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Sensitivity on Earth Core and Mantle densities using Atmospheric Neutrinos

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Abstract. Neutrino radiography may provide a tool, alternative to conventional seismic studies, to study the very deep structures of the Earth. The aim of this paper is to assess how well the core and mantle averaged densities can be reconstructed through atmospheric neutrino radiography. We find that about a 2\% sensitivity for the mantle and 5\% for the core could be achieved for a ten year data taking at an underwater km\textsuperscript{3} Neutrino Telescope. This result does not take into account systematics related to the details of the experimental apparatus.

1. Introduction
Earth tomography with high–energy neutrinos is based on the fact that cosmic neutrinos with an energy of a few TeV have an interaction length of the order of the Earth radius and thus sample the density profile along the path \cite{1}. Detecting at a km\textsuperscript{3} Neutrino Telescope the flux of emerging charged leptons (mainly muons) versus the arrival direction can be therefore a promising approach, complementary to the more conventional seismic studies, for measuring at least some of the features of the Earth density radial profile as recently discussed in Ref. \cite{2}. Until energies of the order of 100 TeV the neutrino flux crossing the Earth is essentially made of Atmospheric Neutrinos (AN) which are produced in collisions of cosmic rays with nuclei in the Earth’s atmosphere. On the other hand, at higher energies a considerable prompt neutrino flux from the decay of heavy mesons is expected, as well as an extragalactic neutrino component. We are limited in our analysis by the transparency of the Earth to the neutrinos of the lowest energies, and by their prompt and yet uncertain extragalactic flux components at the highest energies. So, we use the electron and muon (anti)neutrino fluxes calculated in Ref. \cite{3} in the energy range \((10^3 – 10^4)\) GeV and extrapole it as a power-law behavior till \(10^5\) GeV. We notice that neutrino flavor oscillations can be neglected in the energy range we are interested in, since they are only effective at energies lower than 1 TeV.

The detection perspectives of high energy neutrinos have received a great interest in the past few years, in view of several proposals and R&D projects for Neutrino Telescopes (NT’s) in the deep water of the Mediterranean sea \cite{4}, leading to the construction of a km\textsuperscript{3} telescope as pursued by the KM3NeT project \cite{5}. Furthermore, IceCube experimental setup, a cubic-kilometer under-ice neutrino detector \cite{6} is now under construction and already taking data.

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In Ref. [2] the authors point out the possibility to use the arrival direction distribution of events in ten years of data taking at IceCube, to distinguish, at 3\sigma level, between the Earth matter density profile of the Preliminary Reference Earth Model (PREM) [7] and a homogeneous Earth toy model. However, in Ref. [2] no indication of the real sensitivity of neutrino Earth radiography to PREM parameters is reported. In this contribution we present a study of the sensitivity of an underwater NT to the Earth interior in the case of a simplified PREM (sPREM), where the Earth is divided in three constant density layers (crust, mantle, and core). We assume an Earth radius of 6378 km and a crust with a thickness of 37 km, while the crust density is fixed to be 2.68 g cm$^{-3}$.

2. Simulation and data analysis

We choose as an example of undersea NT a km$^2$ detector placed at NEMO site, and generate a large number of tracks crossing the NT fiducial volume (for simplicity a cube of 1 km edge placed at 100 m from seabed) by means of a detailed Digital Elevation Map of the under-water Earth surface (details can be found in [8]). We perform a Monte Carlo simulation, following tracking particles inside the rock with a maximum of 5 zones of 3 different densities, corresponding to the two regions of sPREM, as well the crust thin layer. This leads to three possible kinds of neutrino tracks inside the Earth: those going i) through the core, ii) through mantle and crust, and iii) through the crust only. We inject a number of electron and muon (anti)neutrinos for a given energy at each angular bin according to the flux of AN given in [3]. We do not consider tau neutrino contribution in this range of energy, since we are neglecting neutrino oscillations.

The detectable events can be classified in two categories: the track events where the charged lepton is produced outside the fiducial volume, and the contained ones, where neutrino converts inside the NT.

