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The study of geo-neutrinos

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In the last years, thanks to the measurements of the different components of solar ν fluxes, the solar nuclear fusion has been definitively proven and closer insights into the deep stellar cores have become feasible. In a similar fashion the study of geo-neutrinos is helping us to get information about the deep Earth composition and energetic, since, to this respect, our planet is mainly unexplored.

The aim of this contribution is to describe the status of this new very promising interdisciplinary field. First of all, the structure, composition, and sources of information about the Earth will be reviewed together with the many open issues and the importance of the geo-neutrino study highlighted.

Then the running experiments will be presented and the available data on geo neutrino fluxes discussed. Combined analyses of present results are already starting to put some constraints on geological model but new more precise measurements are needed. New generation experiments for geologically highly significant results are in progress.

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1. Introduction

Geo-neutrinos, the anti-neutrinos from the progenies of U, Th and ^{40}K decays in the Earth, bring to the surface information about the whole planet, concerning its content of natural radioactive elements [1-2]. They represent a new direct probe of our planet interior that can be exploited as a consequence of two fundamental advances occurred in the last years: the development of extremely low background neutrino detectors and the progress on understanding neutrino propagation (as a sake of example the recent results on θ_{13} by Day-Bay and RENO experiments).

The ratio of the released radiogenic heat and the geo-neutrino flux is fixed and well known, so geo-neutrino detection could shed light on the deep Earth composition and on the sources of the terrestrial heat flow.

Presently there are only two running experiments able to measure geo-neutrinos: Borexino at LNGS (Italy) and KamLand in the Kamioka mine (Japan). Both experiments have successfully observed the geo-neutrino signal at ~ 4 σ C.L. and they are presently taking further data in order to increase the precision. Combined analysis of available results is starting to put constraint on geological models.

The status of this new very promising interdisciplinary field is reviewed and the future perspectives discussed.

2. The Earth and the geo-neutrinos

Information about the Earth's interior composition has insofar come exclusively from indirect probes. Geophysics, studying the propagation of mechanical waves through the Earth, constrains the density profile and the phase state. Geochemistry has limited sources of direct data as well and develops models of the Earth bulk composition based on indirect information. The deepest drill hole ever made (12 km, Kola, Russia) represents enormous technical difficulties, but it is negligible with respect to the Earth radius of ~6400 km. Some geological processes bring the deep rocks to the surface (volcanism, obduction, xenolites...) but their chemical composition can be altered during the transport and the deep mantle is completely unreachable.

Similar trends of relative abundances of chemical elements in meteorites and in the Sun's photosphere indicate that the Solar system developed from a chemically homogeneous nebula.

It is believed= that the Earth was created via accretion as a homogeneous object. The metallic core (3500 km radius) was the first to separate from the silicate primordial mantle that further differentiated into the current mantle (3000~km thickness) and the crust (5 to 75 km).

By assuming relative elemental abundances like in meteoritic samples for the primordial Earth and by taking into account the rock melting process that produced the current rocks, the Bulk Silicate Earth (BSE) models were developed, describing the composition of the primitive mantle. The BSE model therefore describes the composition of the silicate Earth, i.e. the mean composition of the Earth after the metallic core separation and before the crust-mantle differentiation. Several authors developed such models [3-9].

In these models the absolute abundances of the long-lived radioactive elements producing geo-neutrinos differ up to a factor of 2-3, while the predictions of their relative proportions are in a much better agreement (within 10%).

The total terrestrial surface heat flux is deduced from the temperature-gradient measurements along ~40,000 drill holes distributed around the world. It is important to note that these drill holes are not distributed homogeneously, they are mostly concentrated on the continental crust, while almost missing in the hottest regions along the mid--ocean ridges.

Using these temperature gradient data, geophysical models typically conclude that the present surface heat flux is (47 ± 2) TW [10].

This conventional view has been challenged by an alternative flux estimate of (31±1) TW [11] and other authors predict 44 TW [12]. Such big discrepancies indicate that some systematic errors or model assumptions are out of the control. Indeed the heat flow close to mid-oceanic ridges is particularly controversial.

There are several possible sources contributing to the total terrestrial surface heat flux and the radiogenic heat is generally considered as a main contribution to the total heat budget. The main long-lived radioactive elements producing this radiogenic heat are ^{238}U, ^{235}U, ^{232}Th, and ^{40}K. The ^{235}U chain contribution to the total heat is presently very small (< 1%) but it was relevant in the past. The range of the BSE predicted abundances translates into a present radiogenic heat contribution varying in the window of 12 – 30 TW (crust + mantle). No contribution is expected from the core.

