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Geoneutrinos

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Summary. — Geoneutrinos, antineutrinos produced by the radioactive decays within the Earth, are irreplaceable probes for studying the deep terrestrial interior. The data, obtained until now by only two experiments, KamLAND and Borexino, provide a robust evidence that the technique to measure geoneutrinos has been developed and that the first hints on the Earth's radiogenic heat, on the presence of Th and U in the mantle, and on the bulk U/Th mass ratio start to emerge.

1. – Introduction

In order to understand the importance of geoneutrino studies, it is useful to recall some basic notions of the Earth structure.

Our planet consists of several concentric layers differing either in composition and/or mechanical properties, sometimes separated by the so called transition regions. The center of the Earth is an Inner Core, a solid Fe-Ni alloy sphere, with a size close to the Moon dimensions, at ∼5700 K of temperature and ∼330 GPa of pressure. It is surrounded by an Outer Core, ∼2260 km thick, liquid Fe-Ni alloy with about 10% admixture of light elements, at a temperature between 4100 and 5800 K; the motion of its conductive liquid plays a key role in the process of generation of the Earth's geomagnetic field (Geodynamo).

The metallic core is separated from the overburden silicate Earth by a relatively thin (∼190 km) transition region, called D" layer. The ∼3100 km thick Lower Mantle surrounds the Outer Core, it is solid but viscose, and consists of rocks with a high Mg/Fe ratio. In the Lower Mantle, high temperature gradients produce important convection movements, which drive plate tectonics and correlated volcanism activities. The Upper Mantle is only ∼250 km thick and surrounds the Lower Mantle.

The uppermost layer is the Crust, which is divided in Oceanic and Continental. The Oceanic Crust is only ∼10 km thick and is continuously created along the mid-ocean ridges. The Continental Crust has a more complex history, it is older and more differentiated, 30 to 70 km thick, and consists of igneous, metamorphic, and sedimentary rocks.

Until recently, only seismology and geochemistry provided information about the deep Earth. Seismology studies the propagation, speed, and behavior of seismic waves;

it provides information on the phase (liquid or solid) and on the density of the crossed terrestrial regions. Geochemistry investigations are based upon direct rock samples from the surface and from the bore-holes. Different tectonic and volcanic processes can bring to the surface rocks from the deep crust or even from the upper mantle, but they can be altered during the transportation. Bore holes, which reach a maximum depth of 12 km, are useful for studying the crust composition, but not the mantle.

Geochemical models are developed taking into account the composition of direct rock samples, the carbonaceous chondritic meteorites([1]), and their similarity with the composition of the Sun's photosphere. The paradigmatic model is the Bulk Silicate Earth (BSE) describing the composition of the primordial mantle, before the crust-mantle differentiation but after the separation of the metallic core.

2. – Surface heat flux

The evaluation of the Earth's surface heat flux is based on the measurements of the temperature gradients along several thousands of bore holes. Several approaches yielded quite discrepant results, but the recent and well accepted result is 47±2 TW [1].

Important contribution to the surface heat flux comes from the radiogenic heat having its origin in the radioactive decays of long lived radioactive elements inside the Earth. The estimates of the radiogenic heat range between 11 and 33 TW [2]. The lower limit is obtained by cosmochemical models, while the highest value is resulting from the geodynamical models analyzing the energetics of the mantle convection.

3. – Geoneutrinos

Geoneutrinos are electron antineutrinos produced inside the Earth by the decays of the components of the two natural radioactive families: ^{238}U and ^{232}Th and by ^{40}K. Their total products can be summarized as follows:

$$^{238}\mathrm{U} \rightarrow ^{206}\mathrm{Pb} + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7 \quad \mathrm{MeV} \tag{1}$$

$$^{232}\mathrm{Th} \rightarrow ^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7\ \mathrm{MeV} \tag{2}$$

$$^{40}\mathrm{K} \rightarrow ^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.31\ \mathrm{MeV}\ (89.3\%) \tag{3}$$

With a small isotopic abundance and with a minor contribution the family of ^{235}U is also present in the Earth. ^{40}K can decay to ^{40}Ar + ν_e+ 1.505 MeV via an electronic capture, with ∼11% branching ratio. The total geoneutrinos flux is estimated to be of the order of 10^6 cm^{-2} s^{-1}.

