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Neutrinos and energetics of the Earth

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Abstract

We estimate terrestrial antineutrino and neutrino fluxes according to different models of Earth composition. We find large variations, corresponding to uncertainties on the estimated U, Th and K abundances in the mantle. Information on the mantle composition can be derived from antineutrino flux measurements after subtracting the crust contribution. This requires a good description of the crust composition in the region of the detector site. Measurements of terrestrial antineutrinos will provide a direct insight on the main sources of Earth's heat flow.

1. Introduction

Earth emits a tiny heat flux with an average value $\Phi_{\rm H} = 80\ {\rm mW\,m^{-2}}$, definitely smaller than the radiation coming from the Sun, $K_\odot = 1.4\ {\rm kW\,m^{-2}}$, larger however than the energy deposited by cosmic rays, $\Phi_{\rm c} \simeq 10^{-8}\ {\rm W\,m^{-2}}$. When integrated over the Earth surface, the tiny flux translates into a huge heat flow, $H_\oplus \simeq 40$ TW, the equivalent of ten thousand nuclear power plants [1].

We would like to recall to the particle physics community that the sources of Earth energy flow are not understood quantitatively and that measurements of (anti)neutrinos from the Earth in the next few years should be capable of determining the radiogenic contribution.

A comparison between the Sun and Earth energy inventories may be useful for illustrating the differences in the two cases. Clearly, a heat flow H can be sustained for a time t provided that an energy source of at least $U = Ht$ is available.

For the Sun, $U = H_\odot t_\odot \simeq 5 \times 10^{43}$ J and clearly neither gravitation ($U_{\rm G} \simeq GM_\odot^2/R_\odot = 4 \times 10^{41}$ J) nor chemical reactions ($U_{\rm ch} \simeq (0.1\ {\rm eV})N_\odot = 2 \times 10^{37}$ J, where $N_\odot$ is the number of nucleons) are enough, and only nuclear energy ($U_{\rm nuc} \simeq (1\ {\rm MeV})N_\odot = 2 \times 10^{44}$ J) can sustain the solar luminosity over the solar age, as beautifully demonstrated gallium experiments in the last decade [2]. On the other hand for the Earth one has $U_{\rm G} \simeq 4 \times 10^{32}$ J, $U_{\rm ch} \simeq 6 \times 10^{31}$ J and $U_{\rm nuc} \simeq 6 \times 10^{30}$ J (assuming some that some 10^{-8} of Earth mass consists of radioactive nuclei), so that each of the previous mechanisms in principle can account for $U_\oplus = 5 \times 10^{30}$ J. In order to understand the energetics of the Earth one has to clarify the roles

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of the different energy sources, their locations and when they have been at work. At the end of a review on the Earth energy sources Verhoogen [3] summarized the situation with the following words: "*What emerges from this morass of fragmentary and uncertain data is that radioactivity by itself could plausibly account for at least 60 percent, if not 100 percent, 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 core, separation of inner core, tidal friction,... meteoritic impact...*)*, the total supply of energy may seem embarrassingly large. ... Most, if not all of the figures mentioned above are uncertain by a factor of at least 2, so that disentangling contributions from the several sources is not an easy problem*."

In this respect a determination of the radiogenic contribution is most important. Radiogenic heat arises mainly[1] from the decay (chains) of ^{238}U, ^{232}Th and ^{40}K. All these elements produce heat together with antineutrinos, with well fixed ratios heat/neutrinos. A measurement of the antineutrino flux, and possibly of the spectrum, would provide a direct information on the amount and composition of radioactive material inside Earth and thus would determine the radiogenic contribution to the heat flow.

On the other hand, until recently the neutrino fate could not be predicted reliably, as testified by the thirty years old solar neutrino puzzle [4]. The disagreement between theory and observation by factors of order two suggested that (anti)neutrino survival probabilities were essentially known within factors of two. Thus observation of terrestrial (anti)neutrinos could not be useful for improving our knowledge of Earth radioactivity. The situation has dramatically changed since the SNO results [6], which clearly prove that a fraction of electron neutrinos change their flavor during the trip form Sun to Earth. When combined with the results of other solar and terrestrial neutrino experiments, the picture is converging towards the so-called large mixing angle (LMA) oscillation solution. In other words, now we can predict reliably the fate of terrestrial neutrinos and antineutrinos, in their trip from production site to detectors.