Concerning muon neutrinos, which provide the main contribution to the total amount of events, the Monte Carlo simulates their interaction in the Earth and propagates the outgoing lepton. In this respect, we take into account the phenomenon of neutrino regeneration for a neutral current neutrino interaction. In the case of a charged current neutrino interaction, we consider the muon energy loss in matter due to ionization, bremsstrahlung, $e^+ e^-$ pair production and nuclear interaction. An energy threshold of 1 TeV is considered in counting the muons detected in the fiducial volume and the condition of a minimal track length of 300 m in the apparatus defines detectable events. This energy threshold value results to be a good compromise between the need of a sufficiently large statistics, thus a not too high lower energy threshold, and the necessity to reduce the neutrino interaction length in order to increase the sensitivity to Earth density profile. Contained events, which take contributions both from electron and muon neutrinos, are treated separately. To be conservative, in analogy to track ones we assume that they are detected if charged lepton energy is larger than 1 TeV. This, of course, does not take into account the amount of energy released in the hadronic channel accompanying the charged current interaction that for contained events could be in principle detectable. Since the contribution of contained processes is in any case subdominant with respect to the track one, we assume this conservative point of view which has the advantage to make our analysis almost independent of the details of the experimental apparatus.

In order to carry out a sensitivity study, we vary the mantle and core densities in a grid of $5 \times 4$ values: $\rho_m = \{4.00, 4.25, 4.50, 4.75, 5.00\}$ g cm$^{-3}$, $\rho_c = \{9.0, 10.0, 11.0, 12.0\}$ g cm$^{-3}$, and calculate with the Monte Carlo the corresponding number of events in ten years of data taking, $N_i(\rho_m, \rho_c)$, in the five equally spaced angular bins of $\cos \vartheta$ in the interval $[0,1]$ (upgoing events correspond to $\cos \vartheta = 1$). For each pair of chosen values of $\rho_m$ and $\rho_c$, the radius of the core/mantle boundary $R_c$ is constrained by the mass of the Earth.

We then compare the counts $N_i(\rho_m, \rho_c)$ with the expected counts $N_i^0$ for the benchmark case, $\rho_m = 4.48$ g cm$^{-3}$, $\rho_c = 11.0$ g cm$^{-3}$, $R_c = 3450$ km, by means of a likelihood analysis, in which
the likelihood function, \( \mathcal{L}'(\rho_m, \rho_c, \xi, \eta) \propto \exp(-\chi(\rho_m, \rho_c, \xi, \eta)^2/2) \), is defined using the following expression for the \( \chi^2 \):

\[
\chi(\rho_m, \rho_c, \xi, \eta)^2 = \sum_{i=1}^{5} \frac{[N_i(\rho_m, \rho_c)(1 + \xi)(1 - \eta \langle \cos \vartheta \rangle_i) - N_i^0]^2}{N_i^0} + \left( \frac{\xi}{\Delta \xi} \right)^2 + \left( \frac{\eta}{\Delta \eta} \right)^2,
\]

where \( \xi \) takes into account an overall uncertainty of the atmospheric neutrino fluxes and neutrino interaction cross-section \((\Delta \xi = 0.25)\), while \( \eta \) encodes the uncertainty between horizontal and vertical events \((\Delta \eta = 0.05)\) [2].

We show in Fig. 1 the 68 and 95% C.L. contours of the marginalized function with respect to \( \xi \) and \( \eta \), \( \mathcal{L}(\rho_m, \rho_c) = \int \mathcal{L}'(\rho_m, \rho_c, \xi, \eta) \, d\xi \, d\eta \). By using \( \mathcal{L}(\rho_m, \rho_c) \) we can derive the “measured” values of the densities and the radius of core/mantle boundary at 1\( \sigma \)(2\( \sigma \)):

\[\rho_m = 4.47 \pm 0.03 \ (\pm 0.04) \g \cm^{-3}, \quad \rho_c = 11.0 \pm 0.3 \ (\pm 0.5) \g \cm^{-3}, \quad R_c = 3440 \pm 30 \ (\pm 70) \km.\]

Our analysis hence suggests that a 2% and 5% uncertainties (at 2\( \sigma \) level) on the averaged mantle and core densities respectively, can be reached in a neutrino radiography campaign with a ten years of data taking at a typical km\(^3\) NT, placed in the NEMO site. Note that these results are obtained in a very simplified PREM model, and this justifies the good level of sensitivity reachable on \( \rho_m \) and \( \rho_c \) determinations. Notice also that we do not take into account systematics related to the details of the experimental apparatus.

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