Perspectives for geo-neutrinos after KamLAND[1]

Giovanni Fiorentini[1], Marcello Lissia[2], Fabio Mantovani[3] and Barbara Ricci[1]

[1]Dipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy and Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, I-44100 Ferrara, Italy
[2]Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, I-09042 Monserrato (CA), Italy and Dipartimento di Fisica, Università di Cagliari, I-09042 Monserrato (CA), Italy
[3]Dipartimento di Scienze della Terra, Università di Siena, I-53100 Siena, Italy and Centro di GeoTecnologie CGT, I-52027 San Giovanni Valdarno, Italy and Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, I-44100 Ferrara, Italy

E-mail: `fiorenti@fe.infn.it, marcello.lissia@ca.infn.it, fabio.mantovani@unisi.it, ricci@fe.infn.it`

Abstract. We discuss the implications of KamLAND result on geo-neutrinos for the radiogenic contribution of Uranium to terrestrial heat. We also discuss the potential of future experiments for assessing the amount of Uranium and Thorium in different reservoirs (crust, mantle and core) of the Earth.
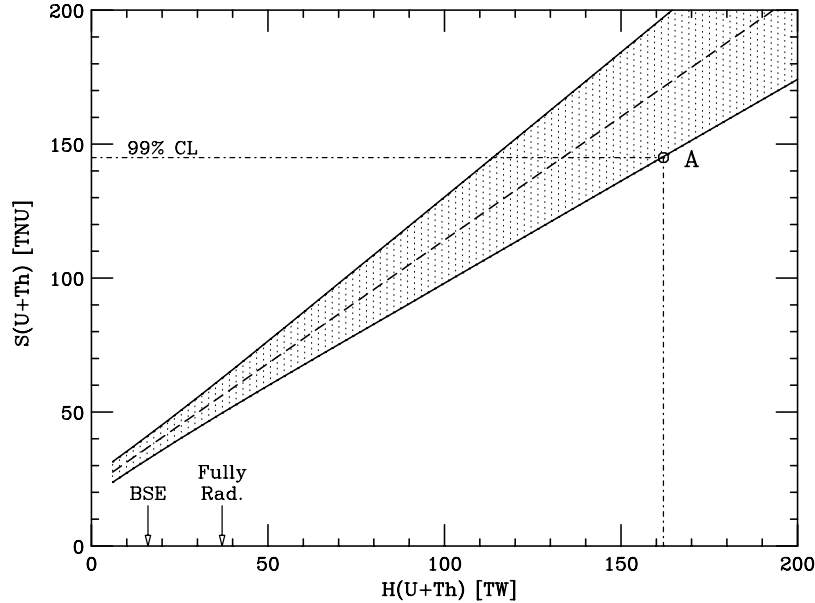
1. Introduction
The KamLAND collaboration has recently published [1] new experimental results, claiming some 28 geo-neutrino events from Uranium and Thorium decay chains in a two-year exposure. This important step shows that the technique for exploiting geo-neutrinos in the investigation of the Earth's interior is now available. In order to understand where to go with geo-neutrinos, we have to know where we stand in the light of the available data. In this spirit, the first aim of this talk is to discuss the implication of the KamLAND result on the contribution of Uranium and Thorium decay chains to the terrestrial heat. Next we discuss the potential of future experiments for assessing the amounts of U and Th in different reservoirs (crust, mantle and core) of the Earth.

2. The geo-neutrino signal and the radiogenic terrestrial heat
The mass of Uranium in the crust, $m_c(U)$, looks rather well constrained by geological data, in the interval $(3 \div 4) \times 10^{16}$ kg. Also, the ratio of Thorium to Uranium masses in the Earth is rather well fixed by geochemical and cosmochemical arguments, $m(Th)/m(U) = 3.9 \pm 0.1$. The main uncertainty is the amount of Uranium (and Thorium) in the mantle. Geo-neutrinos should provide us with this information.

For a given value of, *e.g.*, the Uranium mass in the Earth, $m(U)$, the contributed heat production rate from the Uranium decay chain is uniquely determined, $H(U) = 0.95$ TW $\times m(U)/(10^{16}$kg$)$, whereas the flux and signal of geo-neutrinos depend on the detector location

---

[1] Invited talk presented at the conference by G. F.

