PROCEEDINGS OF SCIENCE

Results on geo-neutrinos at Borexino

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The latest geo-neutrinos Borexino results, published in Ref. [1], are briefly presented and discussed. Borexino [2] is a liquid scintillator detector located at the Gran Sasso National Laboratory in Italy, whose primary purpose is the real-time spectroscopy of low energy solar neutrinos. It is the only experiment so far to have provided an evidence of geo-neutrinos existence beyond a 5σ significance level. The geo-neutrinos measurement and analysis, along with implications from the geological point of view, are shortly discussed.

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1. Introduction

Geo-neutrinos [3] are electron antineutrinos ($\overline{\nu}_e$) produced in the radioactive decays occurring in the Earth interior layers. Their sources are the natural radioactive chains of nuclides, through β^- decays. The three natural chains of interest, starting respectively with ^{238}U, ^{232}Th or ^{40}K, can be globally summarized as follows:

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\mathrm{e}^- + 6\overline{\nu}_\mathrm{e} + 51.7\,\mathrm{MeV} \tag{1.1}$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4\mathrm{e}^- + 4\overline{\nu}_\mathrm{e} + 42.7\,\mathrm{MeV} \tag{1.2}$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^- + \overline{\nu}_\mathrm{e} + 1.31\,\mathrm{MeV} \tag{1.3}$$

It is important to underline the two-fold geo-neutrinos scientific interest. First of all, they can be considered as unique messengers of information coming from the innermost Earth layers. Their flux and the radiogenic heat, released in radioactive decays, are found in a well-known ratio thanks to our knowledge of natural radioactive chains. Thus it is possible to measure the total geo-neutrino flux, and connect it to the contribution of radiogenic heat released in radioactive decays, and eventually to the total Earth heat flux. Secondly, their flux is critically related to to the abundance and distribution of U and Th in the Earth: these are fundamental inputs for classes of models describing the geological, geophysical, and geochemical processes occurring inside the Earth. Eventually, the geo-neutrino signal provides information about the radiogenic power of the deep mantle, which is completely inaccessible by means of direct sampling.

2. Borexino detector

Geo-neutrinos travel almost undisturbed through the Earth with a very small probability to interact in the detectors; this is due to the very low cross section. This property implies severe detection requirements in order to measure the related flux: large sizes and a very low radioactive background are needed. To overcome successfully these detection constraints, advanced technologies and considerable efforts are needed. Only two experiments so far have the requirements needed to measure and distinguish the geo-neutrino flux [4, 5].

Borexino is a large volume liquid scintillator detector whose primary purpose is the real-time measurement of low energy solar neutrinos [2]. It is schematically drawn in Fig. 1. It is located deep underground (approximately 3800 meters of water equivalent) in the Hall C of the Gran Sasso National Laboratory, in Italy. The Gran Sasso mountain natural shielding, combined with the detector design, allows an extremely high muon flux suppression. Borexino has been data-taking from 2007, achieving important results [6]: it detected and then precisely measured the flux of the ^{7}Be solar neutrinos, ruled out the day-night asymmetry of their interaction rate, made the first direct observation of the pep neutrinos, and set the tightest upper limit so far on the flux of CNO solar neutrinos.

The Borexino design is driven by the principle of graded shielding: a inner scintillating ultra-pure core is found at the center of shielding concentric shells, with decreasing radio-purity from inside to outside. The scintillator is a solution of PPO (2,5-diphenyloxazole) in pseudocumene

(PC, 1,2,4-trimethylbenzene) at a concentration of 2.5 g/l. The main scintillator mass is about 278 ton and is contained in a 125 μm thick spherical nylon Inner Vessel (IV) of approximately 4.25 m radius. 2212 internal photo-multipliers (PMTs) are mounted on a Stainless Steel Surface (SSS) to collect scintillation light and allowing the measurement of the position and of the energy of the detected events.

