R.J. Protheroe, astro-ph/9607165.
[10] K. Mannheim, Astropart. Phys. **3**, 295 (1997).
[11] F.W. Stecker *et al.*, Phys. Rev. Lett. **66**, 2697 (1991).
[12] M. Mori *et al.*, Phys. Lett. B **210**, 89 (1991).
[13] IMB Collaboration, R. Becker-Szendy *et al.*, Phys. Rev. Lett. **69**, 1010 (1992).
[14] M.M. Boliev *et al.*, in *Proceedings of the 3rd International Workshop on the Neutrino Telescope*, Venice, Italy, edited by M. Baldo Ceolin (University of Padua, Padua, 1991), p. 235.
[15] MACRO Collaboration, M. Ambrosio *et al.*, in Proceedings of the 24th ICRC, Rome, Italy, 1995, Vol. 1, p. 730.
[16] Frejus Collaboration, Ch. Berger *et al.*, Phys. Rev. D **40**, 2163 (1989).
[17] Soudan Collaboration, M. Goodman, in Proceedings of the 27th ICRC, Hamburg, Germany, 2001, p. 1085.
[18] J.G. Learned and S. Pakvasa, Astropart. Phys. **3**, 267 (1995).
[19] V.A. Balkatanov *et al.*, Astropart. Phys. **14**, 61 (2000).
[20] E.C. Andrés, Nucl. Phys. B (Proc. Suppl.) **77**, 474 (1999).
[21] G.M. Frichter, J.P. Ralston, and D.W. McKay, Phys. Rev. D **53**, 1684 (1996); D. Seckel *et al*., in Proceedings of the 27th ICRC [17], p. 1137.
[22] J.G. Learned, Philos. Trans. R. Soc. London **A346**, 99 (1994).
[23] P. Monacelli, Nucl. Phys. B (Proc. Suppl.) **70**, 442 (1998).
[24] F. Halzen, hep-ex/9801009; Nucl. Phys. B (Proc. Suppl.) **70**, 409 (1999).
[25] F. Halzen and D. Hooper, Rep. Prog. Phys. **65**, 1025 (2002).
[26] Pierre Auger Project Design Report, Fermilab report, 1997, http://www.auger.org
[27] Telescope Array Design Report, 2000, http://www-ta.icrr.u-tokyo.ac.jp
[28] F. Halzen, hep-ex/9904216.
[29] T.K. Gaisser, F. Halzen, and T. Stanev, Phys. Rep. **258**, 173 (1995).
[30] F. Halzen and D. Saltzberg, Phys. Rev. Lett. **81**, 4305 (1998).
[31] G.M. Frichter, D.W. McKay, and J.P. Ralston, Phys. Rev. Lett. **74**, 1508 (1995).
[32] M. Glück, E. Reya, and A. Vogt, Eur. Phys. J. C **5**, 461 (1968).
[33] R. Gandhi, C. Quigg, M.H. Reno, and I. Sarcevic, Phys. Rev. D **58**, 093009 (1998).
[34] J. Kwiecinski, A.D. Martin, and A.M. Stasto, Acta Phys. Pol. B **31**, 1273 (2000).
[35] R. Gandhi, C. Quigg, M.H. Reno, and I. Sacevic, Astropart. Phys. **5**, 81 (1996).
[36] AMANDA Collaboration, S. W. Barwick *et al.*, in Proceedings of the 27th ICRC [17], p. 1101.
[37] RICE Experiment, I. Kravchenko *et al.*, astro-ph/0206371.
[38] AGASA Collaboration, S. Yoshida *et al.*, in Proceedings of the 27th ICRC HE [17], p. 1142.
[39] A.M. Dziewonski and D.L. Anderson, Phys. Earth Planet. Inter. **25**, 297 (1981).
[40] P. Lipari and T. Stanev, Phys. Rev. D **44**, 3543 (1991).
[41] I.A. Sokalski, E.V. Bugaev, and I. Klimushin, Phys. Rev. D **64**, 074015 (2001).
[42] Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002), p. 240.

[43] S. Iyer Dutta, M.H. Reno, I. Sarcevic, and D. Seckel, Phys. Rev. D **63**, 094020 (2001).
[44] C. Kuo *et al.*, Earth Planet. Sci. Lett. **133**, 95 (1995).
[45] T.L. Wilson, Nature (London) **309**, 38 (1984).
[46] A. Roberts, Rev. Mod. Phys. **64**, 259 (1992).
[47] H.J. Crawford *et al.*, in Proceedings of the 24th ICRC [15], p. 804.
[48] Super-Kamiokande Collaboration, Y. Fukuda *et al.*, Phys. Rev. Lett. **81**, 1562 (1998).
[49] J.L. Feng, P. Fisher, W. Wilczek, and T.M. Yu, Phys. Rev. Lett. **88**, 161102 (2002).
[50] R.C. Shellard, J.C. Dias, and M.G. Amaral, Rev. Fis. Apl. Instrum. **14**, 86 (1999).