

Extreme Energy ν_τ Propagation Through the Earth

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Abstract

The ν_τ propagation through the Earth is studied in detail with a Monte Carlo numerical simulation. All major mechanisms of ν_τ interactions and τ energy loss as well as all its decay modes and decay spectra are properly taken into account. The possibility of ν_τ detection emerging from Earth in future neutrino telescopes is hinted.

1 Introduction

Cosmic neutrinos with energy $> 10^{12}$ eV are a new and exciting observational window for cosmic ray physics and astrophysics. While the lower bound 10^{12} eV is owing to the huge atmospheric neutrino background, many interesting models of cosmic neutrino production predict the existence of neutrinos with an energy up to $10^{18} - 10^{20}$ eV (extreme energy), where the charged particles are expected to be cut off by the so called GZK mechanism. The detection of such extreme energy neutrinos is challenging as it demands very large sensitivity; the experiments of the upcoming generation plan to use underwater-underice Cerenkov detectors (Gaisser 1995) and large field-of-view atmospheric fluorescence detectors (Linsley 1997). The best experimental evidence of cosmic neutrinos would be the detection of neutrinos emerging from the Earth. Indeed, for this class 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 (Naumov 1998). It has been recently pointed out (Fargion 1997, Halzen 1998) that the behaviour of τ -neutrinos, whose existence should be guaranteed in the neutrino oscillation scenario, should be significantly different from ν_μ and ν_e . While the muon neutrino is practically absorbed after one charged current (CC) interaction, the τ lepton created by the ν_τ may decay in flight before losing too much energy, thereby generating a new ν_τ with comparable energy. Hence, ultra high energy τ -neutrinos should emerge from the Earth instead of being absorbed. In order to study this process on a more quantitative ground, it is compelling to estimate the energy loss of τ leptons in crossing Earth matter. In this work a detailed Monte Carlo ν_τ propagation through the Earth has been performed, with special emphasis on the initial ν_τ spectrum deformation as a function of the zenith angle of the emerging particle.

2 Neutrino cross sections and charged lepton interactions

The deep inelastic neutrino-nucleon scattering is the dominant interaction of energetic neutrinos into conventional matter. The charged and neutral current differential cross sections used in this work 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 set beyond accelerator domain, an extrapolation of parton distribution at very low x ($x \geq 10^{-8}$) is necessary. We have used the parton distribution set CTEQ3-DIS, available in the program library PDFLIB (Plathow 1997), with NLO GLAP formalism used for Q^2 evolution 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 (Gluck 1998) the results for cross section calculations do not differ more than 10% from the approach taken here with CTEQ3-DIS plus "brute force" extrapolation (Gluck 1998). The cross sections for radiative electromagnetic interactions of τ leptons are based on QED calculation for Bremsstrahlung (Petrukhin 1968), for direct pair production (Kokoulin 1970) and for photonuclear interactions (Bezrukov 1981) by replacing the muon or electron mass with the τ mass. For all above processes we have implemented stochastic interactions for $\nu = (E_f - E_i)/E_i \geq 10^{-3}$ and continuous loss for $\nu = (E_f - E_i)/E_i \leq 10^{-3}$, where E_i and E_f are the τ energies before and after the interaction respectively.

