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Exploring the Earth's mantle with geoneutrinos

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Summary. — The KamLAND and Borexino experiments have observed, each at $\sim 4\sigma$ level, signals of electron antineutrinos produced in the decay chains of thorium and uranium in the Earth's crust and mantle (Th and U geoneutrinos). Various pieces of geochemical and geophysical information allow an estimation of the crustal geoneutrino flux components with relatively small uncertainties. The mantle component may then be inferred by subtracting the estimated crustal flux from the measured total flux. On the base of this approach we find that crust-subtracted signals show hints of a residual mantle component, emerging at $\sim 2.4\sigma$ level by combining the KamLAND and Borexino data. The inferred mantle flux slightly favors scenarios with relatively high Th and U abundances, within $\pm 1\sigma$ uncertainties comparable to the spread of predictions from recent mantle models.

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1. – An interdisciplinary approach for estimating mantle geoneutrinos

The decay chains of uranium (U), thorium (Th), and potassium (K) in the Earth's interior provide intense sources of terrestrial heat and, at the same time, of low-energy electron antineutrinos ($\overline{\nu}_e$) — the so-called geoneutrinos [1]. Geoneutrinos from Th and U (but not from K) decay are detectable via the inverse beta decay (IBD) reaction, and have recently been observed at $\sim 4\sigma$ level both in the KamLAND (KL) [2] and

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in the Borexino (BX) [3] experiments. These observations will provide unique clues on fundamental geophysical and geochemical issues [4-6], in particular, the total $\overline{\nu}_e$ flux probes the total amount of radiogenic elements in the Earth, while the energy spectrum is sensitive to the different Th and U components [1].

Extracting geophysical and geochemical information is not straightforward, since the geoneutrino flux represents a volume integral over Th and U abundances, weighted by the inverse square distance, and modulated by the IBD cross section and $\overline{\nu}_e$ oscillation probability (see [1] for details). While the latter two ingredients are known with good accuracy, the volume distribution of Th and U is subject to relatively large uncertainties, especially in the mantle [4, 7].

In this proceeding we summarize the main results described in [8] obtained by an interdisciplinary approach, including supplementary constraints or assumptions from Earth science (geophysics and geochemistry). The goal is to infer the mantle component of the geoneutrino flux, which we obtain by subtracting accurately estimated crust components from the total measured fluxes.

Concerning particle physics data, we perform a detailed analysis of the total Th and U geoneutrino fluxes measured in KL and BX, including oscillation effects. In particular, the fit to KL and BX data involves a 7-dimensional manifold,

$$\text{Parameters} = \{\delta m^2,\, \theta_{12},\, \theta_{13};\, R(\text{Th})_{\text{KL}},\, R(\text{U})_{\text{KL}},\, R(\text{Th})_{\text{BX}},\, R(\text{U})_{\text{BX}}\}, \tag{1}$$

where the four R's represent the KL and BX event rates from Th and U geoneutrinos, expressed in Terrestrial Neutrino Units (1 TNU $= 10^{-32}$ events per target proton per year). The mass-mixing oscillation parameters (δm^2, θ_{12}, θ_{13}) govern the flavor survival probability P_{ee} of both geo-$\overline{\nu}_e$ and background reactor $\overline{\nu}_e$. Adopting the reference 1σ ranges $\sin^2\theta_{12} \simeq 0.306 \pm 0.017$ and $\sin^2\theta_{13} \simeq 0.021 \pm 0.007$ from the global analysis of oscillation data (from solar, atmospheric, accelerator, and reactor neutrino experiments) performed in [9], imply $\langle P_{ee}\rangle \simeq 0.551 \pm 0.015$ (1σ).

Concerning Earth science data, we estimate the different crustal flux components in the two experiments, using state-of-the-art geochemical and geophysical information about the crust, on both global and local scales. In order to estimate the crustal geo-ν flux we need a global model for the Earth crust and a sufficiently detailed model for the local contribution. Indeed, the crust portions within and outside a radius of $O(500)$ km from the detector provide comparable flux contributions in both KL and BX [1]. The mantle component in KL and Borexino is then obtained within the reasonable assumption of site-independent mantle flux, by subtraction (mantle = total − crust).