Thorium and uranium are refractory lithophile elements and contribute equally ~80% of the total radiogenic heat production of the Earth, while the remaining fraction is due to ^{40}K, a volatile element (assuming Th/U ~4 and K/U ~10 000).

During mantle melting and because of their chemistry and size, K, Th, and U are quantitatively partitioned into the melt and depleted from the mantle. Thus, the continental crust, has over geologic time, been enriched in these elements and has a sizable fraction (about half) of the planet's inventory, producing radiogenic power of (7.3±1.2) TW [13]. The main unknown remains the abundances of the long-lived radioactive elements and the radiogenic heat produced in the mantle. It is possible that additional heat sources contribute to the total surface heat flux. Such additional heat might originate from accretion, gravitational contraction, latent heat from phase transitions, or from a nuclear reactor in the core/core-mantle boundary [14] or presence of ^{40}K in the metallic core. It can be concluded, that systematic errors in both geochemical and geophysical models are not very well known and the validity of several assumptions on which they are based is not proven.

The dominant neutrino flux on the Earth comes from the electron flavour neutrinos produced in the nuclear reactions powering the Sun: the flux is of about 10^{10} cm^{-2} s^{-1} with energies below ~11 MeV. Electron anti-neutrino fluxes are conversely emitted by the Earth itself (geo-neutrinos with energies below 3.3 MeV and fluxes of the order of 10^{6} cm^{-2} s^{-1}) and by the nuclear reactor plants producing an overall thermal power of ~ 1 TW and anti-neutrinos of energies up to 10 MeV.

In detail the geo-neutrinos producing reactions are listed in the following:

- $^{238}U \rightarrow {}^{206}Pb + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7$ MeV;
- $^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.8$ MeV;
- $^{235}U \rightarrow {}^{207}Pb + 7\alpha + 4e^- + 4\bar{\nu}_e + 44$ MeV;
- $^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e + 1.32$ MeV;

The endpoints of the corresponding geo-neutrinos energy spectra are respectively 3.3 MeV, 2.25 MeV, 1.4 and 1.3 MeV for ^{238}U, ^{232}Th, ^{235}U chains and ^{40}K decay, so a spectral analysis of detected geo-ν allows disentangle the contribution arising from the different radioisotopes.

It is important to note that the ratio of the released radiogenic heat and the geo-neutrino flux is fixed and well known. Therefore, it is in principle possible to determine the amount of the radiogenic heat contributing to the total terrestrial surface heat flux (Urey ratio). By measuring the geo-neutrino flux at different locations through the globe, in different geological settings and/or by being able to identify the incoming direction of detected geo-neutrinos, it might be possible:

- to study the distribution of radioactive elements within the Earth, to determine their abundances in the crust and in the mantle;
- to determine if there are any radioactive elements in the Earth's core;
- to understand if the mantle composition is homogeneous or not;
- to test, validate and discriminate among different BSE models;
- to exclude or confirm the presence of the geo-reactor in the core;
- to determine the so called Urey ratio by measuring the radiogenic heat flux, an important parameter for both geochemistry and geophysics.
- to study the bulk U and Th ratio in the silicate Earth, an important parameter for geochemistry which could shed light on the process of the Earth's formation.

All these information could be important data used as inputs for many geological, geophysical, and geochemical models describing such complex processes as the mantle convection, movement of tectonic plates, geo-dynamo (the process of the generation of the Earth's magnetic field), the process of the Earth formation etc..

On the Earth surface the geo-neutrino fluxes are not expected to be homogeneous: U,Th and K are mostly concentrated on the crust. So the maximal signal is expected where the crust is the thickest, i.e. in correspondence of the Himalayan chain. In order to correctly evaluate the geo-neutrino flux at a given experimental site it is therefore very important to take into account the contribution arising from the local geology: is it expected that half of the signal originates from a region within 500 km from the detector.

By using the available seismic profiles as well as stratigrafic records from a number of exploration holes very precise 3D models down to the Moho depth have been developed for a number of sites of interest [15-16].

Geo-neutrinos are electron flavour anti-neutrinos, but during their propagation form the production to the detector site the relative proportion of the three mass eigenstates could change. The survival probability Pee, i.e. the probability to be detected again as electron antineutrinos, oscillates according to :

$$P_{ee} = P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \cos^4(\vartheta_{13}) \cdot \left(1 - \sin^2(2\vartheta_{12}) \cdot \sin\left(\frac{\delta m^2 L}{4E}\right)\right) + \sin^4(\theta_{13})$$

where θ_{12}, θ_{13}, and δm^2 are mass mixing oscillation parameters and E, L being the anti-neutrino energy and the source-detectors distance in natural units.