Last but not least, the experimental techniques for detection of MeV antineutrinos have enormously improved in the last few years. As testified by the development of KamLAND [7] and Borexino [8], it is now possible to build kiloton size detectors, with extremely low background.

The argument of geo-neutrinos was introduced by Eder [9] in the sixties, it was reviewed extensively by Krauss, Glashow and Schramm [10] in the eighties and it has been considered more recently in [11,12]. Now it is the right time for neutrino physics to contribute in reconstructing the thermal history of the Earth.

2. Energy sources and neutrino luminosities

The heat production rates per unit mass of *natural* U, Th and K are given by:[2]

$$\begin{aligned}\epsilon(\mathrm{U}) &= 0.95\times 10^{-4}\ \mathrm{W\,kg^{-1}},\\ \epsilon(\mathrm{Th}) &= 0.27\times 10^{-4}\ \mathrm{W\,kg^{-1}},\\ \epsilon(\mathrm{K}) &= 0.36\times 10^{-8}\ \mathrm{W\,kg^{-1}}.\end{aligned} \tag{1}$$

This is sufficient to determine the Earth radiogenic heat production rate H in terms of the mass of each element. When heat production is expressed in TW and masses in units of 10^{17} kg one has:

$$H = 9.5\,M(\mathrm{U}) + 2.7\,M(\mathrm{Th}) + \left(3.6\times 10^{-4}\right)M(\mathrm{K}). \tag{2}$$

It is convenient to write this equation in terms of the uranium mass $M(\mathrm{U})$ and of the mass ratios of the other elements to U, as these latter quantities are more regularly distributed in terrestrial and meteoritic samples:

$$H = 9.5\,M(\mathrm{U})\left[1 + 0.28\,\mathrm{Th/U} + \left(3.8\times 10^{-5}\right)\mathrm{K/U}\right]. \tag{3}$$

The specific neutrino production rate (neutrinos per unit mass and time) of each element ϵ_ν, is immediately derived from the isotopic abundance, decay time and the number of neutrinos emitted in each decay, see Table 1. (Anti)Neutrinos luminosities are immediately derived in terms of the mass of each element and

[1] For simplicity we neglect ^{235}U and ^{87}Rb which provide smaller contributions.

[2] The marked difference of ϵ(K) corresponds to the fact that the natural abundance of ^{40}K is 1.2×10^{-4}, i.e., $\epsilon(^{40}\mathrm{K}) = 0.3\times 10^{4}\ \mathrm{W\,kg^{-1}}$.

Table 1
Main radiogenic sources. We report the Q-values, the half lives ($\tau_{1/2}$), the maximal energies ($E_{\max}$) and (anti)neutrino production rates ($\epsilon_{\bar{\nu}/\nu}$) per unit mass for *natural* isotopic abundances. Neutrinos from electron capture are monochromatic

Decay	Q [MeV]	$\tau_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	$\epsilon_{\bar{\nu}/\nu}$ [kg^{-1} s^{-1}]
$^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\ {}^4\mathrm{He} + 6e + 6\bar{\nu}$	51.7	4.47	3.26	7.41×10^7
$^{232}\mathrm{Th} \to {}^{208}\mathrm{Pb} + 6\ {}^4\mathrm{He} + 4e + 4\bar{\nu}$	42.8	14.0	2.25	1.63×10^7
$^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + e + \bar{\nu}$	1.321	1.28	1.31	2.69×10^4
$^{40}\mathrm{K} + e \to {}^{40}\mathrm{Ar} + \nu$	1.513		1.51	3.33×10^3

the appropriate $\epsilon_{\bar{\nu}/\nu}$. Measuring $L_{\bar{\nu}/\nu}$ in units of 10^{24} particles per second and masses in units of 10^{17} kg one has:

$$L_{\bar{\nu}} = 7.4\,M(\mathrm{U}) + 1.6\,M(\mathrm{Th}) + \left(2.7 \times 10^{-3}\right) M(\mathrm{K}), \tag{4}$$

$$L_{\nu} = \left(3.3 \times 10^{-4}\right) M(\mathrm{K}). \tag{5}$$

We have thus the basic equations for determining radiogenic heat production and neutrino flows from models of the Earth composition.

