Geo-Neutrinos And Radiogenic Contribution To Earth's Heat Flow

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Abstract. New measurements of the geo-neutrino flux are available from two independent and complementary experiments: Borexino and KamLAND. These new data decrease uncertainties on the flux and the derived radiogenic contribution to the terrestrial heat flow begins to be significant. The derived heat flow has a theoretical uncertainty from the accepted model of Earth. In the new future the range of the predictions should decrease mainly because of larger statistics collected by the two experiments and of a detailed geological study of the region near Borexino.

Keywords: Geo-neutrinos; Natural radioactivity; Terrestrial heat
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INTRODUCTION

The relevance of neutrinos for astronomical studies was realized many years ago [1]. Low-energy neutrinos have very long mean free path and neutrinos emitted by astronomical bodies carry direct information on their internal composition and structure. Experimental detection of the solar neutrinos has already provided valuable information on radioactive processes inside the stars [2]. Unlike the Sun, Earth emits mainly antineutrinos, the so-called geo-neutrinos. In the sixties geo-neutrinos were introduced by Eder [3] and Marx [4] soon realized their relevance. In the eighties Krauss et al. discussed their potential as probes of the Earth's interior in an extensive publication [5]. In the nineties the first paper on a geophysical journal was published by Kobayashi et al. [6]. In 1998, Raghavan et al. [7] and Rothschild et al. [8] pointed out the potential of KamLAND and Borexino for geo-neutrino detection. A recent review [9] discuss in details geo-neutrino properties, detection, and relevance for the Earth's structure.

Geo-neutrinos are produced in β^--decays of nuclei in the ^{238}U and ^{232}Th chains and of ^{40}K inside the Earth. The main geo-neutrino properties, summarized in Table I, deserve a few comments:

1) geo-neutrinos from different elements yield different energy spectra, *e.g.*, geo-neutrinos with energy $E > 2.25$ MeV are produced only from the uranium decay chain. Therefore the geo-neutrino spectrum gives information on the abundances of U and Th.

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2) only a fraction of geo-neutrinos from U and Th (not those from ^{40}K) are above threshold for the classical antineutrino detection reaction, the inverse beta on free protons:

$$\bar{\nu}_e + p \rightarrow e^+ + n - 1.806 MeV \qquad (1)$$

3) antineutrinos from the Earth are not obscured by solar neutrinos, which cannot yield reaction (Eq. 1).

TABLE 1. The main properties of geo-neutrinos. For each parent nucleus the table presents half-life ($T_{1/2}$), antineutrino maximal energy (E_{max}), Q-value, antineutrino and heat production rates ($\varepsilon_{\bar{\nu}}$ and ε_H) for unit mass for unit mass of the isotope (the corresponding values at natural isotopic composition are obtained by multiplying the isotopic abundance).

Decay	**$T_{1/2}$ [10^9 yr]**	**E_{max} [MeV]**	**Q [MeV]**	**$\varepsilon_{\bar{\nu}}$ [$kg^{-1}s^{-1}$]**	**ε_H [W/kg]**
$^{238}U \rightarrow {}^{206}Pb + 8\,{}^{4}He + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^{7}	0.95×10^{-4}
$^{232}Th \rightarrow {}^{208}Pb + 6\,{}^{4}He + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^{7}	0.27×10^{-4}
$^{40}K \rightarrow {}^{40}Ca + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^{8}	0.22×10^{-4}

The first observation of geo-neutrinos, four events associated with ^{238}U and five with ^{232}Th decay chains by the KamLAND collaboration in 2003 [10], demonstrated that geo-neutrino detection was possible. This achievement was the consequence of two fundamental developments: extremely-low-background neutrino detectors and progress on the understanding neutrino propagation.

Geo-neutrinos are a new probe of the Earth interior [9]. They carry to the surface information about the chemical composition of the whole planet and, differently from other emissions of the planet (*e.g.*, heat or noble gases), they escape freely and instantaneously from the Earth's interior. Geo-neutrinos give precious information on important quantities such as the radiogenic contribution to terrestrial heat production, the abundances of U and Th inside the Earth, or on the validity of different geological models of the Earth.