For an anti-neutrino of a given energy, the P_{ee} changes with distance L. For a ~3 MeV anti-neutrino, the oscillation length is of ~100 km.

Therefore, for geo-neutrinos originating from a continuous source of few thousands of kilometers (the Earth mantle and crust), the oscillation pattern cannot be distinguished on the energy spectrum of detected geo-neutrinos and the δm^2 term can be averaged out: one can consider only the reduction of the total flux by $P_{ee}= (0.551 \pm 0.015)$[17].

The effect of a not null θ_{13} mixing angle translates into a decrease of the expected geo-ν flux of ~ 5%.

3. Geo-neutrino experimental results and their analyses

Presently there are only two running experiments able to measure geo-neutrinos: Borexino at LNGS (Italy) [18] and KamLand in the Kamioka mine (Japan) [19]. Both experiments are based on large volume scintillator detectors of 287 tons and 1 kton, respectively, and placed in underground laboratories in order to reduce the cosmic ray fluxes. Geo-neutrinos are detected via the inverse beta decay reaction on the scintillator protons, with a kinematic threshold 1.806 MeV:

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

It is worth to note that the ^{40}K and ^{235}U geo-ν are below threshold so they cannot by fact be detected but the relative proportions of the elemental abundances are much better known than the absolute abundances. Therefore, by measuring the absolute abundances of ^{238}U and ^{232}Th, the absolute abundance of ^{40}K and ^{235}U can be inferred with a better precision.

In the inverse beta decay process, a positron and a neutron are emitted as reaction products. The positron promptly comes to rest and annihilates emitting two 511 keV γ-rays, yielding a prompt event, with a visible energy E_{prompt} directly correlated with the incident energy anti-ν energy: $E_{prompt}= E_{anti\text{-}\nu}$- 0.782 MeV.

The emitted neutron is typically captured on protons after a mean time of τ= 200-250μs, resulting in the emission of a 2.22 MeV de-excitation γ-ray, which provides a coincident delayed event.

The characteristic time and spatial coincidence of prompt and delayed events offers a clean signature of anti-ν_e interactions. The known anti-ν_e sources are the Earth and reactor power plants while atmospheric and supernova relic anti-ν_e give negligible contributions.

A careful analysis of the expected reactor anti-ν_e rate is necessary for both experiments and indeed the two experimental collaborations are in strict contact with the International Agency of Atomic Energy (I.A.E.A.) and the Consortium of Japanese Electric Power

Companies. The determination of the expected signal from reactor anti-ν_e's requires the collection of the detailed information on the time profiles of the thermal power and nuclear fuel composition for nearby reactors.

In Japan there are many nuclear power plants and in addition the KamLand detector was constructed to measure reactor anti-ν_e oscillations, so it is placed very close to the reactors.

Therefore, the reactor anti-ν_e background for geo-neutrino measurement was quite high in this experiment. To the contrary, in Italy there are no nuclear power plants (the mean reactor distance is of approximately ~1000 km), so the reactor anti-ν_e flux in Borexino is up to a factor of 4-5 lower then in KamLand site.

The extreme detector radio-purity is a must for the success of this measurements: random coincidences and (α,n) reactions in which α's are mostly due to the ^{210}Po decay (belonging to the ^{238}U chain) could in fact mimic the reaction of interest.

For both experiments the active scintillator is placed in the very core of the detector and is shielded by layers of the buffer liquid (mineral oil in KamLand and quenched scintillator in Borexino). The scintillator volume is viewed by arrays of about 2000 photomultipliers mounted on a stainless steel sphere (Inner Detector). The scintillation light isotropically propagates from the interaction point outwards and the number of hit photomultipliers is a measure of energy deposited in the detector. The position of the interaction point can be determined via the time-of-flight measurement of detected scintillation photons. The inner detector is placed inside a ultra-pure water tank viewed by ~200 photomultipliers: the water acts both as a passive shield against external gamma's and neutrons and as an active veto detector against cosmic muons.

Borexino and KamLand are placed in very different geological environments and are also very far from each other. Borexino is placed on a continental crust while KamLand on oceanic crust. The measurements from both experiments are therefore complementary and probing different geological settings, and they could shed light on the hypothesis of a homogeneous vs heterogeneous mantle.