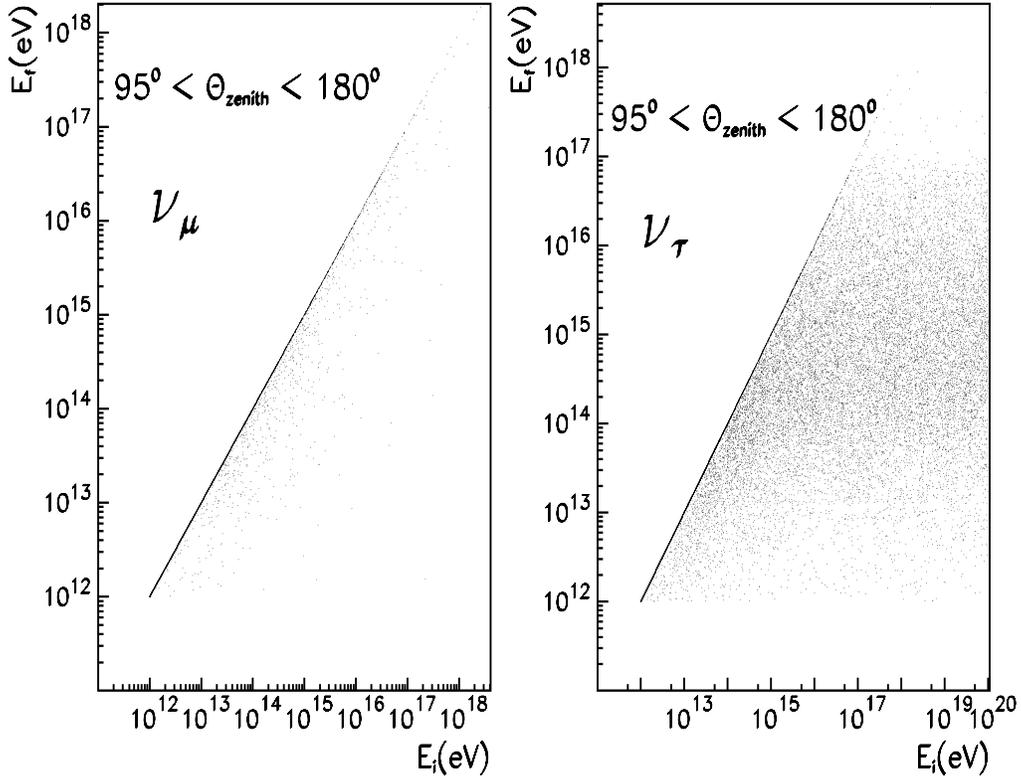


Figure 1: Scatter plot of initial versus final energy. The zenith angles are generated uniformly in the range $95^\circ \leq \theta_{zenith} \leq 180^\circ$.

It is worth mentioning that Bremsstrahlung cross section scales as the inverse square of lepton mass whereas the direct pair production scales according to m_e/m_l (Tannenbaum 1991). As a consequence, the dominant process of τ lepton energy loss is direct pair production. The energy loss per unit length turns out to be much greater than what is obtained (Fargion 1997) by simply rescaling the muon radiation length by m_e^2/m_l^2 . For the τ lepton, along with the electromagnetic interaction, we have considered the weak interactions with nucleons. Actually, they are not completely negligible at $E_\tau \sim 10^{20}$ eV. The τ decay has been simulated by using the TAUOLA package (Jadach 1993).

3 Monte Carlo results

Our Monte Carlo program simulates the propagation of ν_μ, ν_τ and τ leptons through the Earth. The Earth model considered is the preliminary Earth model of ref. (Dziewonski 1981). For the input neutrino spectrum we have assumed a rather hard one, proportional to E^{-1} in the range $10^{12} \leq E \leq 10^{20}$ eV.

In fig. 1 a scatter plot of initial versus final energy is shown. Only muon neutrinos either interacting with

neutral current or not interacting at all are able to cross the Earth; the rest is absorbed because the muon emerging from a charged current interaction has a radiation length which is much lower than its decay length at any energy. On the other hand, the τ generated from a ν_τ charged current interaction loses energy until its decay length becomes comparable to its radiation length, after which it decays into a new ν_τ . Unlike for muons, this occurs around $10^{16} - 10^{17}$ eV and, as a consequence, CC interacting ν_τ 's with $E_\tau \geq 10^{17}$ eV, instead of being absorbed, are shifted to the $E_\tau \leq 10^{17}$ eV region. The comparison between fig. 1 and a similar plot in ref. (Halzen 1998) seems to indicate an essential agreement of the results, although a more quantitative comparison could be more illuminating.

The ν_τ propagation develops in several $\nu_\tau - \tau$ transformations. More matter is traversed during their path, more energy is lost; hence, the accumulation of ν_τ energy below 10^{17} eV is modulated by the zenith angle of the emerging particle. In fig. 2 a scatter plot of final energy versus θ_{zenith} is shown. The input energy spectrum goes again like E^{-1} while the zenith angle distribution is chosen to be constant for a better display of the final energy angular dependence. The final energies cluster around $0.5 \cdot 10^{17}$ eV for nearly horizontal particles and go down to 10^{14} eV for vertically incoming particles. The spectrum deformation of muon and tau neutrinos at various zenith angle shows up in fig. 3. The main feature of ν_τ spectrum is indeed the presence of a characteristic peak before a steep drop. The peak position depends on the zenith angle while its height depends on the slope and maximum energy of the initial spectrum of neutrino flux.

