UHE and EHE neutrino induced taus inside the Earth

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Abstract

Tau neutrinos interacting inside the Earth produce $\tau$ leptons which thereafter can decay inside the atmosphere. The propagation of extremely energetic $\nu_{\tau}$'s and $\tau$'s through the Earth is studied by means of a detailed Monte Carlo simulation, taking into account all major mechanisms of $\nu_{\tau}$ interactions and $\tau$ energy loss as well as decay modes. The rates of $\tau$'s emerging from the Earth are determined as a function of $\tau$'s energy for several cosmic neutrino models.

Keywords: high energy neutrinos, tau neutrino, high energy cosmic rays.
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1 Introduction

Cosmic neutrinos give a unique opportunity to open a new observational window in the field of Astrophysics and Cosmology. The detection of such particles, not deflected or absorbed during their intergalactic path, could be revealing for the identification of sources of Ultra and Extreme High Energy Cosmic Rays (UHECR and EHECR). The detection of such ultra and extreme high energy neutrinos is a challenge as it demands a very large sensitive area. The experiments of the upcoming generation plan to use underwater-underice Cherenkov detectors [1] and large field-of-view atmospheric fluorescence detectors [2] [3].

One of the best evidence of cosmic neutrinos would be the detection of upstream showers/particles emerging from the Earth. For this kind of events the atmospheric muon and primary charged cosmic ray background would be completely suppressed. On the other hand this signature can hardly be observed at extreme energy because the rise of weak cross sections entails the opacity of the Earth with respect to neutrino propagation [4] [5] [6].

The problem of muon neutrino propagation through the Earth can be solved by taking properly into account neutrino-nucleon scattering inside the Earth, either by Monte-Carlo simulation [5] or by approximate iterative solution of the relevant transport equation [6]. It has been recently pointed out in references [7] [8] [9] [10] [6] that the behaviour of $\nu_\tau$-neutrinos, whose existence should be guaranteed in a neutrino-oscillation scenario, should be significantly different from $\nu_\mu$ and $\nu_e$. Whilst muon and electron neutrinos are practically absorbed after one charged current (CC) interaction, the $\tau$ lepton created by the $\nu_\tau$ interaction may decay in flight before losing too much energy, thereby generating a new $\nu_\tau$ with comparable energy. Hence ultra high energy $\tau$-neutrinos and $\tau$’s should emerge from the Earth instead of being absorbed. For a correct evaluation of the energy spectrum of $\nu_\tau$’s and $\tau$’s emerging from the Earth, one has to properly take into account $\nu_\tau$ interactions as well as $\tau$ energy loss and decay. An analytical approach similar to that used in [1] for $\nu_\mu$ has been proposed by S. Iyer et al. [10] neglecting $\tau$ energy loss. This approach holds as long as energy does not exceed $10^{16}$ eV because above this energy $\tau$ interaction length becomes comparable with $\tau$ decay length [6].

In reference [6] a detailed Monte Carlo calculation of $\nu_\tau-\tau$ system propagation through the Earth has been performed for energy up to $10^{20}$ eV including the $\tau$ energy loss contribution, with special emphasis on the initial $\nu_\tau$ spectrum deformation as a function of the zenith angle of the emerging particle. As pointed out in ref. [11] [12] [13] the tau leptons, created by CC $\nu_\tau$ interactions inside the Earth, because of their relative long decay length at high energy, could emerge from the Earth surface and eventually decay inside the atmosphere (fig. 1). Such kind of events could be detected by atmospheric shower detectors as upward going showers. In reference [11] an overview of the physics processes involved in case of $\tau$’s emerging from Earth and mountains is presented, suggesting the possibility of the detection of such events. In reference [12] the rate of expected events in the Auger detector is given on the basis of a Monte Carlo simulation while in reference [13], and more extensively in the present work, the results of a detailed Monte Carlo simulation are presented in a general framework, giving the rate of emerging $\tau$’s for unit Earth surface above a given minimum energy, from $10^{14}$ eV to $10^{22}$ eV and for a large variety of neutrino fluxes. The results are presented considering two different calculations of $\tau$ photomnuclear
cross section and comparing directly the rate of emerging τ events to the rate of Extensive Air Showers (EAS) produced by neutrinos interacting inside the atmosphere.

