Validating the Earth's Core using Atmospheric Neutrinos with ICAL at INO

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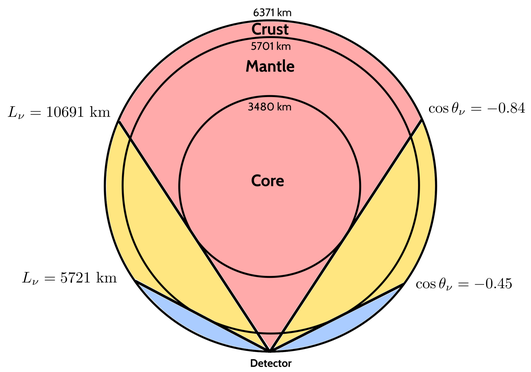
Iron Calorimeter (ICAL) detector at INO [1] can play an important role in validating the presence of Earth's core since it can reconstruct core passing ν_μ and $\bar{\nu}_\mu$ separately with high resolution in the multi-GeV range of energy [2].

- **ICAL@INO:** 50 kton magnetized iron detector
- **Uniqueness:** CID for muons, distinguishes ν_μ and $\bar{\nu}_\mu$
- **Muon energy range:** 1 – 25 GeV, **Muon energy resolution:** ~ 10%
- **Baselines:** 15 – 12000 km, **Muon zenith angle resolution:** ~ 1°

Internal Structure of Earth



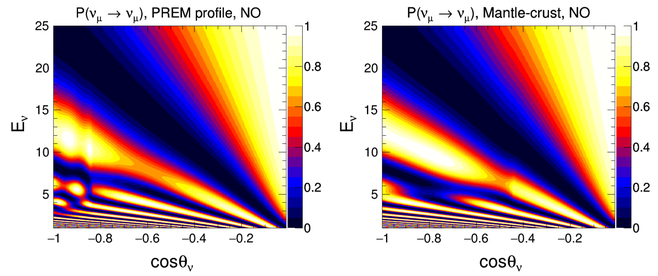
Three layer profile of Earth

Profiles	Boundaries (km)	Densities (g/cm^3)
Core-mantle-crust	(0, 3480, 5701, 6371)	(11.37, 5, 3.3)
Mantle-crust	(0, 5701, 6371)	(6.45, 3.3)
Core-mantle	(0, 3480, 6371)	(11.37, 4.42)
Uniform	(0, 6371)	(5.55)

Neutrino Oscillations in Matter

- The atmospheric neutrinos undergo coherent elastic forward scattering with electrons inside the Earth which leads to the modification of neutrino oscillations[3].
- Neutrinos passing through the mantle feel the Mikheyev-Smirnov-Wolfenstein (MSW) resonance.
- The core-passing neutrinos experience oscillation length resonance or parametric resonance.

Probability Oscillograms



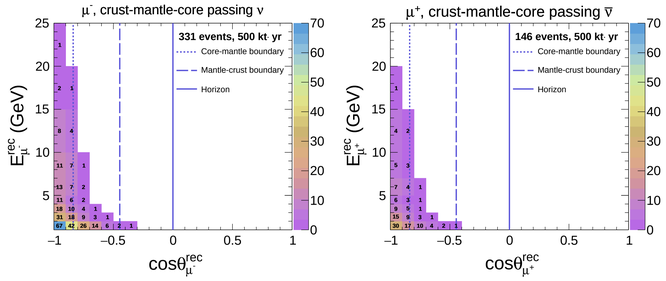
Core -> Parametric resonance

Methodology

- Three-flavor neutrino oscillations in the presence of matter by considering various profiles of Earth based on PREM profile[4].
- Neutrino events are generated for flux at Theni site using NUANCE.
- The detector properties are incorporated using a migration matrix obtained from GEANT simulations performed by the ICAL collaboration.
- Systematics and uncertainty on oscillation parameters are taken into account while performing statistical analysis.

Core Passing Neutrino Events

Regions	$\cos\theta_\nu$	Baseline (km)	μ^- Events	μ^+ Events
Crust-mantle-core	(-1.00, -0.84)	(10691, 12757)	331	146
Crust-mantle	(-0.84, -0.45)	(5721, 10691)	739	339
Crust	(-0.45, 0.00)	(437, 5721)	550	244



Statistical Analysis and Results

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

where,

$$N^{theory}_{ijk} = N^0_{ijk}\left(1 + \sum_{l=1}^{5} \pi^l_{ijk}\xi_l\right)$$

Similarly, χ^2_+ is defined for μ^+

$$\chi^2_{ICAL} = \chi^2_- + \chi^2_+$$

$$\Delta\chi^2_{ICAL\text{-}profile} = \chi^2_{ICAL}\ (\text{Mantle-Crust}) - \chi^2_{ICAL}\ (\text{PREM})$$

• Neutrino Flux: Theni • Exposure: 500 kt·yr • Marginalization over $\sin^2\theta_{23}$: (0.36, 0.66), Δm^2_{eff}: (2.1, 2.6) $\times 10^{-3}$ eV^2, and mass ordering: (NO, IO)

MC Data	Theory	$\Delta\chi^2_{ICAL\text{-}profile}$			
		NO(true)		IO(true)	
		CID	No CID	CID	No CID
PREM Profile	Vacuum	5.52	3.52	4.09	1.67
PREM Profile	**Mantle-Crust**	**7.45**	**3.76**	**4.83**	**1.59**
PREM Profile	Core-Mantle	0.27	0.18	0.21	0.07
PREM Profile	Uniform	6.10	3.08	3.92	1.18

Summary and Conclusion

- Using atmospheric neutrinos at ICAL in 10 years, the presence of Earth's core can be validated at $\Delta\chi^2$ of 7.45 for normal ordering and 4.83 for inverted ordering
- Charge identification capability of ICAL plays a crucial role in establishing the presence of core.

References

[1] A. Kumar et al. "Invited review: Physics potential of the ICAL detector at the India-based Neutrino Observatory (INO)". In: *Pramana* 88.5 (2017), p. 79. ISSN: 0973-7111.

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[4] Adam M. Dziewonski and Don L. Anderson. "Preliminary reference Earth model". In: *Physics of the Earth and Planetary Interiors* 25.4 (1981), pp. 297 –356. ISSN: 0031-9201.