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Neutrino Oscillations in the Earth: A Unique Tool to Probe Dark Matter Inside the Core †

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Abstract: Atmospheric neutrinos, due to their multi-GeV range of energies and wide range of baselines, can probe into the possible existence of dark matter inside the core of the Earth in a unique way via Earth matter effects in neutrino oscillations. We demonstrate that an atmospheric neutrino detector such as the proposed 50 kt Iron Calorimeter detector at the India-based Neutrino Observatory with muon charge identification capability can be sensitive to the presence of dark matter at around a 2σ confidence level with 1000 kt·yr exposure if dark matter constitutes 40% of the mass inside the core. We further demonstrate that it is hard to identify the dark matter profile using neutrino oscillations, but the baryonic matter profile inside the core can be explored as a complement to the seismic measurements.

Keywords: earth tomography; dark matter; atmospheric neutrinos; neutrino oscillations; ICAL; INO

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1. Introduction

The information about the internal structure of the Earth is based on indirect methods such as gravitational and seismic measurements. Based on the data of seismic wave propagation inside the Earth, the most widely used Earth density profile, the Preliminary Reference Earth Model (PREM) [1], has been developed. The PREM profile is based on empirical relations whose parameters depend upon the temperature, pressure, composition, and elastic properties of Earth, which give rise to uncertainties in the profile. The uncertainty in the density is about 5% for the mantle and significantly larger for the core.

Neutrinos, due to the weak nature of their interaction, can penetrate the whole Earth and acquire information about its internal structure. While passing through the Earth, the atmospheric neutrinos undergo charged-current (CC) interactions with the ambient electrons. This process is coherent, forward, and elastic in nature. These CC interactions change the effective mass-splitting and mixing angles of neutrinos, which modifies the neutrino oscillation probabilities. Neutrinos with energies of 5 to 10 GeV, while passing through the mantle, experience the well-known Mikheyev–Smirnov–Wolfenstein (MSW) resonance [2]. Moreover, the core-passing neutrinos with energies of 2 to 6 GeV may experience the so-called neutrino oscillation length resonance (NOLR) [3], or parametric resonance (PR) [4]. These matter effects make neutrino oscillations sensitive to baryonic matter densities inside the Earth.

We consider the proposed 50 kt Iron Calorimeter (ICAL) detector at the India-based Neutrino Observatory (INO) [5] as a concrete example of an atmospheric neutrino experiment. ICAL would be able to detect atmospheric muon-type neutrinos and antineutrinos separately in the multi-GeV range of energies and over a wide range of baselines. It has an excellent angular resolution and a magnetic field of around 1.5 Tesla. These features would enable ICAL to identify core-passing neutrinos and to observe ν_μ and $\bar{\nu}_\mu$ separately by distinguishing between μ^- and μ^+ events.

In this work, we probe the possible presence of dark matter (DM) inside the core of the Earth by analyzing the effects of the remaining baryonic density distribution on neutrino propagation. We assume the mass of the core and the baryonic density profile of the mantle to be completely known.

2. DM Mass Fraction inside the Core

The mass of Earth has been determined via gravitational measurements to a very high precision. However, these measurements would not be able to distinguish the DM and baryonic mass separately. We use the parameter f_D to quantify the DM mass as a fraction of mass of the core:

$$f_{\rm D} \cdot M_{\rm core} = \int_0^{R_{\rm CMB}} 4\pi r^2 (\rho_{\rm PREM}(r) - \rho_{\rm B}(r)) dr \,, \tag{1}$$

where $\rho_{\rm PREM}(r)$ and $\rho_{\rm B}(r)$ are the density distributions for PREM and baryonic profiles, respectively, and $R_{\rm CMB}$ is the core-mantle boundary. Note that neutrino oscillations in the presence of Earth matter effects only depend upon the ambient electron number density and are blind to the specific DM profile. As a result, the neutrino oscillation experiments will be sensitive only to the value of DM mass fraction f_D, and not to the DM profile that gives rise to the value of f_D. Therefore, we define f_D to be an averaged quantity, as in Equation (1). The baryonic mass fraction $f_B(r)$ can be define as

$$\rho_{\rm B}(r) = f_{\rm B}(r)\, \rho_{\rm PREM}(r) \,. \tag{2}$$

To begin with, we choose a toy model with a uniform $\rho_{\rm B}(r) = 1 - f_D$ only for the core, and keep the mantle unaltered. The density of the core is reduced by a uniform DM fraction f_D. The remaining mass is accommodated by DM to keep the mass of Earth constant. We further determine that the baryonic density of the core is always greater than that of the mantle at the core-mantle boundary, i.e., $\rho_{\rm B}(R^-_{\rm CMB}) > \rho_{\rm B}(R^+_{\rm CMB})$. This implies that we can only decrease the density of the core in the range of $0 \leq f_{\rm D} \leq 0.44$. The baryonic density profiles with different values of f_D are shown in Figure 1, based on the 25-layered PREM profile.