In liquid scintillator detectors, which until now are the only ones which succeeded to detect geoneutrinos (see below), ν_e's are detected via a very well tagged interaction, the inverse beta decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n \tag{4}$$

([1]) Chondritic meteorites contains chondrules, small spheres, ∼4.6 billion years old, which had a very fast cooling and maintain almost unchanged their composition.

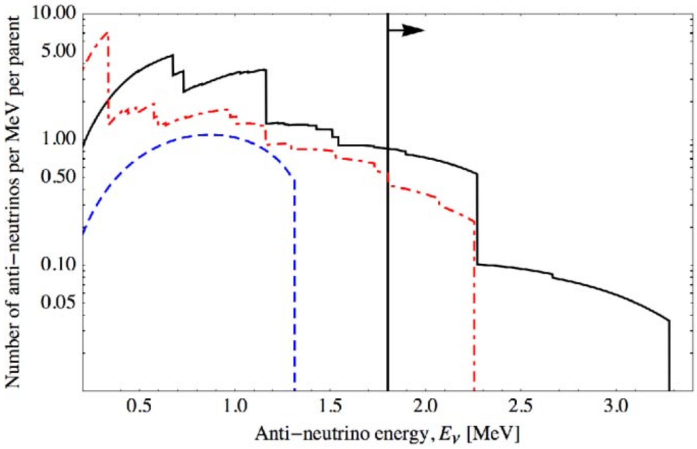

Fig. 1. – Energy spectra of the antineutrinos emitted by the ^{238}U (red), ^{232}Th (green), and ^{40}K (blue). The vertical line represents the kinematic threshold of the detection interaction from Eq. 4.

The positron gives the so called *prompt signal*, as it decelerates and then annihilates, producing two γ's of 511 keV. The neutron is thermalized and after few hundreds of microseconds it is captured by a proton, producing a deuteron with the emission of a 2.2 MeV γ, the so called *delayed signal*. The reaction of eq. 4 has a kinematic threshold of 1.8 MeV. This makes impossible the detection of the ^{40}K geoneutrinos having an energy spectrum with an upper limit below 1.5 MeV, but it allows the measurement of the higher energy tail of geoneutrinos from ^{238}U and ^{232}Th (see fig. 1).

Geoneutrino study can give information on: the radiogenic contribution to the terrestrial heat, the presence of radioactive elements in the crust and in the mantle, the bulk Th/U ratio, checks of the BSE models. The U and Th family members, unlike ^{40}K, have no chemical affinity with the Fe-Ni alloy; therefore it is presumed that they are not present in the Earth's core.

4. – Detectors

Until now only two experiments have been able to study geoneutrinos: KamLAND [3], in Japan, on the border between the oceanic and the continental crust, and Borexino [4], in Italy, on the continental crust.

KamLAND, built originally to study reactor antineutrinos, is installed in the Kamioka mine, with 2700 m water equivalent of overburden rocks; its active volume consists of 1000 tons of liquid scintillator, with an energy and vertex resolution of 6.4% and ∼12 cm, respectively. It is taking data since 2002. With respect to Borexino, KamLAND has definitively more statistics, due to the larger volume and more live days of data taking. On the other hand, it suffers higher background, due to the nuclear reactors installed in Japan and due to the higher internal radioactive contamination of the detector. In September 2011, KamLAND has inserted a vessel, 3.08 m of diameter, containing 13 tons of Xe-loaded liquid scintillator, to study the double beta neutrino-less decay (KamLAND-

Zen). In the period April-June 2012 the Japanese nuclear reactors have been switched off for checks and maintenance: as a consequence, KamLAND was able to take data with a strongly reduced background from reactor antineutrinos.

Borexino has been designed to study the low-energy solar neutrinos, thus its main characteristic is an extreme unprecedented radiopurity, needed to make possible the experiment's mission. It is installed at the Gran Sasso National Laboratory below 3600 m water equivalent of overburden rocks. In central Italy, where LNGS is placed, the antineutrino flux from nuclear reactors is quite low. The Borexino active detector volume is filled with 280 tons of liquid scintillator, with an energy and vertex resolution of 5% and 11 cm at 1 MeV, respectively. Borexino is taking data since May 2007.

5. – The background

The main sources of background for the geoneutrino study are: antineutrinos from nuclear reactors, the internal radioactive background of the detector and the cosmogenic nuclides.

