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Atmospheric neutrino oscillations for Earth tomography

Walter Winter

Deutsches Elektronen-Synchrotron (DESY), Platanenallee 6, D-15738 Zeuthen, Germany

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Abstract

Modern proposed atmospheric neutrino oscillation experiments, such as PINGU in the Antarctic ice or ORCA in Mediterranean sea water, aim for precision measurements of the oscillation parameters including the ordering of the neutrino masses. They can, however, go far beyond that: Since neutrino oscillations are affected by the coherent forward scattering with matter, neutrinos can provide a new view on the interior of the earth. We show that the proposed atmospheric oscillation experiments can measure the lower mantle density of the earth with a precision at the level of a few percent, including the uncertainties of the oscillation parameters and correlations among different density layers. While the earth's core is, in principle, accessible by the angular resolution, new technology would be required to extract degeneracy-free information.

1. Introduction

Using neutrinos for Earth tomography is a dream much older than modern oscillation physics, see Ref. [1] for a review: Early proposals exploit the increase of the neutrino cross sections with energy, leading to significant neutrino absorption over the earth's diameter for energies larger than a few TeV [2–12]. While absorption tomography is conceptually appealing, a technically feasible and scientifically competitive approach to neutrino Earth tomography probably requires neutrino oscillations.

The condensing evidence for neutrino oscillations by the Super-Kamiokande [13], SNO [14], and KamLAND [15] experiments between about 1998 and 2004 was concluded with the mea-

E-mail address: walter.winter@desy.de.

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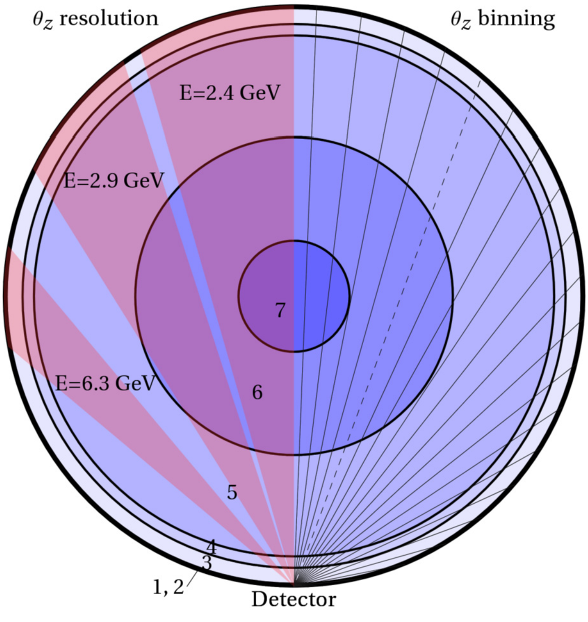

Fig. 1. **Neutrino oscillation model of the earth.** Different layers of the earth used for this analysis, adopted from the PREM model [26]; 1: Crust, 2: Lower Lithosphere, 3: Upper Mesosphere (mantle), 4: Transition zone, 5: Lower Mesosphere, 6: Outer core, 7: Inner core. The right half of the figure shows the θ_z (zenith angle) binning used for the analysis, the left half of the figure illustrates the directional resolution (here for ORCA, $\bar{\nu}_e$ [27], 1σ range) for selected energies and directions.

surement of a non-zero value of the last missing mixing angle θ_{13} by Daya Bay [16] and RENO [17] in 2012 – and was finally rewarded with the Nobel prize in 2015 for the discovery of neutrino oscillations to Takaaki Kajita (Super-Kamiokande) and Arthur B. McDonald (SNO). Modern neutrino oscillation facilities aim for precision measurements and are designed to measure the unknown parameters, such as mass ordering and CP violation. Since coherent forward scattering in Earth matter affects neutrino oscillations [18,19], it can used as an alternative approach for Earth tomography compared to neutrino absorption. It in principle allows for precision matter density measurements along the propagation path of these neutrinos [20,21], and the required energies are much lower. While neutrino absorption tomography can be compared to X-ray tomography, neutrino oscillation tomography has one interesting additional feature: since the quantum mechanical operators in different density layers do not commute, even the reconstruction from a single baseline (propagation distance) carries information how the structure along the propagation path is arranged [22–25].

Atmospheric neutrinos are produced in the earth's atmosphere by the interactions of cosmic rays continuously bombarding the earth. The generic setup, from the point of view of the detector, is illustrated in Fig. 1: neutrinos are detected from different zenith angle directions θ_z (the angle between zenith – from the detector's viewpoint – and incoming neutrino), which correspond to cones through the earth with different baselines $L = 2R_E \cos\theta_z$ (R_E: Earth radius). Within the zenith angle resolution (illustrated in left half of figure), the oscillation paths can be distinguished. We will test the structure of the earth and will identify which parts atmospheric neutrino oscillations are most sensitive within this scenario. We will use proposed experiments such as PINGU ("Precision IceCube Next Generation Upgrade") [28] in the Antarctic ice or