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A brief review on geo-neutrinos

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The detection of neutrinos from U, Th, and K decay in the Earth (geo-neutrinos) will help to fix the total amount of long-lived radioactive elements and thus the radiogenic contribution to the terrestrial heat. Moreover, it will provide a direct test of a fundamental paradigm about the origin, formation and structure of the Earth, i.e., the Bulk Silicate Earth model. Alternative or variant models of Earth (including the presence of potassium or the possibility of a giant reactor in the core) can also be checked. This short review presents the status and prospects in this exciting field of research.

1. DEEP EARTH PROBES

The deepest hole that has ever been dug is about 12 km deep, a mere dent in planetary terms. Geochemists analyze samples from the Earth's crust and from the top of the mantle. Seismology can reconstruct the density profile throughout all Earth, but not its composition. In this respect, our planet is mainly unexplored.

Geo-neutrinos, the antineutrinos from the progenies of U, Th and ^{40}K decays in the Earth, bring to the surface information from the whole planet, concerning its content of radioactive elements. Their detection can shed light on the sources of the terrestrial heat flow, on the present composition and on the origin of the Earth [1].

Geo-neutrino properties are summarized in Table 1, where the last two columns present the heat and anti-neutrino production rates per unit mass and natural isotopic composition.

Geo-neutrinos originating from different elements can be distinguished due to their different energy spectra, e.g., geo-neutrinos with $E > 2.25$ MeV are produced only in the Uranium chain. Geo-neutrinos from U and Th (not those from ^{40}K) are above threshold for the classical anti-neutrino detection reaction, the inverse beta on free protons:

$$\bar{\nu} + p \rightarrow e^{+} + n - 1.8 \text{ MeV} \quad . \tag{1}$$

Anti-neutrinos from the Earth are not obscured by solar neutrinos, which cannot yield reaction (1).

In this short review we shall concentrate on geo-neutrinos from Uranium, which are closer to experimental detection, and on the predictions for Kamioka site hosting KamLAND [2], the only detector which is presently operational.

2. HISTORY

Geo-neutrinos were introduced by Eder in the sixties and Marx soon realized their relevance. In the eighties Krauss et al. discussed their potential as probes of the Earth's interior in an extensive publication. In the nineties the first paper on a geophysical journal was published by Kobayashi et al. In 1998, Raghavan et al. and Rotschild et al. pointed out that KamLAND and Borexino should be capable of geo-neutrino detection.

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Table 1
The main properties of geo-neutrinos.

Decay	Q [MeV]	$\tau_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	ϵ_H [W/Kg]	$\epsilon_{\bar{\nu}}$ [$\mathrm{kg}^{-1}\mathrm{s}^{-1}$]
$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e + 6\bar{\nu}$	51.7	4.47	3.26	0.95×10^{-4}	7.41×10^7
$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e + 4\bar{\nu}$	42.7	14.0	2.25	0.27×10^{-4}	1.63×10^7
$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e + \bar{\nu}$	1.32	1.28	1.31	0.36×10^{-8}	2.69×10^4

In the last two years more papers appeared than in the preceding millennium: in a series of papers Fiorentini et al. [3–5] discussed the potential of geo-neutrinos for determining the radiogenic contribution to the terrestrial heat flow and for discriminating among different models of Earth's composition and origin.

The indication of geo-neutrinos in the first data release from KamLAND [2] was a most important point which stimulated several investigations, see e.g [6].

3. ENERGY SOURCES IN THE EARTH

There is a tiny flux of heat coming from the Earth. It depends on the site and is generally of the order of 60 $\mathrm{mW/m^2}$.

In a recent paper with the same title as this paragraph, Anderson [7] writes: "Global heat flow estimates range from 30 to 44 TW . . . Estimates of the diogenic contribution . . . based on cosmochemical considerations, vary from 19 to 31 TW. Thus, there is either a good balance between current input and output, . . . or there is a serious missing heat source problem, up to a deficit of 25 TW".

We remark that the radiogenic component is essentially based on cosmo-chemical considerations and that a direct determination, as offered by geo-neutrino detection, is important.