Figure 1. Predictions on the combined signal H(U+Th) from Uranium and Thorium geo-neutrinos at Kamioka as a function of the radiogenic heat production rate S(U+Th). The shaded area denotes the region allowed by geochemical and geophysical constraints. The dashed median line represents our best estimate for the relationship between signal and radiogenic power. One TNU corresponds to 10^{-32} $\bar{\nu}_e$ captures per target proton per year.

and on the Uranium distribution inside the Earth. The connection between the signal of geo-neutrinos from the Uranium decay chain, the mass of Uranium in the Earth and the heat production rate from that element was found in Ref. [2], by using global mass balance together with a detailed geochemical and geophysical study of the region surrounding Kamioka. The same analysis was extended to Thorium in ref. [3] assuming a global chondritic Uranium-to-Thorium mass ratio, $m(\text{Th})/m(\text{U}) = 3.9 \pm 0.1$, so that we can now connect the combined signal at Kamioka due to geo-neutrinos from Uranium and Thorium progenies, S(U+Th), with the radiogenic heat production rate from these elements, H(U+Th), see Fig. 1.

The geo-neutrino signal is expressed in Terrestrial Neutrino Units, one TNU corresponding to $10^{-32}\bar{\nu}_e$ captures per target proton per year.

The allowed band in Fig. 1 is estimated by considering *rather extreme* models for the distributions of radioactive elements, chosen so as to maximize or minimize the signal for a given heat production rate, see Ref. [2].

We also remark that, in comparison with the experimental error, the width of the band is so narrow that we can limit the discussion to the median line of the allowed band in Fig. 1, which represents our best estimate for the relationship between signal and radiogenic power.

By using the Bulk Silicate Earth (BSE) model, giving H(U+Th) = 16 TW, our prediction for Kamioka is centered at 37 TNU.

By assuming that Uranium and Potassium in the Earth are in the ratio 1/10,000 and that there is no Potassium in the core, the total radiogenic power is H(U+Th+K) = 1.18 H(U+Th). With these assumptions, a maximal and fully radiogenic heat production rate, H(U+Th+K) = 44 TW, corresponds to H(U+Th) = 37 TW, which gives a signal S(U+Th) $\approx$ 56 TNU.

The KamLAND collaboration has reported [1] data from an exposure of $N_p = (0.346 \pm 0.017) \times 10^{32}$ free protons over a time $T = 749$ days with a detection efficiency $\epsilon = 69\%$: the effective

exposure is thus $E_{eff} = N_p \times T \times \epsilon = (0.487 \pm 0.025) \times 10^{32}$ protons $\cdot$ yr. In the energy region where geo-neutrinos are expected, there are C = 152 counts, implying a statistical fluctuation of ± 12.5. Of these counts, a number R = 80.4 ± 7.2 are attributed to reactor events, based on an independent analysis of higher energy data. Fake geo-neutrino events, originating from $^{13}C(\alpha, n)^{16}O$ reactions following the alpha decay of contaminant ^{210}Po, are estimated to be F = 42 ± 11, where the error is due to a 20% uncertainty on the $^{13}C(\alpha,n)^{16}O$ cross section and a 14% uncertainty on the number of ^{210}Po decays in the detector. Other minor backgrounds account for B = 4.6 ± 0.2 events. The number of geo-neutrino events is estimated by subtraction, N(U+Th) = C - R - F - B, with an uncertainty obtained by combining the independent errors: N(U+Th) = 25^{+19}_{-18}. The geo-neutrino signal is thus S(U+Th) = N(U+Th) / E_{eff} = 51^{+39}_{-36} TNU. From the median line in Fig. 1 one finds

$$H(U+Th) = 31^{+43}_{-31} \text{ TW} \qquad \text{(rate only)} \quad . \tag{1}$$

This "rate only" study has been improved in Ref. [1] by exploiting the shape of the spectrum. A likelihood analysis of the unbinned spectrum yields N(U+Th) = 28^{+16}_{-15}, see Fig. 4b of Ref. [1]. This implies S(U+Th) = 57^{+33}_{-31} TNU and

$$H(U+Th) = 38^{+35}_{-33} \text{ TW} \qquad \text{(rate + spectrum)} \quad . \tag{2}$$

The best fit value is close to the maximal and fully radiogenic model, however the BSE is within 1σ.