## 2 Lepton interactions

Deep inelastic neutrino-nucleon scattering is the dominant interaction of energetic neutrinos into conventional matter. Charged and neutral current differential cross sections [3] used for this simulation [4] have been calculated in the framework of QCD improved parton model. Since a large contribution to cross sections comes from the very low $x$ region, laying beyond present accelerator domain, an extrapolation of parton distribution at very low $x$ ($x \approx 10^{-8}$) is necessary. We have used the parton distribution set CTEQ3-DIS [14], available in the program library PDFLIB [15], with NLO-DGLAP formalism used for the evolution with the invariant momentum transfer between the incident neutrino and outgoing lepton ($-Q^2$) and assuming for very low $x$ the same functional form measured at $x = \mathcal{O}(10^{-5})$. Even if more sophisticated approaches for low $x$ extrapolation have been developed using dynamical QCD [16] the results for cross section calculations (fig. 2) do not differ more than 10% from the approach taken here with CTEQ3-DIS plus “brute force” extrapolation [5] [16].

The electromagnetic interactions of muons with matter, at the considered energies, are dominated by radiative processes rather than ionisation [17]. Cross sections for electromagnetic radiative processes of $\tau$ are lower than muon’s, yet radiative interactions remain the dominant process for $\tau$ energy loss. The cross sections used for radiative interactions of $\tau$ leptons are based on QED calculation for bremsstrahlung [18] and for direct pair production [19] while for photonuclear (PH) interactions references [20] [21] have been used. For all aforementioned processes we have implemented stochastic interactions for $\nu = (E_i - E_f)/E_i \geq 10^{-3}$ and a continuous energy loss approximation for $\nu = (E_i - E_f)/E_i \leq 10^{-3}$, where $E_i$ and $E_f$ are $\tau$ energies before and after the interaction respectively.

It is worth mentioning that bremsstrahlung cross section scales as the inverse square of lepton mass $m_l$ whereas direct pair production and photonuclear interaction cross sections approximately scale according to $1/m_l$ [21] [22]. As a consequence the dominant processes for $\tau$ lepton energy loss are direct pair production and even more photonuclear interaction rather than bremsstrahlung photon radiation [22]. The calculation of cross sections in case of PH interactions has been explicitly performed by Bezrukov and Bugaev [21] only for muons while the recent calculation performed by Iyer et al. [21] includes the $\tau$ lepton. The two calculations, as far as $\tau$ lepton is concerned, differ by almost one order of magnitude at extreme energy (fig. 3) and therefore the rate of emerging $\tau$’s is expected to be sizably affected. The $\tau$ decay has been simulated by using the TAUOLA package [23]. The Monte Carlo simulation has been performed following neutrinos and charged leptons along their path inside the Earth. The Earth model considered is the preliminary Earth model of ref. [24], applied to a perfectly smooth Earth surface with the outer layer made either of “standard rock” or water. For what concerns the Earth composition we have used “standard rock” ($Z = 11, A = 22$) for the crust and the mantle and iron ($Z = 26, A = 55.8$) for the core.
3 Neutrino induced $\tau$’s inside the Earth

3.1 Effective depth

Tau neutrinos interacting in proximity of Earth’s surface can produce $\tau$’s which thereafter may survive until they get into the atmosphere. The production of $\tau$’s which emerge from the Earth is driven by two, not completely separated, mechanisms. The first is the propagation of neutrinos through the Earth, which determines the amount and the energies of neutrinos approaching the crust just below the Earth’s surface. The second is the production and propagation of $\tau$’s in the crust just below the Earth’s surface. In the next section we will show the results of the simulation concerning the whole “story” of propagation of leptons, while in this section we focus the attention only on the second mechanism. Here we want to evaluate the thickness of the Earth’s Crust to be considered active for production of emerging $\tau$’s as a function of the energy of the $\tau$ neutrino as it approaches the emerging surface. Hence no propagation through the whole Earth is considered in this section. The results given here can be useful also for calculations of the rate of horizontal $\tau$’s emerging from mountains.