4. U, Th AND K RESERVOIRS IN THE EARTH

Earth global composition is generally estimated from that of CI chondritic meteorites by using geochemical arguments which account for loss and fractionation during planet formation. Along these lines the Bulk Silicate Earth (BSE) model is built, which describes the "primitive mantle", i.e., the outer portion of the Earth after core separation and before the differentiation between crust and mantle. The model is believed to describe the present crust plus mantle system. It provides the total amounts of U, Th and K in the Earth, as these lithophile elements should be absent in the core. Estimates from different authors [8] are concordant within 10-15%. From the mass, the present radiogenic heat production rate and neutrino luminosity can be calculated, see Table 2.

Table 2
U, Th and K according to BSE

	m [10^{17} kg]	H_R [10^{12} W]	L_ν [10^{24} s^{-1}]
U	0.8	7.6	5.9
Th	3.1	8.5	5.0
^{40}K	0.8	3.3	21.6

The BSE is a fundamental geochemical paradigm. It is consistent with most observations, which however regard the crust and the uppermost portion of the mantle only. Its prediction for the present radiogenic production is 19 TW.

Concerning the distribution of radiogenic elements, estimates for Uranium in the (continental) crust based on observational data are in the range: $m_C(\mathrm{U}) = (0.3 - 0.4)10^{17}$kg. The crust — really a tiny envelope — should thus contain about one half of Uranium in the Earth.

For the mantle, observational data are scarce and restricted to the uppermost part, so the best estimate for its Uranium content $m_M(\mathrm{U})$ is obtained by subtracting the crust contribution to the BSE estimate: $m_M(\mathrm{U}) = m_{\mathrm{BSE}}(\mathrm{U}) - m_C(\mathrm{U})$.

Compositionally, geochemists prefer a two-layered mantle, the lower part being closer to the primitive composition (Uranium mass abundance $a(\mathrm{U}) = 20$ ppb), the upper part being impoverished in these elements, $a(\mathrm{U}) = (5-8)$ ppb. On the other hand, seismological evidence points toward a fully mixed and thus globally homogeneous mantle.

Similar considerations hold for Thorium and Potassium, the relative mass abundance with respect to Uranium being globally estimated as $a(\mathrm{Th}) : a(\mathrm{U}) : a(\mathrm{K}) = 4 : 1 : 10,000$.

Alternatives to the canonical BSE model are discussed in ref. [1].

In summary, the BSE is a fundamental geochemical paradigm accounting for the radiogenic production of about 19 TW. It is consistent with most observations, which however regard the crust and the uppermost portion of the mantle only, most of the Earth being unexplored. It should be tested.

5. NEUTRINO FLUXES AND EVENT RATES

An order of magnitude estimate of the angle integrated flux Φ_{ar} of $\bar{\nu}_e$ arriving at the detector position, is immediately obtained from:

$$\Phi \approx \frac{\langle P_{ee}\rangle L}{4\pi R^2} \quad , \tag{2}$$

where $\langle P_{ee}\rangle = 0.59$ is the average survival probability and R is the Earth's radius. This gives antineutrino fluxes of order 10^6 cm^{-2}s^{-1}, comparable to that of ^{8}B neutrinos from the Sun. From the cross section for reaction (1) the reaction rates $S(\mathrm{U})$ and $S(\mathrm{Th})$ in a detector containing N_p free protons are:

$$S(\mathrm{U}) = 13.2\frac{\Phi_{\mathrm{ar}}(\mathrm{U})}{10^6\mathrm{cm}^{-2}\mathrm{s}^{-1}}\frac{N_p}{10^{32}}\ \mathrm{yr}^{-1} \tag{3}$$

$$S(\mathrm{Th}) = 4.0\frac{\Phi_{\mathrm{ar}}(\mathrm{Th})}{10^6\mathrm{cm}^{-2}\mathrm{s}^{-1}}\frac{N_p}{10^{32}}\ \mathrm{yr}^{-1} \quad . \tag{4}$$

This gives some tens of events per year in a kiloton detector.

