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Geo-Neutrinos: a short review

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Geo-neutrino detection will determine the amount of long lived radioactive elements within our planet and fix the debated radiogenic contribution to the terrestrial heat. In addition, it will provide a direct test of the Bulk Silicate Earth model, a fundamental cosmochemical paradigm about the origin of the Earth. Unorthodox models of Earth's core (including the presence of potassium or the possibility of a giant reactor) can also be checked. This short review presents status and prospects of the field.

1. PROBES OF THE EARTH'S INTERIOR

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.

They represent a new probe of our planet, which is becoming practical as a consequence of two fundamental advances that occurred in the last few years: a) development of extremely low background neutrino detectors and b) progress on understanding neutrino propagation.

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.

For each element there is a strict connection between the geo-neutrino luminosity L (anti-neutrinos produced in the Earth per unit time), the radiogenic heat production rate H_R and the mass m of that element in the Earth:

$$L = 7.4 \times m(\mathrm{U}) + 1.6 \times m(\mathrm{Th}) + 27 \times m(^{40}\mathrm{K}) \quad (1)$$

$$H_R = 9.5 \times m(\mathrm{U}) + 2.7 \times m(\mathrm{Th}) + 3.6 \times m(^{40}\mathrm{K}) \quad (2)$$

where units are 10^{24} s^{-1}, 10^{12} W and 10^{17} kg, respectively.

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:

$$\bar{\nu} + p \rightarrow e^+ + n - 1.8\ \mathrm{MeV} \quad . \quad (3)$$

Anti-neutrinos from the Earth are not obscured by solar neutrinos, which cannot yield reaction (3).

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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]	$\epsilon_{\bar{\nu}}$ [kg^{-1}s^{-1}]
$^{238}\text{U} \rightarrow {}^{206}\text{Pb} + 8\,{}^4\text{He} + 6e + 6\bar{\nu}$	51.7	4.47	3.26	0.95×10^{-4}	7.41×10^7
$^{232}\text{Th} \rightarrow {}^{208}\text{Pb} + 6\,{}^4\text{He} + 4e + 4\bar{\nu}$	42.7	14.0	2.25	0.27×10^{-4}	1.63×10^7
$^{40}\text{K} \rightarrow {}^{40}\text{Ca} + e + \bar{\nu}$	1.32	1.28	1.31	0.36×10^{-8}	2.69×10^4

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 [1], the only detector which is presently operational.

2. A BIT OF HISTORY

Geo-neutrinos were introduced by Eder [2] in the sixties and Marx [3] soon realized their relevance. In the eighties Krauss et al. discussed their potential as probes of the Earth's interior in an extensive publication [4]. In the nineties the first paper on a geophysical journal was published by Kobayashi et al. [5]. In 1998, Raghavan et al. [6] and Rotschild et al. [7] pointed out that KamLAND and Borexino should be capable of geo-neutrino detection.

In the last two years more papers appeared than in the preceding millennium: in a series of papers Fiorentini et al. [8–10] 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 [1] was a most important point which stimulated several investigations [11–19].

3. ENERGETICS OF THE EARTH AND THE MISSING HEAT SOURCE MYSTERY

There is a tiny flux of heat coming from the Earth. It depends on the site and is generally of the order of 60 mW/m^2. By suitably integrating over the Earth surface one obtains a total flow H_E in the range 30-45 TW, the equivalent of some 10^4 nuclear plants. A frequently quoted estimate is $H_E = (44 \pm 1)$ TW [20], where the statistical error does not account for the systematic uncertainties (in particular concerning the contributions of the oceanic crust). For sure, heat released from radiogenic elements is important, however its role is not understood at a quantitative level.

Verhoogen in 1980 [21] makes the following summary : "... What emerges from this morass of fragmentary and uncertain data is that radioactivity itself could possibly account for at least 60 per cent if not 100 per cent of the Earth's heat output ... If one adds the greater rate of radiogenic heat production in the past, possible release of gravitational energy (original heat, separation of the core ...) tidal friction ... and possible meteoritic impact ... the total supply of energy may seem embarrassingly large".