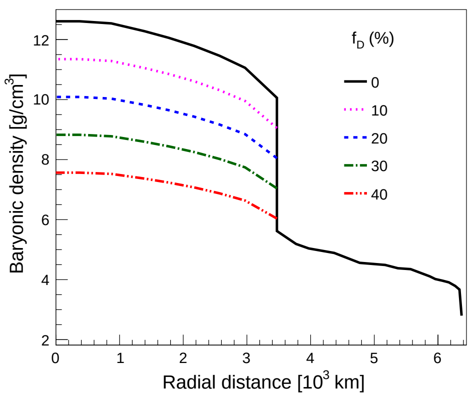

Figure 1. Baryonic density profiles of the Earth, obtained by reducing the density of the core by the DM fraction $f_{\rm D}$. In the scenario without DM, the density profile is represented by the standard 25-layered PREM profile, given by the black curve. Different line-style curves correspond to different values of f_D. The same will follow in the later figures. This figure is taken from Ref. [6].

To study the effect of the presence of DM inside the core on neutrino oscillation probability, we plot the three-flavor ν_μ survival probability oscillograms with energy E_ν and arrival zenith angle θ_ν for the PREM profile without dark matter (left panel), and a baryonic profile with 40% DM fraction inside the core (right panel) in Figure 2. We consider the benchmark values of neutrino oscillations parameters mentioned in Table 1, and normal mass ordering for our analysis. In the left panel of Figure 2, the region around $-0.8 < \cos\theta_\nu < -0.5$ and 6 GeV $< E_\nu <$ 10 GeV, seen as red patch, is the result of MSW resonance, whereas the yellow patches around $\cos\theta_\nu < -0.8$ and 3 GeV $< E_\nu <$ 6 GeV are due to the NOLR/parametric resonance. In right panel of Figure 2, the NOLR/parametric resonance region is significantly diluted due to the 40% DM fraction f_D inside the core.

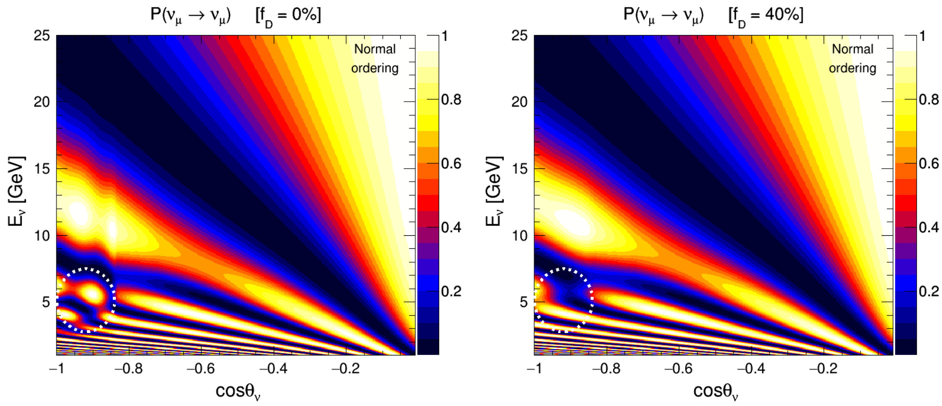

Figure 2. Three-flavor ν_μ survival probability oscillograms in the (E_ν, $\cos\theta_\nu$) plane. (**Left panel**): PREM profile with no dark matter. (**Right panel**): modified PREM profile with DM fraction $f_D = 40\%$ in the core. In the right panel, the NOLR/PR resonance around (5 GeV, -0.9) is significantly diluted as indicated by white circles. This figure is taken from Ref. [6].

Table 1. The benchmark values of oscillation parameters used in this analysis. These values are consistent with the current neutrino global fits [7].

$\sin^2 2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2 2\theta_{13}$	$\Delta m^2_{\rm eff}$ [1] (eV^2)	Δm^2_{21} (eV^2)	$\delta_{\rm CP}$	Mass Ordering
0.855	0.5	0.0875	2.49×10^{-3}	7.4×10^{-5}	0	Normal

[1] The $\Delta m^2_{\rm eff}$ is the effective atmospheric mass-squared difference and related to Δm^2_{31} by $\Delta m^2_{\rm eff} = \Delta m^2_{31} - \Delta m^2_{21}(\cos^2\theta_{12} - \cos\delta_{\rm CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23})$.