By using the median line in Fig. 1, the 99% confidence limit on the signal (145 TNU) corresponds to 133 TW. If we include the uncertainty band of the theoretical models, we find an upper bound of 162 TW, see point A in Fig. 1. This point corresponds to a model with a total Uranim mass $m(U) = 80 \times 10^{16}$ kg, an uranium poor crust, $m_c(U) = 3 \times 10^{16}$ kg, the rest of the Uranium being placed at the bottom of the mantle, and global chondritic Thorium-to-Uranium ratio.

This 162 TW upper bound is much higher than the 60 TW upper bound claimed in Ref. [1], which was obtained by using a family of geological models which are *too narrow* and are also *incompatible* with well-known geochemical and geophysical data, see Ref. [3].

We remark that the bound H(U+Th)<162 TW which we have extracted from KamLAND data does not add any significant information on Earth's interior, since anything exceeding H(U+Th)= 37 TW (i.e. H(U+Th+K)=44 TW) is unrealistic. The upper limit simply reflects the large uncertainty in this pioneering experiment.

On the other hand, what is important for deciding the potential of future experiments is the relationship between geo-neutrino signal and heat production in the physically interesting region, H(U+Th)$\leq$ 37 TW. The basic parameter is the slope, dS/dH, which expresses how the experimental error translates into an uncertainty on the deduced heat production. For our models we find from Fig.1 dS/dH $\simeq$ 1 TNU/TW. This slope is the same at any location. Discrimination between BSE and fully radiogenic models, which requires a precision $\Delta H \sim$ 7 TW, requires thus an experiment with an accuracy $\Delta S \sim$ 7 TNU.

3. The geo-neutrino signal and the $^{13}C(\alpha, n)^{16}O$ cross section.

As already remarked, a major uncertainty for extracting the geo-neutrino signal originates from the $^{13}C(\alpha, n)^{16}O$ cross section[2]. The values used in Ref. [1] are taken from the JENDL [4] compilation, which provides an R-matrix fit of relatively old data. A 20% overall uncertainty

---

[2] In fact, the claim of 9 geo-neutrino events in Ref. [6] should be dismissed: more than half of these events are to be considered as fake signal, produced from $^{13}C(\alpha, n)^{16}O$ reaction.
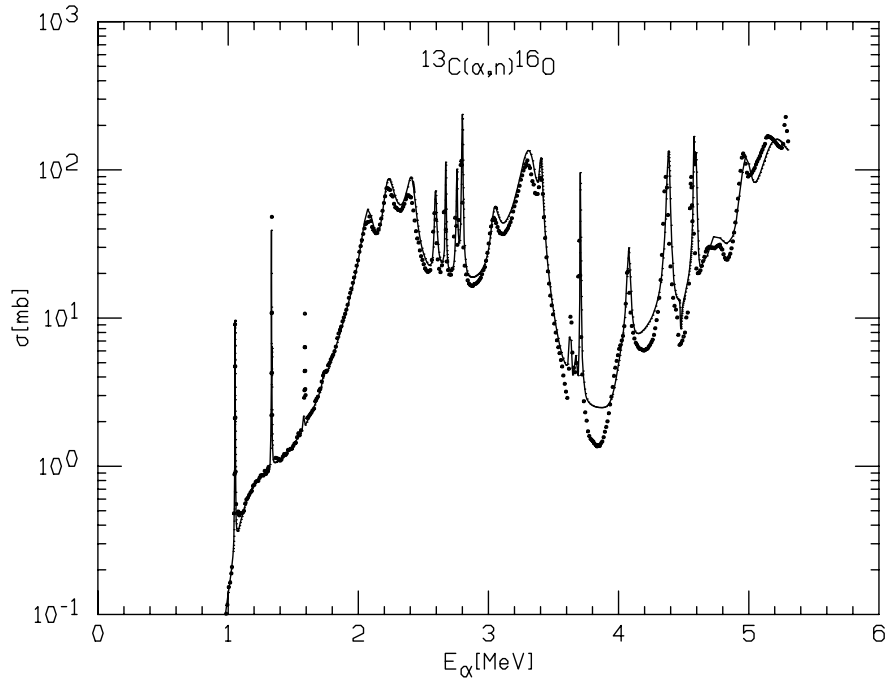
Figure 2. Cross section of $^{13}C(\alpha,n)^{16}O$. The solid line corresponds to the JENDL compilation, dots are the experimental points from Ref. [5].

has been adopted in [1], corresponding to the accuracy claimed in the original experimental papers, see *e.g.* Ref. [7].