The energy spectrum of antineutrinos produced by nuclear reactors is well known. The latest parametrization of the $\bar{\nu}_e$ spectra per fission of ^{235}U,^{238}U, ^{239}Pu, and ^{241}Pu isotopes can be found in [5]. The reactor antineutrino energy spectrum extends up to about 9 MeV, well above the end point of geoneutrinos which is at about 3 MeV (fig. 1). The expected signal from reactor antineutrinos can be calculated with a few % precision and a detailed information about the fuel composition, reactor-to-detector distance, and a time profile of the reactor thermal power are required.

The internal radioactive background can mimic the coincidence signal from the reaction of eq. 4. The major contribution is given by the (α, n) interactions (mostly ^{13}C(α,n)^{16}O in which α's are from ^{210}Po contamination of the detector) and by accidental coincidences. Cosmogenic ^{9}Li and ^{8}He are background sources due to their $\beta +$ neutron decay branch; their contribution due to muons passing through the overburden rocks is reduced by a veto applied after every muon crossing the detector.

6. – Expected geoneutrino signal from the crust

The measured geoneutrino signal is due to radioactive decays occurring both in the Earth's crust and mantle. In order to estimate the amount of radioactive elements in the mantle, which is one of the hottest issues in this field, it is crucial to estimate the crustal signal. The area of few hundred km around the detector represents a significant portion of the total geoneutrino rate [6, 7]. For the evaluation of the Local Crust (LOC) contribution, the chemical composition of rocks in the area around the experimental site as well as 3D geological structures are studied. Since the Gran Sasso area is dominated by dolomitic rocks poor in radioactive elements [8], the LOC contribution to the Borexino rate (9.7$\pm$1.3) TNU(2) is about one half of that in KamLAND, (17.7$\pm$1.4) TNU [9], placed within a complicated geological structure around the subduction zone surrounding the Kamioka mine [7]. The Rest Of the Crust (ROC) contribution is evaluated using comprehensive models of the crust based on several geochemical compilations of the crustal rocks and results to be $13.7^{+2.8}_{-2.3}$ TNU for Borexino and $7.3^{+1.5}_{-1.2}$ TNU for KamLAND [10].

(2) 1 TNU = 1 event/year/10^{32} protons. 10^{32} target protons correspond roughly to 1 kton of liquid scintillator.

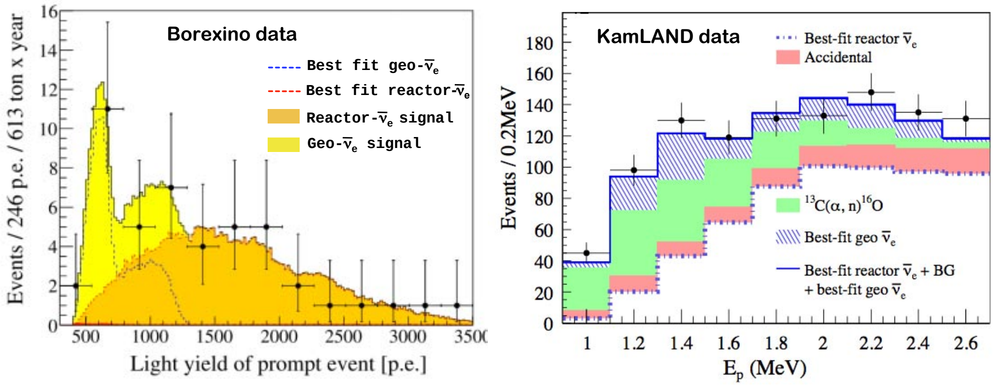

Fig. 2. – The energy spectra of prompt signals. Left: Borexino 2013 results [12] shown in the total number of detected photoelectrons (p.e.) (1 MeV corresponds to ∼500 p.e.). The black data points are the sum of contributions from: geoneutrinos (yellow area), antineutrinos from reactors (orange area), and other backgrounds (small red area bottom left). Right: KamLAND 2013 results [11]. The black points are the data. Different contributions are: geoneutrinos (blue dashed area), antineutrinos from nuclear reactors (white area), internal background from the ^{13}C(α,n)^{16}O reaction (green area) and from accidental coincidences (pink area).

7. – The data

Geoneutrinos have been measured so far only by two experiments, KamLAND [11] and Borexino [12]. In fig. 2 the energy spectra of prompt signals, as measured by Borexino (left) and KamLAND (right) are shown. Table I summarizes the measured geoneutrino signal as well as the levels of main background components. In both experiments, the hypothesis of no geoneutrino observation is rejected at 99.997% C.L. The measured geoneutrino signal in Borexino is (38.8 ± 12) TNU and (30 ± 7) TNU in KamLAND; in both cases, the chondritic Th/U ratio of 3.9 was assumed in the fit.