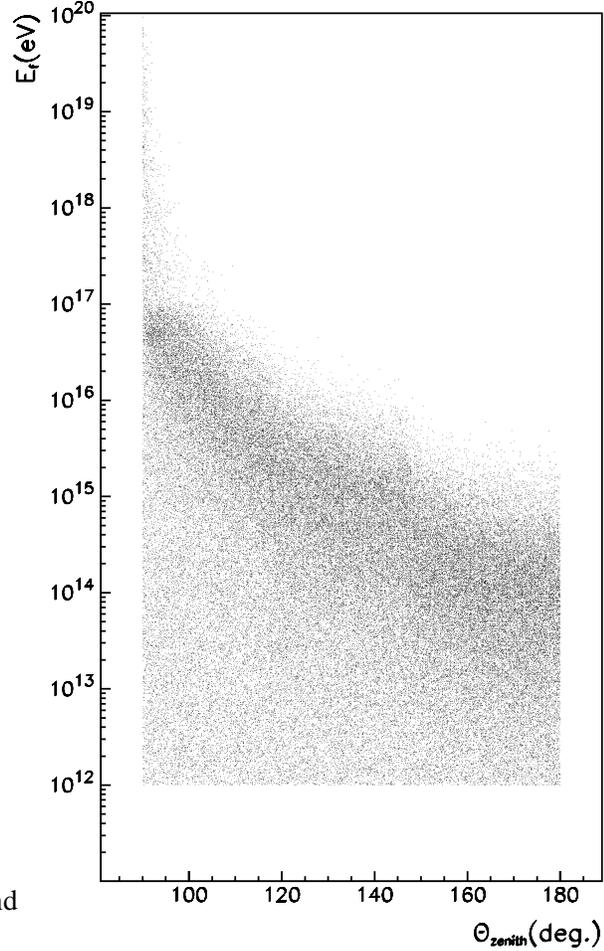


Figure 2: Scatter plot of final energy versus zenith angle θ_{zenith} . The initial energy spectrum is proportional to E^{-1} and the flight direction is generated uniformly in the interval $90^0 \leq \theta_{zenith} \leq 180^0$

4 Conclusions

As expected, the Earth start to be opaque for muon neutrino propagation at energies around 10 TeV. On the other hand, a regeneration mechanism of tau neutrinos ultimately linked to the short τ lepton decay length, prevents a ν_τ impinging on Earth from being absorbed. Nevertheless, the unavoidable radiative τ energy loss sets an upper bound on the energy of emerging ν_τ 's to 10^{17} eV. Therefore, for underwater-underice neutrino telescopes, whose sensitivity will cover the whole neutrino spectrum, ν_τ 's could be the major source of neutrino events above the PeV region. In such detectors the characteristic peaks of fig. 3 could be also recognized as a signature of tau neutrinos. For atmospheric fluorescence detectors the effective cut-off of 10^{17} eV could be below their energy threshold. If this is the case, those detectors should be able to detect only horizontal ν_τ 's and ν_μ 's.

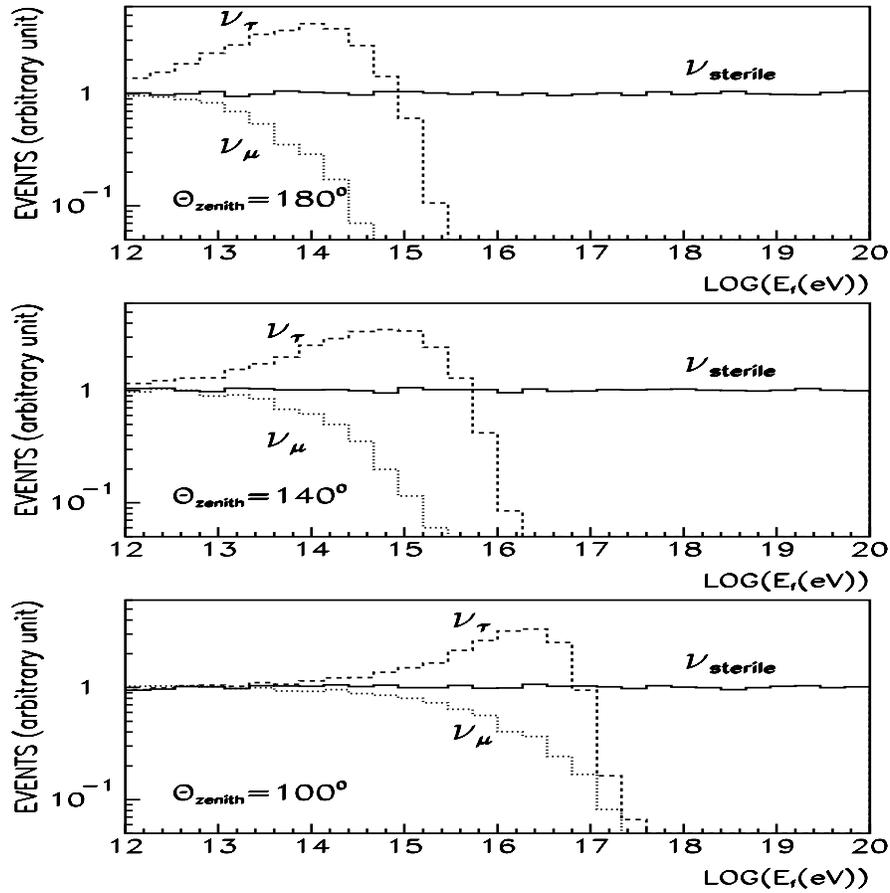


Figure 3: Energy spectra of neutrinos emerging for three different zenith angles for an initial energy spectrum $\propto E^{-1}$. The sterile neutrinos are meant to be non-interacting.

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