In a recent paper with the same title as this paragraph, Anderson [22] has a more cautious approach: "Global heat flow estimates range from 30 to 44 TW ... Estimates of the radiogenic contribution ... based on cosmochemical considerations, vary from 19 to 31 TW. Thus, there is either a good balance between current input and output, as was once believed, ... 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 IN THE EARTH: HOW MUCH AND WHERE?

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 [23] are concordant within 10-15%. From the mass, the present radiogenic heat production rate and neutrino luminosity can be immediately calculated by means of Eqs. (1) and (2) and are shown in the following 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:

$$m_C(\mathrm{U}) = (0.3 - 0.4)10^{17}\mathrm{kg} \quad . \tag{4}$$

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:

$$m_M(\mathrm{U}) = m_{\mathrm{BSE}}(\mathrm{U}) - m_C(\mathrm{U}) \quad . \tag{5}$$

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 $a(\mathrm{Th}) : a(\mathrm{U}) : a(\mathrm{K}) = 4 : 1 : 10,000$.

Geochemical arguments are against the presence of radioactive elements in the (completely unexplored) core, as discussed by McDonough in an excellent review of compositional models of the Earth [23].

For a comparison, let us summarize some — less orthodox or even heretical — alternatives to the canonical BSE model:

a) it is conceivable that the original material from which the Earth formed is not wholly the same as inferred from CI-chondrites. A model with initial composition as that of enstatite chondrites could account for a present production of some 30 TW [24,25].

b) A model where the BSE abundances of U, Th and K are proportionally rescaled by a factor of 2.3 cannot be excluded by the observational data, if one assumes that the missing radiogenic material is hidden below the upper mantle. This model gives a present radiogenic heat production of 44 TW, the maximum which can be tolerated by Earth energetics since it takes time to bring heat to the surface and more heat was produced in the past.

c) Several authors have been considering the possibility that a large amount of Potassium is sequestered into the Earth's core, where it provides the light element to account for the right core density, the energy source for driving the terrestrial dynamo and — more generally — an additional contribution to Earth energy budget.

d) Herndon [26] has proposed that a large drop of Uranium has been collected at the center of the Earth, forming a natural 3-6 TW breeder reactor, see also [27]. In this case nuclear fission should provide the energy source for terrestrial magnetic field, a contribution to missing heat, and the source of the anomalous ^{3}He/^{4}He flow from Earth.

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. FROM LUMINOSITY TO FLUX AND SIGNAL

The goal with geo-neutrinos is the determination of the neutrino luminosities L produced in the Earth (for each element), which immediately give the amounts of radioactive material in the Earth's interior.

What is measured is the angle integrated flux $\Phi_{\rm ar}$ of $\bar{\nu}_e$ arriving at the detector position. An order of magnitude estimate is immediately obtained from:

$$\Phi \approx \frac{\langle P_{ee}\rangle L}{4\pi R^2} \quad , \tag{6}$$

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 (3) the reaction rates S(U) and S(Th) in a detector containing N_p free protons are:

$$S(\mathrm{U}) = 13.2 \frac{\Phi_{\rm ar}(\mathrm{U})}{10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}} \frac{N_p}{10^{32}} \ \mathrm{yr}^{-1} \tag{7}$$

$$S(\mathrm{Th}) = 4.0 \frac{\Phi_{\rm ar}(\mathrm{Th})}{10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}} \frac{N_p}{10^{32}} \ \mathrm{yr}^{-1} \quad . \tag{8}$$

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 geo-neutrinos:

i) For the world crust, one resorts to geological maps of the Earth crust. A $2^\circ \times 2^\circ$ map, distinguishing seven crust layers, has been used in Ref. [10]. 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. Depending on the adopted values, the Uranium mass in the crust $m_C(\mathrm{U})$ is in between $(0.3 - 0.4) \times 10^{17}$ kg, the larger the mass, the bigger the signal.