3. Results

We simulate the unoscillated neutrino events with the ICAL geometry using the NUANCE Monte Carlo (MC) neutrino event generator with the Honda 3D neutrino flux at the INO site. The simulation details are outlined in [5]. For this work, we consider the 20-yr MC data of the 50 kt ICAL detector which corresponds to 1 Mt·yr exposure. We use the reconstructed muon energy $E_\mu^{\rm rec}$, muon direction $\cos\theta_\mu^{\rm rec}$, and hadron energy $E'^{\rm rec}_{\rm had} \equiv (E_\nu - E_\mu)^{\rm rec}$ as reconstructed observables [8] to calculate the expected median sensitivity of the ICAL detector to the presence of DM.

For numerical analysis, we define the following Poissonian χ^2_- in terms of μ^- reconstructed observables $E_\mu^{\rm rec}$, $\cos\theta_\mu^{\rm rec}$, and $E'^{\rm rec}_{\rm had}$ following Refs. [8,9]:

$$\chi^2_- = \min_{\xi_l} \sum_{i=1}^{N_{E'^{\rm rec}_{\rm had}}} \sum_{j=1}^{N_{E^{\rm rec}_\mu}} \sum_{k=1}^{N_{\cos\theta^{\rm rec}_\mu}} \left[2(N^{\rm theory}_{ijk} - N^{\rm data}_{ijk}) - 2N^{\rm data}_{ijk} \ln\left(\frac{N^{\rm theory}_{ijk}}{N^{\rm data}_{ijk}}\right)\right] + \sum_{l=1}^{5}\xi_l^2, \quad (3)$$

with

$$N_{ijk}^{\text{theory}} = N_{ijk}^{0}\left(1 + \sum_{l=1}^{5} \pi_{ijk}^{l}\xi_{l}\right). \tag{4}$$

Here, N_{ijk}^{theory} and N_{ijk}^{data} correspond to the expected and observed number of reconstructed μ^- events in a given (E_μ^{rec}, $\cos\theta_\mu^{\text{rec}}$, $E'^{\text{rec}}_{\text{had}}$) bin, respectively. The quantity N_{ijk}^{0} represents the expected number of events without systematic uncertainties. We use the well-known method of pulls [8,9] to incorporate the systematic uncertainties. We consider the optimized binning scheme as mentioned in the Table 4 of Ref. [9]. Similar to the Equation (3), we define χ^2_+ for μ^+ events and add the separate contributions of both χ^2_- and χ^2_+ to calculate the total χ^2:

$$\chi^2 = \chi^2_- + \chi^2_+ . \tag{5}$$

To quantify the statistical significance of ICAL detector to rule out the baryonic density profile with a given DM fraction inside the core with respect to the PREM profile without DM, we define $\Delta\chi^2_{\text{DM}}$ as follows:

$$\Delta\chi^2_{\text{DM}} = \chi^2(\text{Dark matter}) - \chi^2(\text{without Dark matter}). \tag{6}$$

Figure 3 presents the sensitivity with which the ICAL detector may exclude the DM fraction f_D, in terms of $\Delta\chi^2_{\text{DM}}$. These results correspond to the 25-layered PREM profile. From Figure 3, it is clear that sensitivity to DM increases with f_{D}, reaching $\Delta\chi^2_{\text{DM}} \approx 4$ (2σ) for an exposure of 20 years, utilizing the CID capability of ICAL. Note that without this CID capability, the sensitivity for DM would be lower by almost 40%.

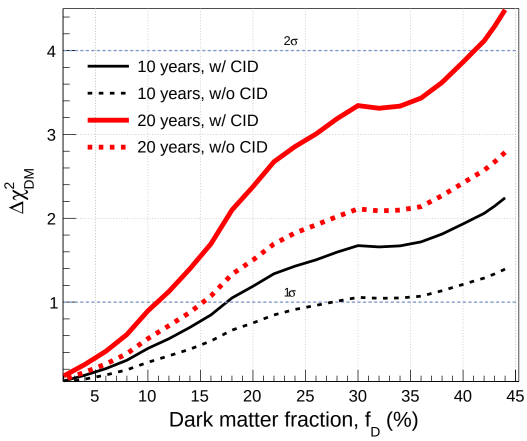

Figure 3. The sensitivity with which ICAL may exclude a given value of f_{D} in terms of $\Delta\chi^2_{\text{DM}}$. The thin (thick) curves correspond to 10 (20) years of exposure. The solid (dashed) curves correspond to with (without) CID capability of the ICAL detector. This figure is taken from Ref. [6].