2.1. A naive chondritic Earth

The simplest model assumes that the global composition of the Earth is similar to that of the oldest meteorites, the carbonaceous chondrites (CI).

The typical values of CI [5] are $\mathrm{Th/U} = 3.8$, $\mathrm{K/U} = 7 \times 10^4$ and $\mathrm{U/Si} = 7.3 \times 10^{-8}$ [1]. Silicon represents about 15% of the Earth mass, $M_{\oplus} = 5.97 \times 10^{24}$ kg. If these elements have not been lost in the Earth formation process, one obtains $M(\mathrm{U}) = 0.653 \times 10^{17}$ kg, $M(\mathrm{Th}) = 2.48 \times 10^{17}$ kg and $M(\mathrm{K}) = 4.57 \times 10^{21}$ kg.

The contribution to heat flows and neutrino luminosities are reported in the first column of Table 2. Radiogenic production in the chondritic model easily accounts for 75% of the observed heat flow, and it could easily saturate it when uncertainties are included. Uranium and thorium provide comparable contributions, each a factor of two below that of potassium. Concerning antineutrinos, potassium dominates by an order of magnitude at least, as a consequence of the more favourable neutrino/energy ratio.

2.2. The bulk silicate Earth model

Uranium, thorium and potassium are lithophile elements, so they should accumulate in the Earth crust. Actually, upon averaging data over the huge differences between continental and oceanic components, it is found that Earth crust contains some 3/4 of the uranium predicted for the whole Earth by the chondritic model [1]. Within large variations, Th/U is consistent with the chondritic prediction. On the other hand, the crust looks depleted in potassium, the typical ratio being $\mathrm{K/U} = 10\,000$, a factor 7 below that of CI.

Observational data on the mantle, which are anyhow limited to the upper part, suggest that uranium and potassium are globally more abundant than the CI prediction, Th/U is consistent with the chondritic value and the potassium depletion is confirmed. No observational data are available on the core, which should consist of siderophile elements without significant amount of U, Th or K.

Actually, when deriving Earth composition from meteoritic data, one has to take into account the volatilization of a significant fraction (some 17%) [15] of the total SiO_2, so that a larger amount of meteoritic material is needed for Earth formation.

The origin of potassium depletion, also observed in the Moon, Venus and Martian meteorites, is somehow uncertain. Elements of the atomic weight of potassium cannot be lost from the terrestrial planets, even at elevated temperatures, once these bodies have reached their present size [16]. The most reasonable explanations seems that this element was depleted in the precursor planetesimals from which the inner planets accumulated.[3]

[3] It has been suggested that potassium behaves as a metal at high pressure, and thus it can be buried in the planetary cores. This hypothesis could work for Earth, and it provides a suitably placed energy source for sustaining the terrestrial magnetic field, see [1]. However it does not explain potassium depletion in Mars, where the central pressure, only 400 kbars, is insufficient for potassium to enter a Martian core.

Table 2
Masses, heat and neutrino production rates. M, H and L are in units of 10^{17} kg, 10^{12} W and 10^{24} s^{-1}, respectively. $H_{\rm NR}$ is defined as the difference between total heat flow $H_\oplus$ and the radiogenic production

Model	Chondritic	BSE	Fully radiogenic
M(U)	0.65	0.84	1.7
M(Th)	2.5	3.4	6.5
M(K)	4.6×10^4	0.84×10^4	1.7×10^4
H(U)	6.2	7.9	16.3
H(Th)	6.7	8.6	17.6
H(K)	16.4	3.0	6.1
$H_{\rm NR}$	10.7	20.5	0
$L_{\bar\nu}$(U)	4.8	6.2	12.7
$L_{\bar\nu}$(Th)	4.0	5.2	10.6
$L_{\bar\nu}$(K)	123	22.5	46.0
L_ν(K)	15.2	2.8	5.7

All this brings us to the Bulk Silicate Earth (BSE) model, which provides a description of geological evidence coherent with geochemical information. It describes the primordial mantle, prior to crust separation. The estimated uranium mass is:

$$M(\mathrm{U}) = 0.8\times10^{17}\ \mathrm{kg}, \tag{6}$$

within some 20% [17], the ratio Th/U is close to the chondritic value and K/U = 10 000. The present crust and mantle should contain respectively about one half of each element.

