KamLAND results and the radiogenic terrestrial heat

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Abstract

We find that recent results from the KamLAND collaboration on geologically produced antineutrinos, N(U+Th)= 28^{+16}_{-15} events, correspond to a radiogenic heat production from Uranium and Thorium decay chains H(U+Th)=38^{+35}_{-33} TW. The 99% confidence limit on the geo-neutrino signal translates into the upper bound H(U+Th)$<$ 162TW, which is much weaker than that claimed by KamLAND, H(U+Th)$<$ 60TW , based on a too narrow class of geological models. We also performed an analysis of KamLAND data including recent high precision measurements of the ^{13}C(α,n)^{16}O cross section. The result, N(U+Th)=31^{+14}_{-13} corroborates the evidence ($\simeq 2.5\sigma$) for geo-neutrinos in KamLAND data.

I. INTRODUCTION

The potential of geologically produced antineutrinos (geo-neutrinos) for providing information on the energetics and composition of the Earth has been discussed in [1,2] and more recently in [3]. The KamLAND collaboration has just published [4] their experimental results, claiming some 28 geo-neutrino events from Uranium and Thorium decay chains in a two year exposure. The aim of this note is to discuss the implication of this result on the contribution of Uranium and Thorium decay chains to the terrestrial heat.

II. THE GEO-NEUTRINO SIGNAL AND THE RADIOGENIC TERRESTRIAL HEAT

For a given value of, *e.g.*, the Uranium mass in the Earth, the contributed heat production rate from the Uranium decay chain is uniquely determined, whereas the flux and signal of geo-neutrinos depend on the detector location 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. [3], by using global mass balance together with a detailed geochemical and geophysical study of the region surrounding Kamioka.

We remark that the mass of Uranium in the crust is rather well constrained by geological data, in the interval $(3-4)\cdot 10^{16}$ kg, and the same holds for Thorium. The main uncertainty is the amount of Uranium and Thorium in the mantle. Geo-neutrinos should provide us with this information.

We have extended the same calculations of ref. [3] to Thorium geo-neutrinos, so that we can now connect the combined signal of 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 *extreme* models for the distributions of radioactive elements, chosen so as to maximize or minimize the signal for a given heat production rate, see [3].

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 power.

For the Bulk Silicate Earth (BSE) model, 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 [4] data from an exposure of $N_p = (0.346 \pm 0.017)\cdot 10^{32}$ free protons over a time T=749 days with a detection efficiency ϵ= 69% (the effective exposure is thus $E_{eff}=N_p \times T \times \epsilon = (0.487 \pm 0.025) \cdot 10^{32}$ protons×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

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

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

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

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, much higher than the bound of 60 TW claimed in ref. [4]. This last bound has been obtained by using a family of geological models which is *too narrow and is also incompatible* with well known geochemical and geological data.

In fact, the authors of [4] start with a reference BSE model derived from [5]: the total Uranium mass is $m_{BSE} = 8 \cdot 10^{16}$ kg, roughly half in the crust and the rest in the mantle, and the abundance ratio is Th/U =3.9. This model corresponds to H_{BSE}(U+Th)=16 TW and predicts a signal of 38.5 TNU, very close to our prediction for BSE. The signal *is assumed* to scale with the total mass or U+Th, so that heat production and signal are also proportional:

$$S(U+Th)= (38.5\ \text{TNU}/16\ \text{TW})\ H(U+Th)\,. \tag{3}$$

In this way, the 99% upper limit on the signal, 145 TNU, is translated into 60 TW [4].

This scaling assumption, however, produces a too limited series of models. The points in the shaded area of Fig. 1 correspond to all models which are compatible with available geochemical and geophysical data: most of these models cannot be obtained by Eq. 3 and predict for a given signal a larger power than Eq. 3, which therefore cannot be used to derive an upper bound on the radiogenic power production.

Furthermore, Eq. 3 implies that Uranium in the crust (and in the mantle) scales linearly with the total Uranium mass. This becomes incompatible with the geochemical data on the crust ($m_c(U) < 4 \cdot 10^{16}$ kg) already for total masses slightly above the BSE estimate, i.e. for models where H(U+Th)>20 TW. For example, in the model yielding 60 TW the crust should contains about $13 \cdot 10^{16}$ kg of Uranium, four times larger than the largest geochemical estimate. This inconsistency is clearly seen in Fig. 1, which shows that the family of models labelled as "rescaled models" lie essentially in the geochemically excluded region.