Neutrino oscillations can only constrain the baryonic density profile of the core and are independent of the DM density profile inside the core. To demonstrate this, the baryonic matter density profile inside the core can be parametrize as

$$\rho_B(r) = a - b \cdot (r/R_{\text{CMB}})^2 , \tag{7}$$

where a and b are positive constants having units of density. In this profile, the density is deceasing monotonically with the radius. We ensure that the density of the core is always greater than the density of the mantle. In further constraining

$$\int_0^{R_{\text{CMB}}} 4\pi r^2 \rho_B(r) dr \le M_{\text{core}} , \tag{8}$$

we assure that the baryonic mass inside the core is less than the total mass of the core. In Figure 4, each point in the triangular region constructed by the white line, black line, and x-axis corresponds to an allowed baryonic profile. The gray regions are non-physical.

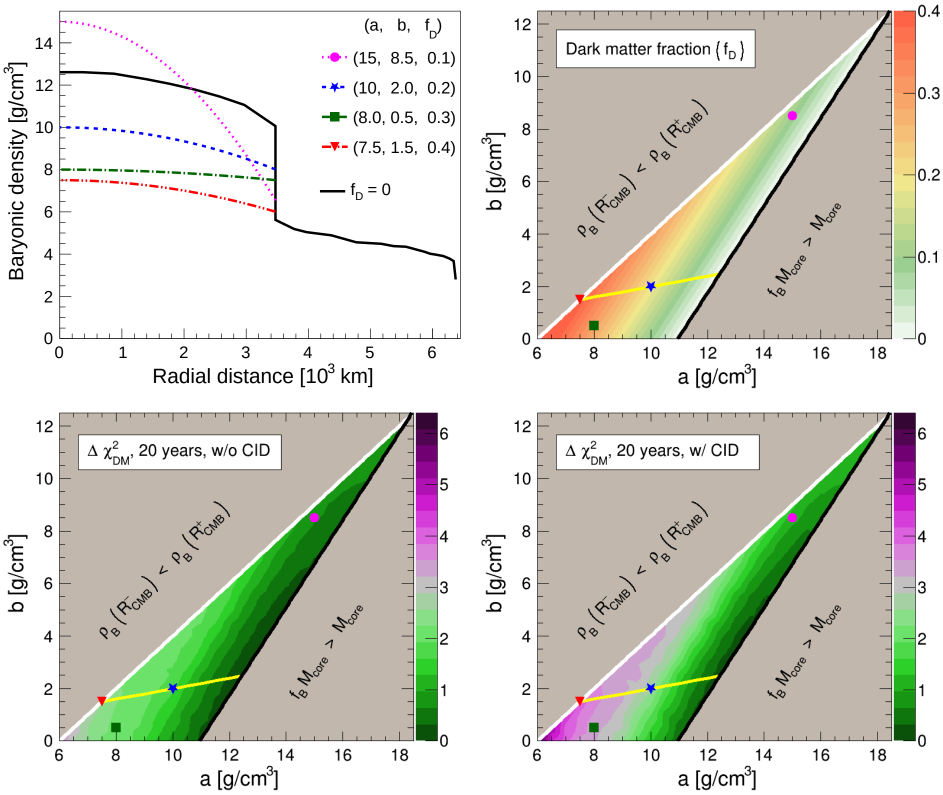

Figure 4. (**Top left**): some representative baryonic density profiles with the form $\rho_B(r) = a - b(r/R_{\mathrm{CMB}})^2$. (**Top right**): color gradients of f_{D} inside the core in the (a, b) plane. (**Bottom panels**): color gradients of $\Delta\chi^2_{\mathrm{DM}}$ in the (a, b) plane, the left panel without CID and the right panel with CID. The markers with different colors and types show density profiles in the top left panel corresponding to the markers with the same colors and types in the other three panels. The yellow line of the form $b = \gamma a$ shows the various core density profiles that look almost similar to the scaled-down versions of the 25-layered PREM profile inside the core. This figure is taken from Ref. [6].

4. Conclusions

In this work, we use the weak interactions of neutrinos as a complementary tool with which to probe the internal structure of the Earth. Atmospheric neutrinos have energies in the multi-GeV range where the Earth matter effects are significant; hence, they serve as probes of the internal structure of Earth. We show that an atmospheric neutrino detector, such as ICAL, which is sensitive to the mult-GeV neutrinos and can differentiate between neutrinos or antineutrinos, would be able to rule out a density profile with a dark matter fraction of around $\sim$40% with a precision of $\Delta\chi^2_{\mathrm{DM}} \approx 4$ (2σ) using 1000 kt·yr exposure. The sensitivity to a specific baryonic profile depends mainly, but not entirely, on the net DM fraction in the core. The neutrino data are, however, insensitive to the DM density profile.

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Conflicts of Interest: The authors declare no conflict of interest.

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