In this BSE model the (present) radiogenic production, mainly from uranium and thorium, accounts for about one half of the total heat flow. The antineutrino luminosities from uranium and thorium are rescaled by a factor 1.3 whereas potassium, although reduced by a factor of 5, is still the principal antineutrino source.

2.3. A fully radiogenic model

At the other extreme, one can conceive a model where heat production is fully radiogenic, with K/U fixed at the terrestrial value and Th/U at the chondritic value, which seems consistent with terrestrial observations. All the abundances are rescaled so as to provide the full 40 TW heat flow (last column of Table 2). All particle production rates are correspondingly rescaled by a factor of two with respect to the predictions of the BSE model.

In summary, the discussion of these somehow extreme models shows that particle luminosities are uncertain by a factor of order two, the relative contributions to heat production are strongly model dependent whereas potassium is anyhow the principal neutrino and antineutrino source.

3. From luminosity to flux and signal

An (anti)neutrino detector near the Earth surface ($R = R_\oplus$) is sensitive to the flux impinging onto it from any direction:

$$\Phi = \frac{1}{4\pi}\int d^3r\,\frac{A(\vec r)}{|\vec R-\vec r|^2}, \tag{7}$$

where the integral is taken over the Earth volume and A is the number of particles produced per unit volume and time.[4] The flux depends on the geometrical distribution of the sources, and we can write:

$$\Phi_{\bar\nu/\nu} = \frac{GL_{\bar\nu/\nu}}{4\pi R_\oplus^2}, \tag{8}$$

where G is a geometrical factor of order unity. One has: $\Phi/(10^6\ \mathrm{cm^{-1}\,s^{-1}}) = 0.2\,GL/(10^{24}\ \mathrm{s^{-1}})$.

In order to estimate fluxes, one needs to know the distribution of radioactive elements in the Earth interior, and not only their total abundances. Concerning the crust, these elements are mainly concentrated

[4] This is different from the flux normal to the Earth surface, which in the case of spherical symmetry is given by $\Phi_\perp = \frac{1}{4\pi R_\oplus^2}\int d^3r\,A(r)$.

Table 3
Mass distribution and (anti)neutrino fluxes. M and Φ are in units of 10^{17} kg, and 10^6 cm^{-2} s^{-1}, respectively. Uranium mass in the crust is fixed at the value estimated from Ref. [13]. $\Phi_{\bar{\nu}}$ (reactor) corresponds to the flux from a nuclear reactor with $P_{\rm th} = 2.8$ GW at 100 km

Model	Chondritic	BSE	Fully radiogenic
		Uranium	
M(crust)	0.42	0.42	0.42
M(mantle)	0.23	0.42	1.29
$\Phi_{\bar{\nu}}$(crust)	2.1	2.1	2.1
$\Phi_{\bar{\nu}}$(mantle)	0.5	1.0	3.0
$\Phi_{\bar{\nu}}$ (tot)	2.6	3.1	5.1
$\Phi_{\bar{\nu}}$(reactor) ($E \leqslant 3.26$ MeV)		0.4	
		Thorium	
M(crust)	1.6	1.6	1.6
M(mantle)	0.89	1.6	4.9
$\Phi_{\bar{\nu}}$(crust)	1.8	1.8	1.8
$\Phi_{\bar{\nu}}$(mantle)	0.4	0.8	2.5
$\Phi_{\bar{\nu}}$(tot)	2.2	2.6	4.3
$\Phi_{\bar{\nu}}$(reactor) ($E \leqslant 2.25$ MeV)		0.3	
		Potassium	
M(crust)/10^4	0.42	0.42	0.42
M(mantle)/10^4	4.15	0.42	1.29
$\Phi_{\bar{\nu}}$(crust)	7.7	7.7	7.7
$\Phi_{\bar{\nu}}$(mantle)	34.9	3.5	10.9
$\Phi_{\bar{\nu}}$(tot)	42.6	11.2	18.6
Φ_{ν}(crust)	0.95	0.95	0.95
Φ_{ν}(mantle)	4.33	0.44	1.04
Φ_{ν}(tot)	5.28	1.39	1.99
$\Phi_{\bar{\nu}}$(reactor) ($E \leqslant 1.31$ MeV)		0.2	