The purpose of this paper is the comparison of the latest geo-neutrino measurements with the predicted signals from various models of the Earth. In 2010 Borexino collaboration presented the first observation of geo-neutrinos at Gran Sasso National Laboratory with more than 4σ C.L thanks to their low background; their measured signal should be compared with the prediction of the Reference Model for this area [11]. The KamLAND collaboration updated their first 2005 result [12] with larger statistics and lower background observing also geo-neutrinos with more than 4σ C.L. This improved observation combined with the existing Refined Reference model [13] for the Kamioka area is of great scientific interest.

OVERVIEW OF KAMLAND AND BOREXINO DETECTORS

Several detectors (KamLAND, Borexino, SNO+, LENA, Hanohano, Baksan) were proposed for geo-neutrino measurements. KamLAND and Borexino are the only two of them which are currently operative. The structure of these two detectors is almost the same [14, 15] and the antineutrinos are detected by the inverse beta-decay reaction

(Eq. 1). The energy threshold of the reaction, 1.806 MeV, is low enough to detect a part of geo-neutrinos from ^{238}U and ^{232}Th-series, but not those from ^{40}K. The reaction makes two correlated signals. The first signal, prompt signal, is made by the positron and two 0.51 MeV gamma particles generated by annihilation of the positron. The second signal, delayed signal, is made by a 2.2 MeV gamma particle, which is emitted in subsequence of thermal neutron capture on proton. This thermalization and capture process take about 200 sec, and positions of neutron capture are typically 30~50 cm apart from the neutrino reaction vertices [16].

The liquid scintillator (LS) essentially consists of hydrocarbons (C_nH_{2n}) which provide the hydrogen nuclei acting as targets for antineutrinos. An outer part filled with water acts as an active shield for cosmic muons whose Cerenkov light is detected. KamLAND has larger statistics due to its bigger fiducial volume and longer total run time. Borexino has higher purity, much lower flux of antineutrinos from reactors, and better energy resolution.

KamLAND (Kamioka Liquid scintillator Anti-Neutrino Detector), the largest low-energy antineutrino detector ever built, consists basically of about 1000 tons of ultra-pure LS contained in a 6.5 m radius spherical vessel viewed by 1879 17" photomultiplier tubes (PMT) that cover 34% of the sphere [16]. The detector is located 1000 m underground in the Kamioka mine, just beneath the Mt. Ikenoyama summit, Gifu, Japan. The 2700 m water equivalent thickness of rock covering the detector reduces cosmic muon flux by a factor 10^5.

The Borexino detector with its about 300 ton of LS [17, 18] is located deep underground, in the Hall C of the National Laboratory at Gran Sasso. The 3800 m of water equivalent above the detector reduce the muon flux by a factor of about 10^6. The LS is confined within a thin spherical nylon vessel with a radius of 4.25 m. The scintillation light is detected by 2212 8" PMT's, which cover nearly 30% of the sphere.

EXPECTED SIGNALS IN KAMLAND AND BOREXINO

A Reference Model (RM) is a necessary starting point for comparison of experimentally measured geo-neutrino signal with abundances of radioactive elements in the Earth.

Recently several such models have been presented in the literature [11, 19, 20, 21]. All these models rely on the geophysical 2° × 2° crustal map of [22, 23] and on the density profile of the mantle as given by PREM [24]. Signals predicted by these authors are in good agreement with each other. The small differences are due to the adopted abundances of U and Th in the crust and upper mantle, and to the model of mantle. All papers use the BSE mass constraint in order to determine the abundances in the lower portion of the mantle.