As a first approximation, the $\tau$ decay length $\gamma_\beta c \tau$ can be used to estimate the effective depth, defined as the thickness of Earth’s Crust to be considered as a source for such emerging $\tau$’s.

An accurate calculation of the effective depth has to properly take into account the differential cross sections describing the neutrino interactions and tau energy loss and decay. The total neutrino cross section influences the number of produced $\tau$’s but not the effective depth. We have simulated a number $N_{\nu \int}$ of $\nu_\tau$ CC interactions induced by vertical neutrinos and uniformly distributed along a column of Earth’s Crust within a depth $L$. One can then define the effective depth as the limit:

$$L_{\text{eff}} = \lim_{L \to \infty} L \epsilon(L)$$

where $\epsilon(L)$ is the number of emerging $\tau$’s divided by the number of simulated $\nu$ interactions $N_{\nu \int}$. The effective depth is shown in fig. 4 where it is compared with the $\tau$ decay length with $E_\tau = E_\nu$. At low energy, $L_{\text{eff}}/E_\nu$ slowly increases with $E_\nu$ because the fraction of energy carried by the $\tau$ increases with energy in the CC $\nu_\tau$ interactions. Above $\approx 10^{17}$eV the effect of $\tau$ energy loss becomes relevant and the energy degradation of $\tau$’s prevents a sizeable fraction of them from reaching the surface. Consequently, $L_{\text{eff}}/E_\nu$ drops and $L_{\text{eff}}$ roughly approaches the value of $\tau$ radiation length in the outer layer of Earth’s Crust ($\approx 10$ km for the highest energies and PH in ref. [20]).

3.2 Effective aperture

In this section the calculation of the fluxes of $\tau$’s emerging from the Earth has been performed by means of a full simulation of $\nu_\tau - \tau$ system propagation through the Earth.

Fig. 5 shows the result of the simulation for an isotropic flux of $\nu_\tau$’s impinging on the Earth with an energy $E_\nu = 10^{20}$eV. Most $\tau$’s with zenith angles larger than $94^0$ emerge with energies $10^{16}$eV-$10^{17}$eV for which, assuming PH interaction in ref. [20], $\tau$ decay length becomes comparable with its radiation length.
For zenith angles corresponding to a path length in the Earth larger than $\nu_\tau$ interaction length in the Crust ($L_{\nu_{int}} \approx 70$ km for $E_\nu = 10^{20}$ eV), neutrinos interact far away from the Earth surface, and the produced $\tau$'s lose energy and decay before getting out. Owing to this mechanism, the energy of the $\nu_\tau$-$\tau$ system decreases as zenith angle increases (fig. 5) and the probability for a $\nu_\tau$ to emerge as a $\tau$ drops at large zenith angles. For $\nu_\tau$ energy lower than $E_\nu = 10^{20}$ eV the behaviour of the $\nu_\tau$-$\tau$ system is similar but shifted to larger values of zenith angles.

The number of emerging $\tau$'s with energy larger than $E_{min}$ (minimum energy) from an Earth infinitesimal surface $dS$ can be calculated in a unidimensional approach as:

$$dN_\tau(E_\tau \geq E_{min}) = \int_{E_\nu \geq E_{min}} d^2N(E_\nu) P_{\nu_\tau \rightarrow \tau}(\cos(\Theta), E_\nu, E_{min}) dS |\cos(\Theta)| d\Omega dE_\nu$$

(1)

where $d^2N(E_\nu)$ is the cosmic $\tau$ neutrino flux, $\Theta$ is the zenith angle of the emerging particles, $P_{\nu_\tau \rightarrow \tau}(\cos(\Theta), E_\nu, E_{min})$ is the probability that a $\nu_\tau$ impinging on the Earth surface will emerge as a $\tau$ with an energy $E_\tau \geq E_{min}$. Assuming a spherical shaped Earth and an isotropic neutrino flux, Eq. 1 turns into:

$$N_\tau(E_\tau \geq E_{min}) = S \int_{E_\nu \geq E_{min}} d^2N(E_\nu) \int P_{\nu_\tau \rightarrow \tau}(\cos(\Theta), E_\nu, E_{min}) |\cos(\Theta)| d\Omega dE_\nu$$

(2)

where $S$ is a portion of Earth surface.