in the continental part. Recent estimates of the uranium average mass abundance in the continental crust (CC) are near $a_{\rm CC}(U) = 1.7$ ppm [13]. The abundance in the oceanic crust (OC) is an order of magnitude smaller, $a_{\rm OC} \simeq 0.1$ ppm. If one also considers that OC is much thinner than CC ($M_{\rm CC} = 2.3 \times 10^{22}$ kg and $M_{\rm OC} = 0.6 \times 10^{22}$ kg) one concludes that the contribution of the oceanic crust to neutrino production is definitely smaller. In this way we estimate the total uranium mass in the crust:

$$M_{\rm c}({\rm U}) = 0.4 \times 10^{17}\ {\rm kg}. \tag{9}$$

For the sake of a first estimate, we shall assume that $M_{\rm c}$(U) is uniformly distributed over the Earth surface within a layer of thickness $\bar{h} = 30$ km. We associate to the mantle an uranium mass $M_{\rm m}({\rm U}) = M({\rm U}) - M_{\rm c}({\rm U})$, where M(U) was estimated in the previous section for each model and $M_{\rm c}$(U) is given from Eq. (9). Furthermore, we shall assume uniform distribution within the mantle. We also assume a uniform distribution of Th/U and K/U. Within these approximations the geometrical factors G are easily calculated.

For a spherical shell with radii $r_1 = x_1 R_\oplus$ and $r_2 = x_2 R_\oplus$ and uniform distribution one has:

$$G = \frac{3}{2(x_2^3 - x_1^3)} \left\{ \frac{1}{2}\left(1 - x_1^2\right) \ln \frac{1 + x_1}{1 - x_1} - x_1 - \frac{1}{2}\left(1 - x_2^2\right) \ln \frac{1 + x_2}{1 - x_2} + x_2 \right\}. \tag{10}$$

For the crust ($r_2 = R_\oplus$ and $r_2 - r_1 = \bar{h} \simeq 30$ km) and for the mantle ($r_2 \simeq R_\oplus$ and $r_1 \simeq R_\oplus/2$) one has:

$$G_{\rm c} \simeq \frac{1}{2}\left[1 + \ln(2R_\oplus/\bar{h})\right] = 3.5, \qquad G_{\rm m} = 1.6. \tag{11}$$

Table 4
Flux dependence on uranium abundance in the crust and distribution in the mantle. Fluxes are calculated for $M_{\text{crust+mantle}}(\text{U}) = 0.84 \times 10^{17}$ kg. The total flux $\Phi(\text{tot})$ is the sum of the contribution from the crust, upper mantle and transition zone + lower mantle. Same units as in Table 3

	Uranium		
	High a_{CC}	Low a_{CC}	Depleted upper mantle
M(crust)	0.42	0.21	0.42
M(upper mantle)	0.06	0.09	0
M(transition + lower mantle)	0.36	0.54	0.42
Φ(crust)	2.1	1.0	2.1
Φ(upper mantle)	0.21	0.32	0
Φ(transition + lower mantle)	0.79	1.2	0.92
Φ(tot)	3.1	2.5	3.0

This allows the calculation of the fluxes for each Earth model reported in Table 3.

One remarks that fluxes are of the order of magnitude of the solar boron neutrino flux. Potassium (anti)neutrinos are the dominant component in any model. The various models yield significantly different predictions. Contributions from crust and mantle look comparable.

Indeed in order to reach these results we used several approximations, which is worth discussing, also in view of obtaining more precise estimates.

