Sensitivity on earth core and mantle densities using atmospheric neutrinos


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Outlook

- Are earthquakes useful?
- Why neutrinos?
- Which neutrinos?
- How neutrinos?
- Results and conclusions
The Earth mass

- **Eratostene** (273-192 b.C.)
  - First measure of the Earth circumference (and then of the Earth radius)

- **Galilei** (1564-1642)
  - Determination of the acceleration due to gravity

- **Newton** (1642-1727)
  - Formulation of the laws of gravitation

- **Cavendish** (1731-1810)
  - Determination of $G_N$
  - Calculation of the Earth mass and then of its average density:
    \[ \rho_{av} \sim 5.5 \, g \, cm^{-3} \]
The Earth internal structure

On the other side, the Earth crust density is about 2.7-2.8 g cm$^{-3}$ (direct observations arrive to ~20 km). Information from samples brought to the surface by volcanic activity and by measuring the travel times of earthquake waves to seismograph stations. It is found that:

- the velocity generally increases gradually with depth in Earth, due to increasing pressure and rigidity of the rocks
- however, there are abrupt velocity changes at certain depths, indicating layering
The utility of earthquakes...

As the result of a earthquakes, explosions, or some other process (the incessant pounding of ocean waves, referred to as the microseisms, and the wind), seismic waves are continuously excited on Earth. Earth quakes create two types of waves, body waves and surface waves:

- **P waves** (primary waves) are longitudinal body waves
- **S waves** (secondary waves) are transverse body waves
- **L and R waves** (Love and Raleigh waves) are horizontal and elliptical surface waves
- **free oscillations** are surface wave with wavelength comparable with the circumference of the Earth
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In solids, the P waves generally travel almost twice as fast as S waves and can travel through any type of material. S waves can travel only through solids, as fluids (liquids and gases) do not support shear stresses.
Limits of seismic tomography

• Global seismic tomography is limited by the irregularity in time and space of the source, and by the incomplete coverage of recording stations. The primary source is earthquakes, which are impossible to predict and only occur at certain locations around the world. In addition, the global coverage of recording stations is limited due to economic and political reasons. Because of these limitations, seismologists must work with data that contains crucial gaps.

• Free-oscillation data only reveal 1-dimensional structure.
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Although this information is more precise than what we can realistically expect from neutrino radiography in the near future, aspects of the global structure of the earth require confirmation.
Earth radiography by neutrinos

First proposal to use neutrino beams for Earth radiography by De Rujula, Glashow, Wilson, and Charpak in 1983: a neutrino moving in rock produces a shower which ionizes the medium and generates an acoustic signal. Moreover, the muons accompanying the neutrino beam can be detected at the point of emergence from the Earth.

\[ \lambda = \frac{1}{\sigma_{vN} \rho N_A} \]

\[ \lambda \sim 2 R_{\text{earth}} \iff E \sim 10 \text{ TeV} \]


Neutrinos

Neutrinos are one of the components of cosmic radiation. The atmospheric and the extragalactic contributions, which are mainly isotropic, dominates on the galactic component in two energy regimes. In particular, for $E \leq 10^5$ GeV the statistics of atmospheric $\nu$ is larger than that expected from other cosmic sources.
Probe of geophysical structures

Event rate can be written as

\[
\Gamma(E_\nu) = \int d\Omega A_{\text{eff}} \frac{d\phi}{d\Omega}
\]

where the effective area, \( A_{\text{eff}} \equiv \rho \sigma N_A V_{\text{eff}} \) (the detector effective volume, \( V_{\text{eff}} = A_p l \), divided by the neutrino interaction length) is sensible to the density of matter crossed by neutrinos.

- \( A_p = \) area of the detector projected against the neutrino direction

- \( l = \) portion of the neutrino path to which the detector is sensible
For high $E_{th}$ the attenuation factor due to the earth density becomes relevant and the number of detected events gives information on the earth density.
Ratio of zenith angle distribution of expected events for the sPREM over the expectations with an homogeneous Earth matter distribution for different values of the energy. The error bars in the figure show the expected statistical error in 10 years of data taking.