The first experimental indication of a geo-neutrino measurement (~2.5σ C.L.) was reported by the KamLand collaboration [20-21]. The observation of geo-neutrinos at 99.997 % C.L. was then achieved by both Borexino [22] and KamLand [23]. The observed energy spectra of the prompt candidates are showed in Fig. 1 (a) and (b).

Borexino detected in total 21 candidates with an exposure of 253 t·yr (see Fig.1).

The result of an unbinned maximum likelihood fit of the prompt energy spectrum gives the number of detected geo--neutrinos $N_{geo} = 9.9^{+4.1}_{-3.4}$ and the number of reactor anti-neutrinos $N_{react} = 10.7^{+4.3}_{-3.4}$. In the fit the Th/U ratio was fixed to the chondritic value of 3.9. The contribution of other background resulted negligible. The number of geo-ν events corresponds to an anti-ν_e flux of $(7.2^{+2.9}_{-2.4})\ 10^6\ cm^{-2}s^{-1}$.

These results hint at a higher rate for geo-ν than the BSE [24] predicts, but the large uncertainty prevents any conclusions (see Fig.2).

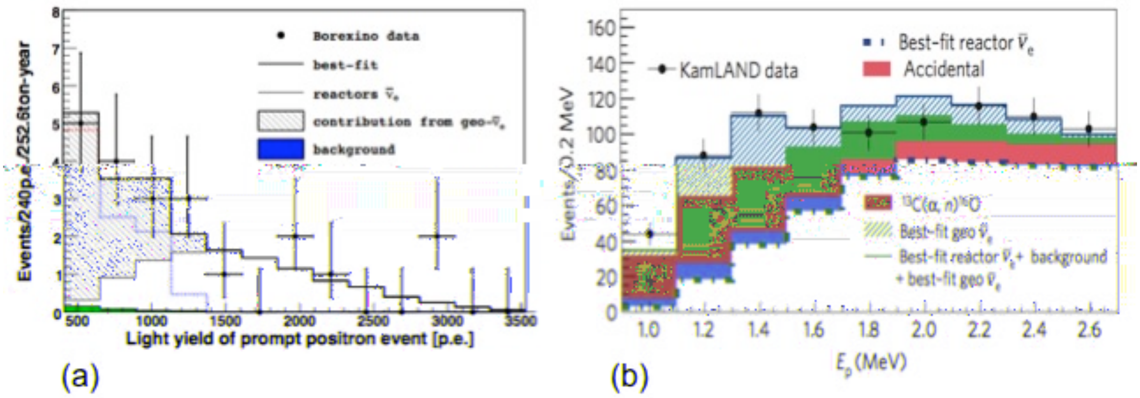

Fig. 1: (a) Borexino data and fit from [22], the conversion from p.e. to energy is about 500 p.e./MeV.the red dotted line is the geo-neutrino signal from the fit; (b) Kamland data and fit (from[23]).

KamLand detected 841 anti-neutrino candidates in the prompt energy window between 0.9 MeV and 2.6 MeVand with an exposure of ~4100 t·yr. The best fit with the Th/U ratio fixed to the chondritic value of 3.9 resulted in the number of detected geo-neutrinos $N_{geo} = 106^{+29}_{-28}$, corresponding to an anti-ν_e flux of $(4.3^{+2.1}_{-1.9})\ 10^6\ cm^{-2}s^{-1}$. This result is in agreement with the prediction of the BSE model from [16] but other models cannot be firmly excluded yet.

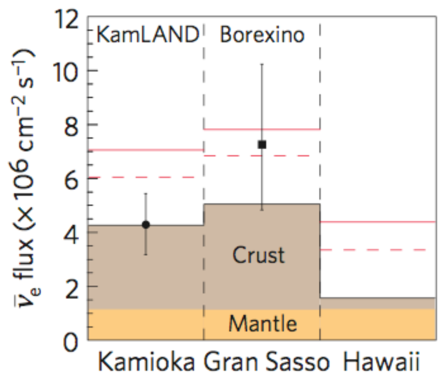

Fig.2 Measured geo-neutrino flux and models at Kamioka and Gran Sasso compared to expectations at these sites and Hawaii. The solid and dashed red lines represents, respectively the fluxes for a fully radiogenic model assuming the homogeneous and sunken-layer hypotheses (from [23]).