(i) *Global effects*. There are significant uncertainties on the value of $a_{\text{CC}}(\text{U})$. For the lowest value found in the literature, $a_{\text{CC}}(\text{U}) = 0.91$ ppm [14], the uranium mass in the crust is halved with respect to the reference value in Eq. (9). In addition, there are indications that the upper part of the mantle is impoverished in the content of radioactive elements. The effect of these uncertainties are shown in Table 4, where $\Phi_{\bar{\nu}}(\text{U})$ is calculated for a fixed (BSE) value of the crust + mantle uranium mass. A change of the U-abundance in the crust by a factor of two corresponds to a 15% change in the flux. If uranium is completely removed from the upper mantle the flux is reduced by 3%. All these effects are thus smaller with respect to the uncertainty on the total uranium mass, which is reflected in changes of fluxes by factor two when going through the extreme chondritic and fully radiogenic models. Similar considerations hold for thorium and potassium.

(ii) *Regional effects*. The fluxes reported in Table 3 are averaged values and one has to remind that Earth crust is significantly variable in thickness and composition. Thus one has to expect significant variations of the actual fluxes, depending on the detector location. As a few significant examples, the Gran Sasso laboratory sits on a thick continental crust, whereas Kamioka is on an island arc in between the Eurasian plate and the Pacific plate. Following the approach of Ref. [12] we have estimated $\Phi_{\bar{\nu}/\nu}$ at the two sites, in a model which distinguishes between CC and OC and includes a variable crust thickness. The model is based over a global crustal map at $5^\circ \times 5^\circ$, and assumes uniform distribution within the mantle. Uranium mass in the crust and in total Earth are kept fixed at the values of Eqs. (6) and (9). Table 5 shows that fluxes at specific sites can differ significantly from the average value and thus a crust map is really needed for a precise flux estimate at the detector size. On the other hand, the difference between Gran Sasso and Kamioka is at the level of 15%.

(iii) *Local effects*. The flux from the crust within a distance d from the detector is easily estimated using planar geometry ($d \ll R_\oplus$):

$$\Phi(<d) = \frac{A}{2}\left[d\arctan(h/d) + (h/2)\ln\left(1 + d^2/h^2\right)\right], \tag{12}$$

where h is the local crust thickness and A is the local activity. This has to be compared with the total flux from the crust:

$$\Phi_{\text{c}} = G_{\text{c}}\bar{A}\bar{h}, \tag{13}$$

where $\bar{A}$ and $\bar{h}$ are the mean crustal activity and thickness.

A significant quantity is the relative contribution $R = \Phi(<d)/\Phi_{\text{c}}$. By suitable expansions of Eq. (12) one immediately derives the contribution of the nearby rocks (say $d = h/3$) and of the local area, i.e., up to a

Table 5
Flux dependence on the detector location. Fluxes in unit of 10^6 cm^{-1} s^{-2} are calculated for $M_{\rm crust}({\rm U}) = M_{\rm mantle}({\rm U}) = 0.42 \times 10^{17}$ kg, Th/U = 3.8 and K/U = 10^4. The last column is the average flux for the same values of $M_{\rm crust}$(U) and $M_{\rm mantle}$(U) (BSE model)

	Kamioka	Gran Sasso	Average
Uranium	4.0	4.6	3.1
Thorium	3.4	3.9	2.6
Potassium ($\bar{\nu}$)	14	17	11
Potassium (ν)	1.8	2.1	1.4

distance $d \ll R_\oplus$:

$$R_{\rm nea} = 0.07\, Ah/(\bar{A}\bar{h}), \tag{14}$$

$$R_{\rm loc} = (1/7)\big[1 + \ln(d/h)\big]\, Ah/(\bar{A}\bar{h}). \tag{15}$$

If $A = \bar{A}$ and $h = \bar{h} = 30$ km one finds that the rocks within 10 km contribute 7% with respect to the total from the crust. Within 100 km one has about 30% of the crust contribution and about 15% of the total flow, from crust and below. A more detailed geochemical information of this area is thus needed if one aims at a few percent accuracy.