2. – Mantle geoneutrinos and mantle models

In table I we summarize our estimated "low" and "high" Th and U mantle geoneutrino rates as derived from different mantle models, together with the associated total heat $H(\text{Th} + \text{U})$. The "high rate" (homogeneous) scenario is obtained by subtraction of the Th and U crustal masses at the lower end of their 1σ range, and distributing the reminder in the whole mantle at constant density. The "low rate"(inhomogeneous) scenario is obtained by subtracting from the primitive mantle the Th and U crustal masses at the upper end of their 1σ range, and placing all the reminder in the so-called D" layer (250 km thickness) just above the core-mantle boundary. In both cases, averaged oscillations are included. Note that the various models are based on different assumptions or input values

Table I. – *Geoneutrino event rates derived from various models of the primitive mantle, under different assumptions about the Th and U distributions in the present mantle, leading to "low" and "high" rates. After crustal subtraction and redistribution of the remaining Th and U masses in the present mantle, we derive the oscillated Th and U mantle event rates and the Th+U heat as reported in the last six columns, for the "low" and "high" scenarios.*

Model Reference	Present mantle, "low" scenario			Present mantle, "high" scenario		
	R(Th) [TNU]	R(U) [TNU]	H(Th + U) [TW]	R(Th) [TNU]	R(U) [TNU]	H(Th + U) [TW]
Turcotte & Schubert 2002 [10]	2.7	9.8	17.0	3.9	14.7	19.0
Anderson 2007 [11]	2.3	8.4	14.5	3.4	12.8	16.6
Palme & O'Neil 2003 [12]	1.3	5.7	9.1	2.1	9.2	11.2
Allegre *et al.* 1995 [13]	1.1	4.7	7.7	1.9	8.0	9.8
McDonough & Sun 1995 [14]	1.1	4.7	7.7	1.9	8.0	9.8
Lyubetskaya & Korenaga 2007 [15]	0.7	3.3	5.0	1.2	6.0	7.0
Javoy *et al.* 2010 [16]	0.0	1.0	0.8	0.4	3.0	2.8

about the primitive chondritic material, which lead to further differences in the Th and U contents and in the associated radiogenic heat in the present mantle.

In fig. 1 we show a comparison between theory and data in terms of the Th+U mantle rate (in TNU) and radiogenic heat (in TW). The various model predictions, shown as lines connecting the "low" and "high" cases in table I, can be compared to the mantle rate shown as a horizontal 1σ band. The experimental total rates of Th and U geoneutrino events in KamLAND (KL) and Borexino (BX), are analyzed and described in details in [8]. The approach used is based on the calculation of crustal flux at the two detector sites, using updated information about the global and local Th and U distribution. After subtraction of the estimated crustal component from the total fluxes, we find hints for residual mantle components at $\sim 1.5\sigma$ in both KL and BX. In the KL+BX combination, the statistical significance of the mantle signal reaches the

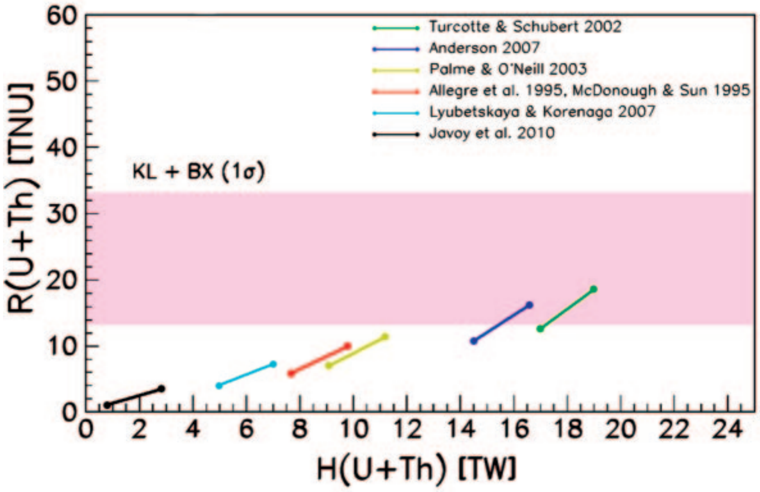

Fig. 1. – Comparison of KL+BX constraints (1σ horizontal pink band) and model predictions (slanted lines) in the plane charted by the Th+U geoneutrino rate and radiogenic heat for the mantle.

2.4σ level. In particular, for typical Th/U mantle ratios, we estimate a total mantle rate of $R(\mathrm{Th}+\mathrm{U}) \simeq 23 \pm 10\,\mathrm{TNU}$ (including oscillation effects). The $\pm 10\,\mathrm{TNU}$ error is comparable to the spread of rate predictions derived from various published models of the mantle. Among these, a preference is found for models with relatively high radiogenic contents (corresponding to present mantle Th+U heat $\sim 13\,\mathrm{TW}$ at $\sim 1\sigma$). However, no model can be excluded at $\sim 2\sigma$ level yet.

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