In the same paper a combined analysis of the KamLand and Borexino results is presented: a contribution of $20.0^{+8.8}_{-8.6}$ TW to the Earth's heat flux from ^{238}U and ^{232}Th chain was deduced. According to this analysis the radiogenic heat seems to contribute to about one half of the total Earth's energy budget.

Experimental data are compared with the expectations from the fully radiogenic model: this model is based on the hypothesis that all the Earth heat flux is due to radioactive decays, the "extra"-U/Th nuclides being embedded homogeneously in the mantle (in the homogeneous model), or placed at the mantle/core boundary (in the sunken-layer model). Present data allows to exclude the fully radiogenic homogeneous model at 97.2% C.L. (see Fig.2).

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A beautiful combined analysis of the Borexino and KamLand results have also been performed by Fiorentini et al. [17]: the aim of this analysis was to put some constrains on the geo-ν fluxes coming from the mantle.

To this purpose the prompt energy spectra of both experiments has been fitted by leaving the Th/U ratio unconstrained in order to get the separate signal coming from the Th and U chains. The crustal contribution for both sites was known thanks to geological surveys and 3D models of local crustal composition and thickness [15,16] and then subtracted.

Under the hypothesis of a site independent mantle flux, the $\Delta\chi^2$ profiles of Th versus U rates have been summed up and they are shown in Fig.3. The hypothesis of a null mantle signal could be rejected at 2.4 σ level. The predictions of some models are also shown for comparison. Even if the statistical significance is still low, data seems to prefer models with high radiogenic content (corresponding to present mantle Th+U heat ≥ 13 TW at ~1σ) and disfavour at ~ 2σ those with low content (i.e. [9]).

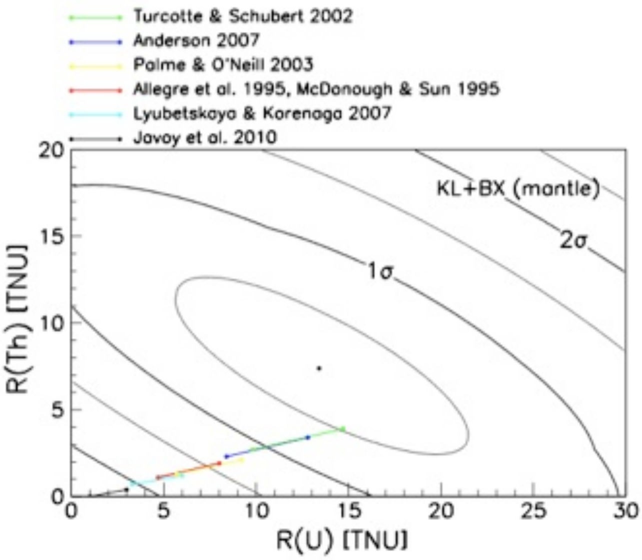

Fig.3 Comparison of experimental constraints and model predictions in the plane charted by the Th and U mantle rates (from [17]). The KL+BX constraints are shown as nσ contours in steps of 0.5σ. One TNU (=Terrestrial Neutrino Unit) corresponds to one event/year/10^{32} target protons.

In conclusion even if the measured geo-ν rate have still large uncertainties, indeed they are already starting to put some constraints on geological models.

4. Future perspectives and conclusions

A new interdisciplinary files is born: two geo-neutrino measurements opened a new door by proving that geo-neutrinos can be detected and that we have a new tool how to learn new things about our planet. In order to find definitive answers to the questions correlated to the radiogenic heat and abundances of radiogenic elements, more data is needed.

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Both Borexino and KamLAND experiments are going on to take data. The earthquake in Japan caused all the reactor power plants in Japan to be switched off since the beginning of May 2012. The strong reduction of the reactor anti-neutrino background could crucial in order to increase the precision of the flux measurement.

A new generation of experiments using liquid scintillators are foreseen: SNO+ at Sudbury mine in Canada [25] is in an advanced construction phase. The site is located on an old continental crust and the signal from reactor anti-neutrinos is about twice as the one at Gran Sasso. Two new ambitious projects have been presented: LENA [26] at Pyhasalmi in Finland or Frejus in France could detect up to 1000 geo-ν per year thanks to the very large mass (50 kt). A few percent precision of the total flux measurement could be reached within the first couple of few years and the individual contribution of the U and Th geo-neutrino flux determined as well. A second interesting project is HANOHANO [27] at Hawaii where the oceanic crust is very thin and the mantle contribution to the total geo-neutrino flux should be dominant.

In conclusion the availability of detectors placed at different geological sites will be really a key point to perform a sort of Earth "tomography" and to get highly significant geological results.

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