In summary, detection of terrestrial (anti)neutrinos is particularly important for determining the amount of radioactive material inside the mantle, where information on the chemical composition is most uncertain, the lower part being completely inaccessible to observation. A suitable approach would thus consist of (i) measuring the (anti)neutrino flux; (ii) subtracting the component originated in the crust, which has been mapped with geological methods, so as to determine the corresponding abundances in the mantle. The previous calculations show that crust and mantle provide comparable fluxes, so that the subtraction procedure is possible. The crust description however has to be more detailed in the proximity of the detector.

A detailed discussion of the (anti)neutrino signal is beyond the aim of this Letter and we would like to remark just a few relevant points.

(i) Due to the different antineutrino energy endpoints [9] ($E_{\rm max} = 3.26$, 2.25 and 1.31 MeV for U, Th and ^{40}K, respectively) it is possible at least in principle to separate the contributions to Earth radioactivity.

(ii) Antineutrinos from U and Th can be detected and separated by means of

$$\bar{\nu} + p \to e^+ + n - 1.804\ {\rm MeV}, \tag{16}$$

whereas different detection schemes are necessary for K antineutrinos, which are below the energy threshold for (16). The monochromatic ($E = 1.513$ MeV) neutrinos from ^{40}K are essentially obscured by the dominant solar flux ($\Phi(pep) = 1.4 \times 10^8$ cm^{-2} s^{-1} at $E = 1.44$ MeV and $\Phi({\rm CNO}) \sim 10^9$ cm^{-2} s^{-1} MeV^{-1}).

(iii) So far we did not consider the effect of neutrino oscillations. If LMA is the correct solution, with $\Delta m^2 \simeq 5.5 \times 10^{-5}$ eV^2 and $\sin^2 2\theta \simeq 0.83$ [18], the oscillation length $L = 4\pi E/\Delta m^2$ of 1 MeV antineutrino is around 45 km and the (distance averaged) survival probability of electron antineutrinos $P_{ee} = 1 - 1/2 \sin^2 2\theta \simeq 0.58$. The present uncertainty on $\sin^2 2\theta$ (about 20%) translates into a 15% uncertainty on the fluxes.

(iv) Events from U and Th antineutrinos in a organic scintillator detector have been estimated in the range (20–100) kton^{-1} yr^{-1} [11,12], so that a flux measurement with a 10% accuracy should be feasible in a few years. The main background source [19] is antineutrinos from nuclear power plants (see last row of Table 3), which depends on the detector location.

4. Concluding remarks

We have estimated terrestrial antineutrino and neutrino fluxes according to different models of Earth composition. We find large variations, corresponding to uncertainties on the estimated U, Th and K abundances in the mantle. Information on the mantle composition can thus be derived from (anti)neutrino flux measurements after subtracting the crust contribution. This requires a good description of the crust composition in the region of the detector site and in return it will provide direct insight on the main sources of Earth's heat flow.

Just a few years after the celebrated slow neutron studies of the Rome group, Bruno Pontecorvo devel-

oped the neutron well log [20], an instrument which is still used in geology for the search and analysis of hydrogen containing substances (water and hydrocarbons). Possibly it is now the time for applying to different disciplines what we have learnt so far on neutrinos. In fact, there are several attempts in this direction, see, e.g., [21] and references therein. The determination of the radiogenic component of the terrestrial heat is an important and so far unanswered question. It looks to us as the first fruit which we can get from neutrinos, and KamLAND will catch the firstlings very soon.

Addendum

After this Letter was submitted, the first results of KamLAND have become available [22]. From an exposure of 1.39×10^{31} protons year, 9 geo-neutrino events are reported. For the best fit survival probability $P(\bar{\nu}_e \to \bar{\nu}_e) = 0.55$ [22], from the average fluxes calculated in Table 3 one predicts 2.6, 3.1 and 5.1 events, respectively for the chondritic, BSE and fully-radiogenic models. Predictions from fluxes calculated specifically for the Kamioka site are 3.5, 4.0 and 6.0 events, respectively. They are all consistent with the experimental value, within its statistical fluctuation of ± 5.7 events [23].

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