III. THE GEO-NEUTRINO SIGNAL AND THE ^{13}C(α,N)^{16}O CROSS SECTION.

As already remarked, a major uncertainty for extracting the geo-neutrino signal originates from the ^{13}C(α,n)^{16}O cross section[1]. The values used in [4] are taken from the JENDL [6] compilation, which provides an R-matrix fit of relatively old data. A 20% overall uncertainty has been adopted in [4], corresponding to the accuracy claimed in the original experimental papers, see e.g. [9].

Recently a series of high precision measurements for this cross section has been performed [7]. In the relevant energy range (1-5.3) 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[2].

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 :

$$H(U+Th) = 36^{+35}_{-33}\mathrm{TW} \qquad (\text{rate+new } ^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}). \tag{4}$$

We also performed an analysis of the binned spectrum reported in Fig. 3 of [4][3]. This gives N(U+Th) =31 $^{+14}_{-13}$ counts, corresponding to S(U+Th)= 63^{+28}_{-25} TNU and thus:

$$H(U+Th) = 44^{+31}_{-27}\ \mathrm{TW} \qquad (\text{rate+spectrum+new } ^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}). \tag{5}$$

[1] In fact, the claim of 9 geo-neutrino events in [8] should be dismissed: more than half of these are to be considered as fake signal, produced from ^{13}C(α,n)^{16}O reaction.

[2] Indeed ref. [4] mentions that an alternative analysis including the time structure of the scintillation light from different particles produced a slightly larger geo-neutrino signal, which is consistent with the result presented here.

[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 [4].

IV. CONCLUDING REMARKS

In summary, the new data on ^{13}C(α,n)^{16}O corroborate the evidence for geo-neutrinos in KamLAND data, which becomes near to 2.5σ.

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.

At present geo-neutrinos provide an upper limit of 162 TW for the radiogenic power of Uranium and Thorium in the Earth.

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.

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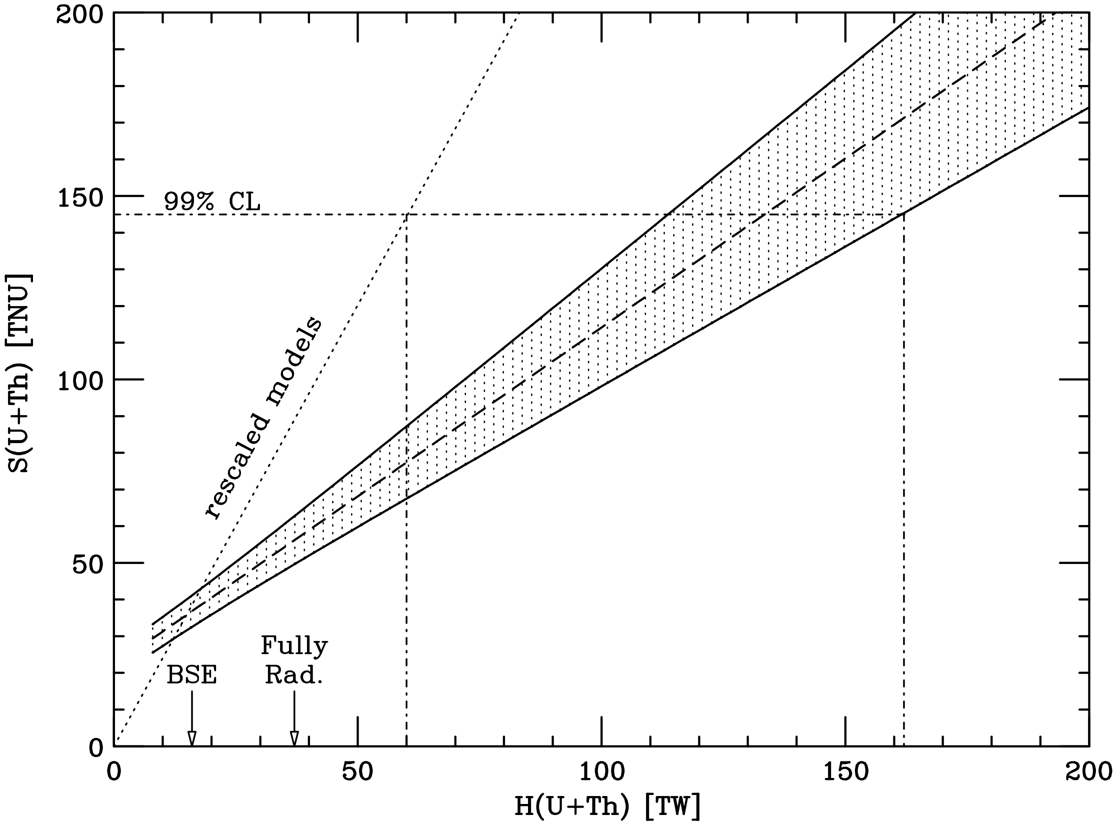