Recently a series of high precision measurements for this cross section has been performed [5]. In the relevant energy range $(1 \div 5.3)$ MeV, the absolute normalization has been determined within a 4% accuracy. The measured values are generally in very good agreement with those recommended in JENDL, see Fig. 2; however, we find that the neutron yield per alpha particle is 5% smaller. It follows that the number of fake neutrinos is lower, $F = 40 \pm 5.8$, and geo-neutrino events obviously increase.

The "rate only" analysis gives now 27^{+16}_{-15} geo-neutrino events, corresponding to S(U+Th) $= 55^{+33}_{-31}$ TNU. From the median line of Fig. 1, the radiogenic power is now:

$$H(U+Th) = 36^{+35}_{-33} \text{ TW} \qquad (\text{rate} + \text{new } ^{13}C(\alpha,n)^{16}O) \quad . \tag{3}$$

We also performed an analysis[3] of the binned spectrum reported in Fig. 3 of Ref. [1]. This analysis gives N(U+Th) $= 31^{+14}_{-13}$ counts, corresponding to S(U+Th) $= 63^{+28}_{-25}$ TNU and thus:

$$H(U+Th) = 44^{+31}_{-27} \text{ TW} \qquad (\text{rate} + \text{spectrum} + \text{new } ^{13}C(\alpha,n)^{16}O) \quad . \tag{4}$$

4. Future prospects

The present situation can be summarized in the following points:

i)   KamLAND has shown that the technique for exploiting geo-neutrinos in the investigation of the Earth's interior is now available.

---

[3] A complete analysis requires several details (the un-binned spectrum, the energy dependence of the detection efficiency, ...) which are not available to us. Just for a comparison, the binned spectrum analysis using the JENDL cross sections with 20% uncertainty gives us N(U+Th)=28.5^{+15}_{-14}, in agreement with [1].
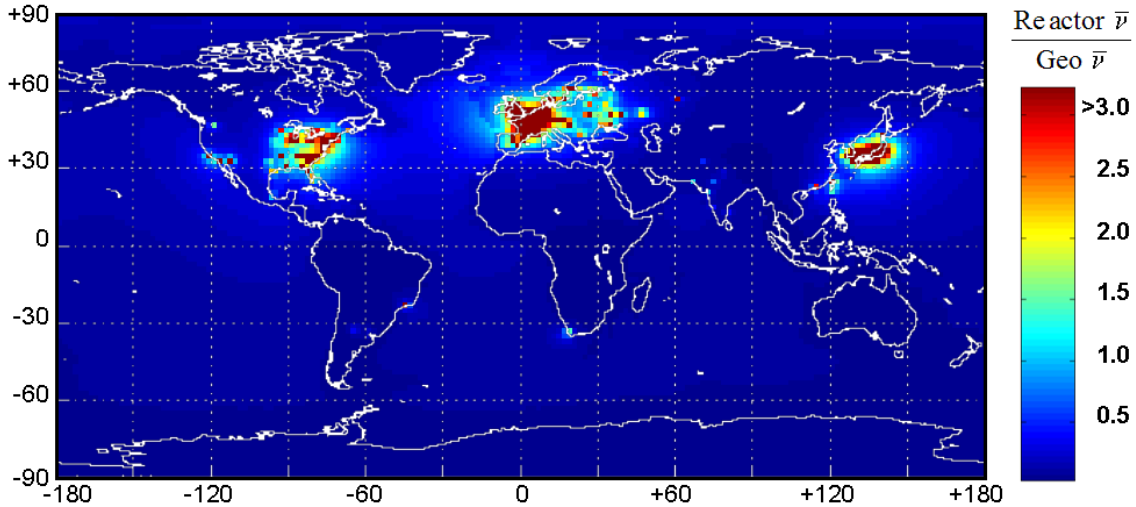
Figure 3. The ratio of reactor anti-neutrino events (in the geo-neutrino energy region) to the expected geo-neutrino events all over the globe.