The minimal amount of radioactive elements in the Earth is the one compatible with lower bounds on measured abundances in the crust. One the other extreme, radiogenic elements cannot produce a global terrestrial heat flow greater than 44 TW, which is the maximal value compatible with extensive local sampling of the terrestrial heat flow [25]. This interval is rather large and can be reduced using geo-neutrino data. In fact the interval of allowed heat flow is considerably smaller if models have a fixed total amount of radioactive elements [13]. Indeed geo-neutrino experiments allow to determine the range of allowed radioactive elements. Models with fixed amount of radiogenic elements should also be consistent with geochemical and geophysical information. Good first approximations are the assumption of spherical symmetry, of a non-decreasing abundance of radioactive elements going down the mantle, and of a non-radiogenic core. These assumptions produce a strong correlation between geo-neutrino flux and radiogenic heat flow; therefore, recent geo-neutrino experimental results begin to give significant information on the Earth’s energetic budget.

For calculation of the geo-neutrino signal from uranium at KamLAND we follow Fiorentini et al. (2005). In this work a detailed geophysical and geochemical study of the region near the Kamioka mine (the closer the source is to the detector the larger its contribution is to the signal) made possible to decrease uncertainties. Signal from the six 2° × 2° tiles near detector is:

$$S_{reg} = (15.41 \pm 3.07) TNU \tag{2}$$

where TNU means terrestrial neutrino units (10^{-32} reactions per second per target nucleus). Signal from the Rest of the World is calculated in the geological framework of RM. For the upper and middle crust, we adopt the values recommended in [25], resulting from a detailed reanalysis of values presented in the literature and incorporating 1σ uncertainties. For the lower crust, values in the literature encompass a large interval. We adopt here a mean value together with an uncertainty indicative of the spread of published values. We have updated the U and Th abundances in the different reservoirs, in accordance with recent reviews.

The amount of uranium in the crust, according to abundances in literature, is within the interval $m_C = 0.3 \cdot 10^{17} - 0.4 \cdot 10^{17} kg$. Clearly the larger the mass is the bigger the signal is, the extreme values being

$$\begin{aligned} S_C^{\min} &= 6.448 \quad TNU \quad for \quad m_C = 0.3 \cdot 10^{17} kg \\ S_C^{\max} &= 8.652 \quad TNU \quad for \quad m_C = 0.4 \cdot 10^{17} kg \end{aligned} \tag{3}$$

Concerning uranium in the mantle, we assume that spherical symmetry holds and that the uranium mass abundance is a nondecreasing function of depth. It follows that, for a fixed uranium mass in the mantle m_M, the extreme predictions for the signal are obtained by: (1) placing uranium in a thin layer at the bottom and (2) distributing it with uniform abundance over the mantle. These two cases give, respectively:

$$\begin{aligned} S_M^{\min} &= 12.15 \times m_M TNU \\ S_M^{\max} &= 17.37 \times m_M TNU \end{aligned} \tag{4}$$

We can combine the contributions from crust and mantle so as to obtain extreme predictions: for a fixed total $m = m_C + m_M$, the highest signal is obtained by assigning to the crust as much material as consistent with observational data ($m_C = 0.4 \times 10^{17}$ kg) and putting the rest, $m - m_C$, in the mantle with a uniform distribution. Similarly, the minimal flux/signal is obtained for the minimal mass in the crust ($m_C = 0.4 \times 10^{17}$ kg) and the rest in a thin layer at the bottom of the mantle.

We remind that the total amount of radioactive elements should not produce a heat flow in excess of 44 TW. Radiogenic heat flow can be calculated as:

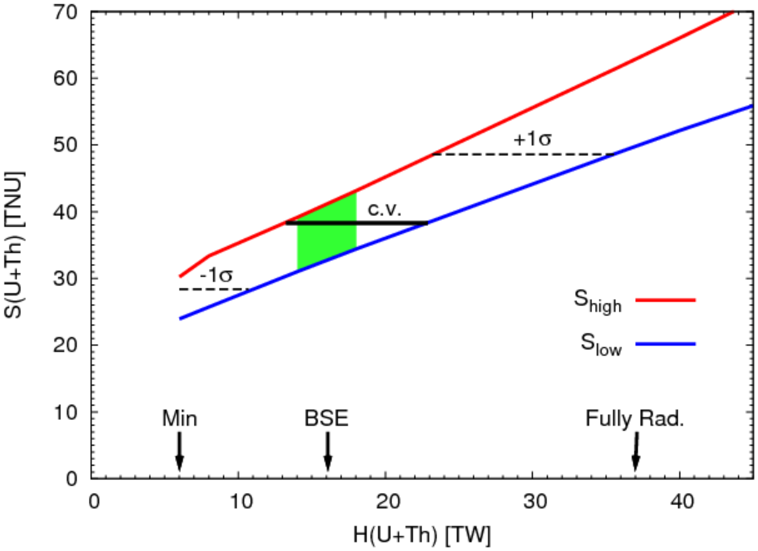

FIGURE 1. The predicted signal S(U+Th) from uranium and thorium geo-neutrinos at KamLAND as a function of radiogenic heat production rate H(U+Th). The green area denotes the region allowed by BSE constraint. The black solid line denotes the central value (c.v.) of the signal measured by KamLAND collaboration [12]; the dotted lines are the 1σ uncertainties of this measurement.

$$H_R = 9.85 \times m(U) + 2.67 \times m(Th) + 3.33 \times 10^{-4} \times m(K) \qquad (5)$$

where units are 10^{12} W and 10^{17} kg, respectively. Assuming the BSE mass ratios:

$$m(U) : m(Th) : m(K) = 1 : 3.9 : 12000 \qquad (6)$$

44 TW correspond to 1.8×10^{17} kg of uranium. The total signal S(U+Th) can be obtained by rescaling the uranium signal, Eqs. 3 and 4, if we assume a fixed Th/U ratio. For the BSE ratio Th/U=3.9 signal from thorium is about 1/5 of the total signal [9].

We can plot the two extreme cases S_{high} and S_{low} for the total signal in KamLAND as a function of heat flow due to uranium and thorium in the Earth, considering a fixed chondritic ratio Th/U (fig. 1). The estimates of the uranium mass within the BSE are all between (0.7 ÷ 0.9) × 10^{17} kg. This implies that the BSE signal is $S(U+Th) = 38.1 \pm 4.4 TNU$.

A detailed geological study of the region near National Gran Sasso Laboratory has been done and results are being analyzed. For the present, it is a good first approximation to use the RM also for region near Borexino. Contribution from the crust for fixed uranium mass (in unit of 10^{17} kg) is:

$$S_C = 69 \times m_C(U) TNU \qquad (7)$$

The spherical symmetric model of the mantle implies that its contribution to Borexino signal is the same as the contribution to KamLAND signal (Eq. 4). Fig. 2

shows the total geo-neutrino signal in Borexino as function of radiogenic heat production due to uranium and thorium with a fixed chondritic ratio. The prediticted signal in Borexino for BSE is $S(U+Th) = 40.5 \pm 6.5 TNU$ [11].