One can now define an effective aperture $A_{eff}(sr)$ containing all the physics of leptons propagation:

$$A_{eff}(E_\nu, E_{min}) = \int P_{\nu_\tau \rightarrow \tau}(\cos(\Theta), E_\nu, E_{min}) |\cos(\Theta)| d\Omega$$

so that Eq. 2 reads:

$$N_\tau(E_\tau \geq E_{min}) = S \int_{E_\nu \geq E_{min}} d^2N/E_\nu d\Omega A_{eff}(E_\nu, E_{min}) dE_\nu$$

(3)

The effective aperture $A_{eff}$ does not depend on neutrino fluxes or detector performance and allows a simple and straightforward calculation of the number of emerging $\tau$'s for any cosmic neutrino flux and detector sensitive area. It must be pointed out that in the definition of $P_{\nu_\tau \rightarrow \tau}(\cos(\Theta), E_\nu, E_{min})$ we also constrain the emerging $\tau$ to decay within an atmospheric slant depth larger than 1000 g/cm$^2$. This condition guarantees the full size formation of an EAS after $\tau$ decay.

The results for the effective aperture by using Bezrukov and Bugaev PH cross section are shown in figs. 6 and 7. They seem to be in fairly good agreement with those in ref. [12] for the Auger detector, though the contribution of the effective Auger sensitivity can not be completely unfolded from quoted results using available informations.

An effective aperture $A_{eff}^{\nu_\tau}$ for downwards going $\nu_e$ CC interactions in the atmosphere is also shown in figs. 6 and 7. For this kind of events, the energy of produced EAS is
the same as $\nu_e$. For an isotropic neutrino flux, the number of EAS induced by $\nu_e$ CC interactions within the atmospheric mass overhanging a portion of Earth surface $S$ is given by:

$$N_{EAS}^{\nu_e}(E_{EAS} \geq E_{\text{min}}) = S \int_{E_\nu \geq E_{\text{min}}} \frac{d^2 N}{dE_\nu d\Omega}(E_\nu) \sigma_{CC}(E_\nu) N_A p 2\pi dE_\nu$$

where $p$ is the atmospheric pressure (column density) at ground level, $N_A$ is the Avogadro number, $\frac{d^2 N}{dE_\nu d\Omega}(E_\nu)$ is the cosmic electron neutrino flux and $\sigma_{CC}(E_\nu)$ is the neutrino CC cross section on isoscalar target. Again, we can define an effective aperture:

$$A_{\nu e}^{\nu_e}(E_\nu) = 2\pi N_A p \sigma_{CC}(E_\nu)$$

such that the number of $\nu_e$ CC interactions can be written as:

$$N_{EAS}^{\nu_e}(E_{EAS} \geq E_{\text{min}}) = S \int_{E_\nu \geq E_{\text{min}}} \frac{d^2 N}{dE_\nu d\Omega}(E_\nu) A_{\nu e}^{\nu_e}(E_\nu) dE_\nu$$

$A_{\nu e}^{\nu_e}(E_\nu)$ increases with energy following the rise of neutrino cross section. At low energies ($E_\nu \ll 10^{18}$eV) the rise with energy of $A_{\nu e}^{\nu_e}$ for emerging $\tau$’s is steeper than the rise of $A_{\nu e}^{\nu_e}(E_\nu)$ because both the increase of $\nu$ cross section and the increase of $\tau$ decay length contribute to enlarge $P_{\nu \rightarrow \tau}(\cos(\Theta), E_\nu, E_{\text{min}})$. $A_{\nu e}^{\nu_e}(E_\nu)$ keeps increasing as long as the increase of $\nu$ cross section enhances the production of $\tau$’s in the Earth. Around $E_\nu \approx 10^{18}$eV the cross section of neutrinos is so high that the probability for neutrinos to have at least one interaction inside the Earth is close to one for most zenith angles and the point of first $\nu$ interaction in the Earth is likely to be far from the emerging point (this latter effect is responsible for the slow decrease of $A_{\nu e}^{\nu_e}$ between $10^{19}$eV and $10^{20}$eV in fig 6). Moreover, the increase of $\tau$ decay length with energy prevents some of the extreme high energy events from producing a detectable shower into the atmosphere (only $\tau$’s decaying within 1000 g/cm$^2$ slant depth are retained). Due to these mechanisms, the value of $A_{\nu e}^{\nu_e}$ at extreme high energies shows an almost flat dependence on energy and strongly depends on the required $E_{\text{min}}$.