ii) New data on $^{13}C(\alpha, n)^{16}O$ corroborate the evidence for geo-neutrinos in KamLAND data, which becomes near to 2.5σ.

iii) On the other hand, the determination of radiogenic heat power from geo-neutrino measurements is still affected by a 70% uncertainty. The best fit of H(U+Th) is close to the prediction of a maximal and fully radiogenic model, however the BSE prediction is within 1σ from it.

iv) The universal slope dS/dH$\simeq$1 TNU/TW means that for determining the radiogenic heat within ±7 TW the experimental error has to be ±7 TNU, i.e. a factor four improvement with respect to present.

It looks to us that the following questions are relevant for the the future:

- How shall we have a definite (at least 3σ) evidence of geo-neutrinos?
- How much Uranium and Thorium are in the Earth's crust?
- How much in the mantle?
- What about the core?

A preliminary point for establishing suitable detectors locations is the reactor background. Fig. 3 shows the ratio of reactor events (in the geo-neutrino energy region) to the expected geo-neutrino events all over the globe. KamLAND location is obviously one of the worst for the study of geo-neutrinos.

The potential of different locations is summarized in Table 1, where we present the separate contributions to the geo-neutrino signal from crust and mantle[4] according to our reference model, as well as the merit figure r=geo-neutrino events /reactor events.

With more statistics KamLAND should be capable of providing a three sigma evidence of geo-neutrinos, but discrimination between BSE and fully radiogenic models definitely requires new detectors, with class and size similar to that of KamLAND, far away from nuclear power plants. Borexino should reach the 3σ evidence, but cannot go much further due to its relatively small size.

---

[4] The mantle contribution is the same at any location since we assume a spherically simmetrical distribution.

Table 1. The U+Th signal expected from the crust and that from the mantle in TNU. The merit figure $r=geo\text{-}neutrino\ events\ /reactor\ events$ is also shown.

	crust	mantle	total	r
LENA	44.0	9.3	53.3	2
Homestake	43.8	9.3	53.1	5
SNO+	43.3	9.3	52.6	0.9
Baksan	43.3	9.3	52.6	5
Borexino	32.8	9.3	42.1	1.1
KamLAND	26.4	9.3	35.7	0.15
Curacao	24.3	9.3	33.6	10
Hawaii	3.6	9.3	12.9	10

SNO+ with liquid scintillator will have excellent opportunities to determine the Uranium mass in the crust, which accounts for about 80% of the geo-neutrino signal at Sudbury. This will provide an important test about models for the Earth's crust.

A detector at Hawaii, very far from the continental crust and reactors, will be mainly sensitive to the mantle composition. We remind that the amount of radioactive materials in this reservoir is the main uncertainty of geological models of the Earth. The expected signal, however, is rather small and this demands a several kilotons size.

For the very long term future, one can speculate about completely new detectors, capable of providing a (moderately) directional information[5]. These should allow the identification of the different geo-neutrino sources (crust,mantle and possibly core) in the Earth, a wonderful as well as extremely challenging project.

Acknowledgments

References

[1] Araki T et al (KamLAND coll.) 2005 *Nature* **436** 499
[2] Fiorentini G, Lissia M, Mantovani F and Vannucci R 2005 *Phys. Rev.* D **72** 03317
[3] Fiorentini G, Lissia M, Mantovani F and Ricci B 2005 *Phys. Lett.* B **629** 77
[4] JENDL Japanese Evaluated Nuclear Data Library, http://wwwndc.tokai.jaeri.go.jp/jendl/
[5] Harissopulos H et al. 2005 *Phys. Rev.* C **72** 06281
[6] Eguchi K *et al.* (KamLAND Collaboration) 2003 *Phys. Rev. Lett.* **90** 021802
[7] Bair J K and Haas F X 1973 *Phys. Rev.* C **7** 1356

[5] We remind that the neutron from inverse beta decay keeps information on the antineutrino detection.