For a precise estimate of the flux as a function of the amount m of the parent element in the Earth one needs to know the distribution of that element inside the Earth. This involves several steps, which we shall elucidate for Uranium geoneutrinos:

i) For the world crust, one resorts to geological maps of the Earth crust. A 2° × 2° map, distinguishing seven crust layers, has been used in Ref. [5]. Concerning element abundances, for each layer minimal and maximal estimates present in the literature are adopted, so as to obtain a range of acceptable fluxes.

ii) For Uranium in the mantle, one assigns to it a mass $m_M(\mathrm{U}) = m(\mathrm{U}) - m_C(\mathrm{U})$. Generally, the minimal (maximal) contributed flux is obtained by placing this Uranium as far (close) as possible to the detector [9]. By assuming spherical symmetry in the mantle and that the Uranium mass abundance is a non decreasing function of depth the two cases corresponds respectively to: (a) placing Uranium in a thin layer at the bottom and (b) distributing it with uniform abundance over the mantle.

iii) This argument can be used again to combine the flux from crust and mantle: for a fixed total m, the highest flux is obtained by assigning to the crust as much as consistent with observational data ($m_C(\mathrm{U}) = 0.4 \times 10^{17}$ kg) and putting the rest $m(\mathrm{U}) - m_C(\mathrm{U})$ in the mantle with a uniform distribution. Similarly the minimal flux is obtained for the minimal mass in the crust ($m_C(\mathrm{U}) = 0.3 \times 10^{17}$ kg) and the rest in a thin layer at the bottom of the mantle.

We remark that *this argument, combining global mass balance with geometry, is very powerful in constraining the range of fluxes, which come out to be determined in a range of about* ±10% *for a fixed value of* $m(\mathrm{U})$.

For a full exploitation of this information one needs a more detailed geochemical and geophysical study of the region within a few hundreds kilometers from the detector, where some half of the signal is generated. The goal is to reduce the error on the regional contribution to the level of the uncertainty on the rest of the world. This has been recently performed [10] for the region near the KamLAND detector, which has been analyzed us-

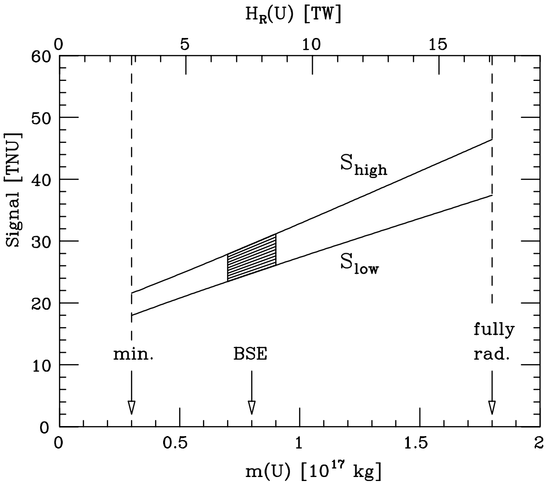

Figure 1. The predicted signal from Uranium geo-neutrinos at KamLAND.

ing geochemical information on a 0.25° × 0.25° grid and a detailed map of the crust depth. The possible (minimal and maximal) effects of the Pacific slab subducting beneath Japan are considered and the uncertainty arising from the debated (continental or oceanic) nature of the crust below the Japan sea is taken into account.

The expected signal from Uranium at KamLAND is presented as a function of the total uranium mass $m(\mathrm{U})$ in Fig. 1. The upper horizontal scale indicates the corresponding radiogenic heat production rate from Uranium. The signal is given in Terrestrial Neutrino Units:

$$1\ \mathrm{TNU} = 1\ \mathrm{event}/(10^{32}\ \mathrm{protons} \cdot \mathrm{yr}) \quad . \tag{5}$$

The predicted signal as a function of $m(\mathrm{U})$ is between the two lines denoted as S_{low} and S_{high}.

Since the minimal amount of Uranium in the Earth is 0.3×10^{17} kg (corresponding to the minimal estimate in the crust and a negligible amount in the mantle), we expect a signal of at least 18 TNU. The maximal amount of Uranium tolerated by Earth energetics, 1.8×10^{17} kg, implies a signal not exceeding 46 TNU.

We remark that estimates by different authors for the Uranium mass within the BSE are all between $(0.7 - 0.9) \times 10^{17}$ kg. This translates into:

$$23 < S(\mathrm{U}) < 31\ \mathrm{TNU} \quad . \tag{6}$$

The measurement of geo-neutrinos can thus provide a direct test of an important paradigm.

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