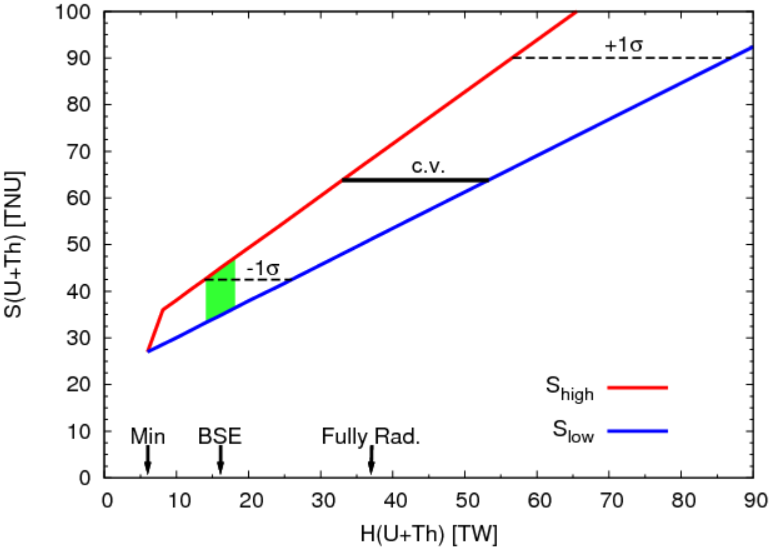

FIGURE 2. The predicted signal S(U+Th) from uranium and thorium geo-neutrinos at Borexino as a function of radiogenic heat production rate H(U+Th). The green area denotes the region allowed by BSE constraint. The black solid line denotes the central value (c.v.) of the signal measured by Borexino collaboration [29]; the dotted lines are the 1σ uncertainties of this measurement.

MEASURED SIGNALS AND HEAT FLOW

KamLAND collaboration for the first time published their result about geo-neutrino signal in 2005 [27]. The data presented in [27] were based on a total detector live-time of 749.1 ± 0.5 days in the period 2002-2005: the total exposure was 0.71×10^{32} target proton years. After a study of the signal, measuring of the cross section of $^{13}C(a, n)^{16}O$ [28] the total geo-neutrino signal was find as $S(U+Th) = 63^{+28}_{-25} TNU$. Two years later Borexino started to collect data and in march 2010 published a first evidence of geo-neutrino with more than 3σ C.L [29]. In spite of a total exposure of only 0.15×10^{32} target proton years, the absence of nearby reactors and the high purity of the LS resulted in a signal with smaller uncertainties $S(U+Th) = 64^{+26}_{-22} TNU$. Soon afterwards the KamLAND collaboration updated their previous result with higher statistic (total exposure 3.49×10^{32} proton×yr), better purified LS, and less background from nuclear power plants, due to the big earthquake that caused problems to some of the nuclear plant close to KamLAND, $S(U+Th) = 38.3^{+10.3}_{-9.9} TNU$ [12].

The data published by KamLAND collaboration in 2010 is in good agreement with the BSE model prediction (fig. 1). Experimental errors still dominate compared to the width of the band containing all models consistent with geochemical and geophysical data. For the sake of the present discussion it is sufficient to consider the central value, which represents our best estimate for the relationship between signal and power. The measured signal implies then a corresponding radiogenic heat flow $\mathrm{H(U+Th)} = 18^{+11}_{-11}\,\mathrm{TW}$.

On the other hand, the signal measured by the Borexino collaboration is closer to the prediction for a fully radiogenic model of Earth: $\mathrm{H(U+Th)} = 43^{+29}_{-23}\,\mathrm{TW}$. Discrimination between BSE and fully radiogenic model of Earth requires smaller errors.

In spite of the still large uncertainties on the heat flow determination from the two experiments, the interval that satisfies both measurements is somehow narrower. If we restrict ourselves to the central model, this interval is about 20 – 29 TW. The geo-neutrino measurements begin to determine radiogenic contribution to terrestrial heat flow within interesting intervals: the era of the combination of data from multiple sites is open.

CONCLUDING REMARKS

Radiogenic contribution to the Earth's heat flow was deduced from the experimental geo-neutrino signals of Borexino and KamLAND. The calculation is robust, but theoretical uncertainties on some reasonable assumptions (source distribution, Th/U and K/U ratios) of the model should be overcome to fully exploit future smaller uncertainties on geo-neutrino flux. To this end, local geological studies, detectors at different locations and with some directionality will be important.

Given the present experimental situation, we used the rather general approach based on the minimal mass of uranium consistent with crust measures (0.3×10^{17} kg), on the maximal total heat flow (44 TW) consistent with experimental local measures, on the U/Th and K/Th BSE ratios and on a non decreasing abundance of radioactive elements in the lower mantle. This approach gives lower and upper bounds on the heat flow and a range of possible values corresponding to a given geo-neutrino flux measurement. The total range of U and Th heat flow consistent with geo-neutrino measurements is still large (14 – 36 TW), but soon multi-site measurements and analysis could restrict it.

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