Analytic results agree with Gonzales-Garcia, Halzen, Maltoni, Tanaka, PRL100 (2008) 061802
Neutrinos through the Earth

- A simplified parametrization of Earth radial density profile (sPREM)

A homogeneous Earth would have $\rho \sim 5.5 \text{ g cm}^{-3}$

- $\rho_{\text{core}} \sim 11 \text{ g cm}^{-3}$
- $\rho_{\text{mantle}} \sim 4.5 \text{ g cm}^{-3}$
- $\rho_{\text{crust}} \sim 2.7 \text{ g cm}^{-3}$
Neutrinos through the Earth

- a simplified parametrization of Earth radial density profile (sPREM)

- three different types of tracks crossing the fiducial volume (described by a Digital Elevation Map)

- neutrinos injected at one side of the tracks according to known spectrum

Honda et al., PR D75:043006 (2007)
Atmospheric Neutrinos

The atmospheric neutrino spectrum falls as $E^{-\gamma}$, with $\gamma \approx 3.3$. The spectral index is similar to the CR one at lower energies, while it becomes steeper at higher energies. This happens because the higher the energy of the mesons produced in the atmosphere, the larger the amount of energy lost during their propagation before they decay.
Atmospheric Neutrinos

The “conventional” part comes from pion and kaon decays (low energy), a “prompt” isotropic contribution from short lived charmed hadrons (high energy). In the energy range of interest, the contribution from kaons dominates (~80%) and decay of muons can be neglected. Tau neutrinos are negligible since oscillation are very suppressed.

Gaisser, Earth Planets Space 58, 1 (2006)
Neutrino interaction

\[ Q^2 \equiv -q^2 = -(k-k')^2 \]
\[ x = Q^2 / (2 m_N \nu) \]
\[ y = \nu / E_\nu = (E_\nu - E_f) / E_\nu \]
\[ Q^2 = 2 m_N E_\nu x y \]

Event simulation

First Interaction

Muon Propagation in matter
Summary of simulation details

- $e$ and $\mu$ (anti)neutrinos injected according to the atmospheric $\nu$ flux in the range $1 \div 10^2$ TeV (Honda et al., 2007). Negligible oscillation -> no $\tau$ contribution
- neutrino regeneration by NC processes
- $\mu$ energy loss in matter (ionization, bremsstrahlung, pair production, nuclear interaction)
- energy thresholds of 1 TeV and 10 TeV
- no details of the experimental apparatus, except for the request of a minimal track length of 300 m in the NT
- detectable events: track and contained events
Particles at the detector

$E_{th} = 1 \text{ TeV}$

- track muons
- contained muons
- electrons

10 years of observations
Likelihood analysis

We consider 5 angular bins for the interval \(\cos \theta = 1\) (upgoing) to \(\cos \theta = 0\) (horizontal) and make the analysis integrating the muons at different energies in the two case \(E_{th} = 1\) TeV and \(E_{th}=10\) TeV.

Observables \(N_i\) produced for a grid of 20 theoretical models of densities. Then, likelihood analysis with likelihood function \(L \propto e^{-\chi^2/2}\) and

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

overall uncertainty on \(\phi\) and \(\sigma\)

uncertainty between h. and v. \(\phi\)

expected counts for the sPREM

\(4 \leq \rho_m/(g\ cm^{-3}) \leq 5\)

\(9 \leq \rho_c/(g\ cm^{-3}) \leq 12\)

\(\Delta \xi = 0.25\)

\(\Delta \eta = 0.05\)
Likelihood analysis

\[ \rho_m = 4.47^{+0.04}_{-0.06} \ \text{g cm}^{-3} \]
\[ \rho_c = 11.0^{+0.5}_{-0.2} \ \text{g cm}^{-3} \]
\[ R_c = 3440 \pm 30^{+70}_{-50} \ \text{km} \]

2% (5%) uncertainty on \( \rho_m \) (\( \rho_c \)) at 2\( \sigma \)

10 years of observations

\[ E_{\text{th}} = 1 \ \text{TeV} \]
Likelihood analysis

\[ E_{th} = 10 \text{ TeV} \]

2% (5%) uncertainty on \( \rho_m (\rho_c) \) at 2\( \sigma \)

\[
\begin{align*}
\rho_m &= 4.47^{+0.02}_{-0.03} \, (^{+0.04}_{-0.06}) \, \text{g cm}^{-3} \\
\rho_c &= 11.0^{+0.3}_{-0.1} \, (^{+0.5}_{-0.2}) \, \text{g cm}^{-3} \\
R_c &= 3440 \pm 30 \, (^{+70}_{-50}) \, \text{km}
\end{align*}
\]

<table>
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<th>( \cos \phi )</th>
<th>sPREM (M)</th>
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<th>B</th>
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<td>[0.8, 1.0]</td>
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<td>27392</td>
<td>26780</td>
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10 years of observations
Conclusions

- study of the sensitivity of a NT to Earth interior for a simplified Earth model (sPREM)
- 2% (5%) uncertainties (at 2σ level) on $\rho_m$ ($\rho_c$) for 10 years of observations and $E_{th}=1$ TeV
- low number of model parameters $\Rightarrow$ good level of sensitivity in their determination
- no details of the experimental apparatus