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 [28]. By assuming spherical symmetry in the mantle and that the Uranium mass abundance is a non decreasing function of depth the two cases correspond 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 ($m_C(\mathrm{U}) = 0.4$) 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 ($m_C(\mathrm{U}) = 0.3$) 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* $\pm 10\%$ *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 [29] for the region near the

KamLAND detector, which has been analyzed using 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 [29]. The upper horizontal scale indicates the corresponding radiogenic heat production rate from Uranium. The signal is given in Terrestrial Neutrino Units:

$$1\ \mathrm{TNU} = 1\ \mathrm{event}/(10^{32}\ \mathrm{protons} \cdot \mathrm{yr}) \quad . \qquad (9)$$

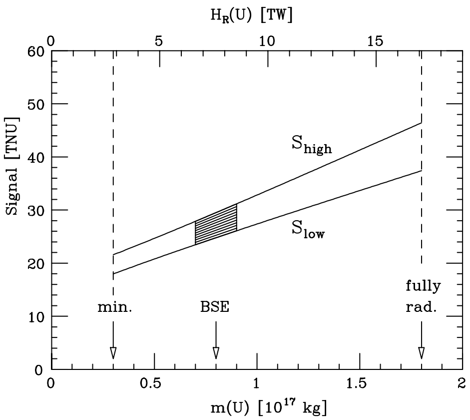

Figure 1. The predicted signal from Uranium geo-neutrinos at KamLAND.

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:

$$23 < S(\mathrm{U}) < 31\ \mathrm{TNU} \quad . \qquad (10)$$

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

6. LOOKING FORWARD TO NEW DATA

At the end of 2002, in the first data release equivalent to an exposure 0.11×10^{32} proton · yr and 100% efficiency, KamLAND reported [1] 4 events from Uranium and 5 from Thorium from a total of 32 counts in the geo-neutrino energy region ($E_{\mathrm{vis}} < 2.6$ MeV), after subtracting 20 reactor events and 3 background counts. Statistical fluctuations imply that the (1σ) error is, at least, 5.7 counts. This means:

$$S(\mathrm{U+Th}) = (82 \pm 52)\mathrm{TNU} \quad . \qquad (11)$$

The uncertainty is so large that the result is just an indication of geo-neutrinos.

By now, KamLAND has accumulated a much larger statistics (see the talk by G. Gratta) and the group is presently analyzing data which might provide a definite geo-neutrino signal.

The vicinity of many nuclear-power reactors, which was essential for the study of neutrino oscillations, is a major drawback for measuring geo-neutrinos, the signal ratio being $S_{\mathrm{rea}}/S_{\mathrm{geo}} = 5 - 10$.

Several projects for geo-neutrino detection are being developed (see Fig. 2 for the predicted signals at a few locations). Borexino at Gran Sasso in Italy is expected to take data in a few years. With respect to KamLAND, its smaller fiducial mass can be compensated by the absence of nearby reactors ($S_{\mathrm{rea}}/S_{\mathrm{geo}} \approx 1$).

Mikaelyan et al. are proposing a 1 Kton scintillator detector in Baksan, again very far from nuclear reactors.

A group at the Sudbury Neutrino Observatory in Canada is studying the possibility of moving to liquid scintillator after the physics program with

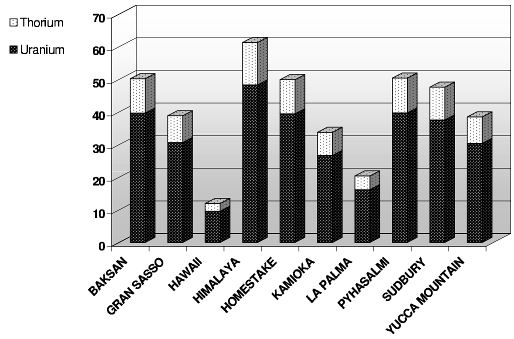

Figure 2. Predicted signals, in TNU [10].

heavy water is completed. With very low reactor background and in the middle of a well studied geological environment it will have excellent opportunity for geo-neutrino studies.

The LENA proposal envisages a 30 Kton liquid scintillator detector at the Center for Underground Physics in the Pyhäsalmi mine (Finland). Due to the huge mass, it should collect several hundreds of events per year.

In conclusion, one can expect that within ten years the geo-neutrino signal from Uranium and Thorium will be measured at a few points over the globe. This will fix the radiogenic contribution of these elements to the terrestrial heat and will provide a direct test of a fundamental paradigm on the origin and the composition of our planet.

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