The effect of decay length selection at extreme energies is shown in fig 8 while fig. 4 shows the $A_{\nu e}^{\nu_e}$ in case of an outer layer of Earth’s Crust made of water and 3 km thick. Due to the reduction of target mass, the values of $A_{\nu e}^{\nu_e}$ in fig. 4 are lower, at low energies, than those in fig. 3. For energies $E_\nu \geq 10^{18}$eV, where $A_{\nu e}^{\nu_e}$ mainly depends on $\tau$ radiation length in the outer Earth’s Crust, the values in fig. 4 are larger than those in fig. 3.

The angular distributions of emerging $\tau$’s are shown in fig. 9. As the initial neutrino energy increases, the maximum of the angular distribution moves towards 90° zenith angle.

In fig. 10, the effective apertures calculated using the recent evaluation of $\tau$ PH cross section given in ref. [21] are compared with the effective aperture of fig. 6. The higher value of $\tau$ energy loss (fig 3) gives rise to a suppression of emerging $\tau$’s for the highest energies. Moreover, $A_{\nu e}^{\nu_e}$ decreases at extreme neutrino energy because of the increase with energy of $\tau$ PH radiation length according to fig. 3.
3.3 Fluxes of emerging $\tau$’s

According to the hypothesis of $\nu_\mu - \nu_\tau$ neutrino oscillations suggested by the Super-Kamiokande experiment [25], half of the original cosmic $\nu_\mu$’s appear as $\nu_\tau$’s after their intergalactic path towards the Earth [26].

Within this scenario, we have used the same fluxes for parent $\nu_\tau$ and $\nu_e$: $\Phi_{\nu_\tau} = \Phi_{\nu_e} = \Phi_{\nu_\mu}^{initial}/2$ and we have calculated the rate of emerging $\tau$’s by using equation (3).

Fig. 11, 12 show the flux of emerging $\tau$’s compared with the rate of $\nu_e$ CC interactions in the atmosphere overhanging the unitary surface. The signal induced by the decay of emerging $\tau$’s dominate for $E_{\text{min}} < \sim 5 \times 10^{17}$eV while for higher minimum energy $E_{\text{min}}$, Earth matter strongly suppresses the upgoing $\tau$ fluxes. It must be emphasized that, in this analysis, we have not taken into account the difference between induced EAS generated by different $\tau$ decay channels. It is worth pointing out that leptonic decays $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ do not produce any EAS.