8. – What can we learn from the geoneutrino results

Despite the low statistics, the geoneutrino data obtained until now provide some hints useful to understand their role in three main aspects: the radiogenic terrestrial heat, the presence of Th and U in the mantle and the bulk Th/U mass ratio.

The comparison between the BSE models expectations and the Borexino and KamLAND measurements seems to favor the geochemical approach, which assumes the chondritic composition but takes into account also the chemical structure of the mantle rocks [13].

The amount of heat producing elements (HPE) in the mantle can be obtained by subtracting the expected LOC and ROC contributions (Sec. **6**) from the total measured geoneutrino rate. In this way, the mantle geo-signal from the Borexino results is (15.4 ± 12.3) TNU and in KamLAND (5.0 ± 7.3) TNU. A combined analysis Borexino + KamLAND assuming a homogeneous mantle gives (7.7 ± 6.2) TNU [14]. An attempt to extract from this result the mantle radiogenic heat brings to a large range between 2.0 and 19.5 TW [14], depending on the distribution of the HPE in the mantle; the extremes

TABLE I. – *The measured geoneutrino signal and the main background components as measured in Borexino and KamLAND.*

	Borexino	KamLAND
Period	Dec'07-Aug'12	Mar'02-Nov'12
Geo-ν events	14.3 ± 4.4	116^{+28}_{-27}
Geo-ν flux (oscill) $[10^6\ cm^{-2}\ s^{-1}]$	4.4 ± 1.4	3.4 ± 0.8
Background		
Reactor anti-ν	$31.2^{+7.0}_{-6.1}$	2017 ± 119
Accidental events	$0/206 \pm 0.004$	125.5 ± 0.1
$^{13}C(\alpha,n)^{16}O$ events	0.13 ± 0.01	207.1 ± 21.4
^{9}Li-^{8}He events	0.25 ± 0.18	31.6 ± 1.9
Geo-ν signal/anti-ν background	0.46	0.032
Geo-ν signal/ non anti-ν background	24.4	0.32
Expected reactor anti-ν events	33.3 ± 2.4	2382 ± 123

correspond to the sunken layer model (all radioactive elements are accumulated on the core-mantle boundary) and to the homogeneous mantle.

The Th/U mass ratio $m(\mathrm{Th})/m(\mathrm{U})$ of 3.9, as measured in the chondritic meteorites, corresponds to a signal ratio $S(\mathrm{U})/S(\mathrm{Th}) \sim 3.66$. Both KamLAND and Borexino collaborations attempted an analysis to extract the individual Th and U contributions from their data by removing the chondritic constraint. The Borexino central value is $S(\mathrm{U})/S(\mathrm{Th}) \sim 2.5$, while KamLAND finds a larger value of ~ 14.5; however, both these results are fully compatible with chondritic values within 1σ.

Borexino and KamLAND have also investigated the hypothesis of a possible geo-reactor [16] due an assumed presence of large Uranium quantities around the core. Both the experiments found an upper limit for a possible geo-reactor power at ~ 3 TW.

9. – Conclusions and future perspectives

But it is clear that more data are needed! Borexino and KamLAND will accumulate more data in the next years, while new experiments are in preparation or in design phase.

SNO+ is a detector similar to SNO, but with the D_2O replaced by 780 tons of liquid scintillator [17]. Its installation site, the Sudbury mine in Canada, is placed on an old continental crust, where the 80% of the geoneutrino signal is expected to come up from the crust [18]. Following BSE previsions, we could expect that SNO+ should detect 28-38 events/year.

A very interesting project is Hanohano [19], 10 kton of liquid scintillator, movable and placed on a deep ocean floor close to the Hawaii. Since Hawaii are placed on the Th-U depleted oceanic crust, 70% of the signal is produced in the mantle! Therefore, this experiment would lead to very important results [18]. Again from BSE, between 60 and 100 events/year are expected. Unfortunately this experiment is not yet approved and funded.

Finally LENA, a 50 kton liquid scintillator detector, has been proposed [20]; the possible installation site is Pyhäsalmi in Finland, on the continental crust with 80% of the signal coming up from the crust. A geoneutrino rate of 800-1200 is foreseen by the BSE models.

We can conclude that a new interdisciplinary field was born, which brings to the study of the deep Earth structure, impossible or very difficult otherwise([3]).

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([3]) A wider discussion of the subject treated in this paper can be found in [21]