FIG. 1. The combined signal from Uranium and Thorium geo-neutrinos and the radiogenic heat production rate.
The shaded area denotes the region allowed by geochemical and geophysical constraints. The dashed median line represents our best estimate for the relationship between signal and power. The dotted line denotes the "rescaled models" of Eq. 3, used in [4]. Note that most of these models are outside the allowed area.
One TNU corresponds to 10^{-32} $\bar{\nu}_e$ captures per target proton per year.

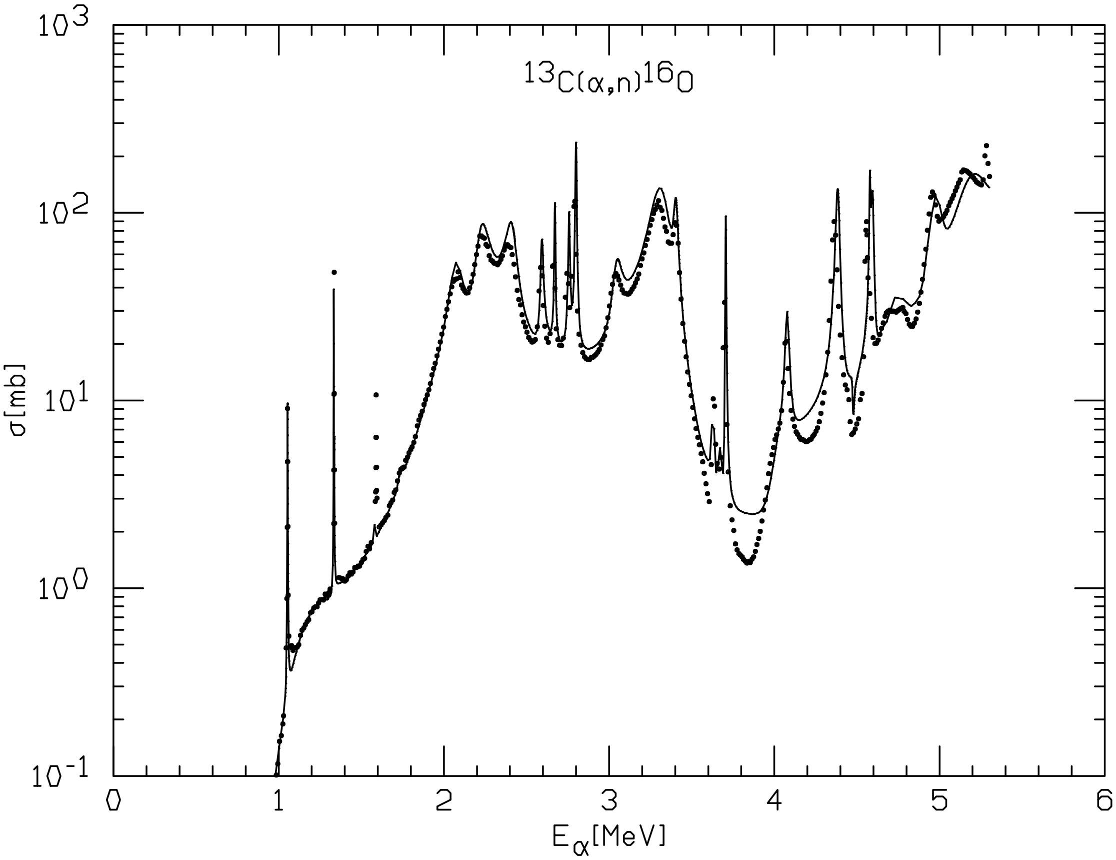

FIG. 2. Cross section of $^{13}C(\alpha,n)^{16}O$. The solid line corresponds to the JENDL compilation, dots are the experimental points of [7].