4 Conclusions

A detailed study of $\nu_\tau$-$\tau$ leptons propagation through the Earth indicates the likely existence of a quite intense flux of upgoing $\tau$’s emerging from its surface. The rate of EAS induced by $\tau$’s decay is larger than the rate of $\nu_e$’s induced EAS for minimum energy $E_{\text{min}} \leq 5 \times 10^{17}$eV, while it drops for larger values of minimum energy. The rate of emerging $\tau$’s at extreme energies strongly depends on photonuclear contribution to energy loss, whose calculation is still controversial as it requires non-trivial extrapolations. The detection of such $\tau$ induced events is challenging at a detector’s energy threshold $E_{\text{thr}} \approx 10^{19}$eV even for new generation experiments, while for $E_{\text{thr}} \ll 10^{18}$eV the detection seems to be realistic for detectors capable of recording signals induced by very inclined showers with sensitive areas $\gg 10^3$ km$^2$. 
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Figure 1: Schematic drawing of atmospheric showers induced by neutrinos. Upward going $\nu_\tau$’s could be detected as upward going showers induced by $\tau$ decay.
Figure 2: Total $\nu_\tau$ CC and NC cross sections on isoscalar nucleon target as a function of energy. Continuous line shows the neutrino CC cross section; dotted line shows the antineutrino CC cross section; dashed line shows the neutrino NC cross section and dotted-dashed line shows the antineutrino NC cross section. CTEQ3-DIS parton distribution has been used for the calculation.
Figure 3: $\beta = \frac{-dE/dX}{E \rho}$ in case of standard rock (A=22, Z=11) for $\tau$ PH interactions by S. Iyer et al. [21] and as it comes out using formulae of double differential cross section of Bezrukov and Bugaev [20] with $\tau$ mass.
Figure 4: *Effective depth* for generation of emerging $\tau$’s (PH cross section from ref. [20] and outer Earth layer made of standard rock). The dotted line shows the expected result for no interacting $\tau$’s created with the same neutrino energy and decaying after one $\tau$ decay length.
Figure 5: Scatter plot of final energies of emerging τ’s ($E_f$) versus emerging zenith angles. The simulation has been performed at $E_\nu = 10^{20}\text{eV}$ for an isotropic flux. PH cross section is from ref [20] and the standard rock is considered for the outer Earth layer.
Figure 6: Effective aperture for different minimum energy $E_{\text{min}}$ and standard rock considered for the outer Earth layer. PH cross section is from ref [20]. Dotted line shows the effective aperture for events induced by downward going $\nu_e$ CC interactions in the atmosphere.
Figure 7: Effective aperture for different minimum energy $E_{\text{min}}$ and 3 km water considered for the outer Earth layer. PH cross section is from ref [20]. Dotted line shows the effective aperture for events induced by downward going $\nu_e$ CC interactions in the atmosphere.
Figure 8: Effective aperture for minimum energy $E_{\text{min}} = 3 \times 10^{19}$eV, standard rock considered for the outer Earth layer and PH cross section from ref \[20\]. The effect of different selections on the slant depth of the decay point is shown.
Figure 9: Angular distribution of emerging $\tau$’s for several primary neutrino energies and several minimum energy $E_{\text{min}}$. PH cross section is from ref [20] and standard rock is considered for the outer Earth layer.
Figure 10: Effective aperture for different minimum energy $E_{\text{min}}$ and standard rock considered for the outer Earth layer. Calculations using Bezrukov and Bugaev $\tau$ PH cross section [20] (curves labeled as PH1) are compared with calculations using S. Iyer at al. cross section [21] (curves labeled as PH2). Dotted line shows the effective aperture for events induced by downward going $\nu_e$ CC interactions in the atmosphere.
Figure 11: Rates of emerging τ’s versus minimum energy: Bezrukov-Bugaev PH cross section \[20\] and standard rock considered for the outer Earth layer (continuous lines), Bezrukov-Bugaev PH cross section \[20\] and 3 km water for the outer Earth layer (dotted lines), S. Iyer et al. PH cross section \[21\] and standard rock for the outer Earth layer (dashed lines). Dashed-dotted lines show the rate of $\nu_e$ CC interactions in the atmosphere above the unit Earth surface. Each plot refers to a different Bottom-Up model of cosmic neutrino flux: (a) AGN (A) from Mannheim \[27\]; (b) AGN (B) from Mannheim \[27\]; (c) GRB from Waxman & Bahcall \[28\] and Vietri extension \[29\]; (d) GZK neutrinos from Protheroe and Johnson \[30\].
Figure 12: Rates of emerging $\tau$'s versus minimum energy: Bezrukov-Bugaev PH cross section [20] and standard rock considered for the outer Earth layer (continuous lines), Bezrukov-Bugaev PH cross section [20] and 3 km water for the outer Earth layer (dotted lines), S. Iyer et al. PH cross section [21] and standard rock for the outer Earth layer (dashed lines). Dashed-dotted lines show the rate of $\nu_e$ CC interactions in the atmosphere above the unit Earth surface. Each plot refers to a different Top-Down model of cosmic neutrino flux: (a) Topological Defect from Protheroe and Stanev [31]; (b) Topological Defect from Sigl et al. [32]; (c) Topological Defect from Sigl [33]; (d) Supermassive Relic Particle from Kalashev et al. [34].