The extremely low intrinsic radioactivity achieved in Borexino, the strong cosmic ray shielding, the high photon yield have made possible a sensitive search for $\overline{\nu}_e$ in the MeV energy range. While the solar neutrinos are measured through the elastic scattering with scintillator electrons, Borexino is also able to measure $\overline{\nu}_e$ through the Inverse Beta Decay reaction $\overline{\nu}_e + p \rightarrow n + e^-$ (IBD). The typical cross section values at the MeV energy range are found around $10^{-44}\,\mathrm{cm}^2$: because of this extremely low cross section the geo-neutrinos detection is very challenging, in spite of the $10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ expected flux on the Earth surface. The IBD kinematic threshold is $E_{\mathrm{thr}} = 1.806\,\mathrm{MeV}$; the antineutrinos produced in the ^{40}K chain cannot be detected because their end-point energy spectrum of 1.31 MeV is found below E_{thr}. Thus, only the U and Th chains related $\overline{\nu}_e$ can be measured in Borexino [4, 7]. The produced positron immediately comes to rest in the liquid scintillator, and it annihilates with an emission of two 511 keV γ, with a visible energy of $E_{\mathrm{prompt}} = E_{\overline{\nu}_e} - 0.782\,\mathrm{MeV}$ (*prompt event*). It is noticeable to underline that the scintillation light of the proton recoil is highly quenched and almost negligible. Instead, the emitted neutron is captured on protons in a mean time of 256 μs, with the emission of a 2.22 MeV de-excitation γ (*delayed event*). The combination of these two events, through the characteristic time, spatial and energetic coincidences, allows Borexino to detect geo-neutrinos in an extremely low-background channel.

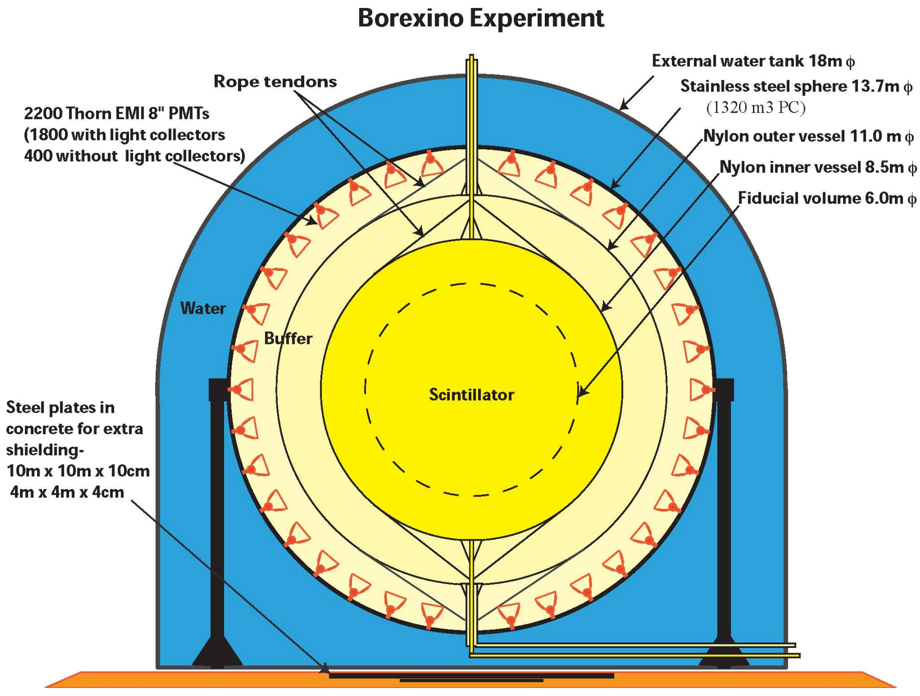

Figure 1: Schematic drawing of the Borexino detector.

3. Data analysis and results

The data reported in the latest geo-neutrino paper (Ref. [1]) from Borexino were collected between December 15, 2007 and March 8, 2015 for a total of 2055.9 days before any selection cut.

The antineutrinos coming from nuclear power plant are the main background for the geo-neutrino data taking. Since no nuclear power plants are present in Italy, the LNGS is an excellent location for geo-neutrinos detection. In order to estimate the nuclear plant contributes, one has to combine a large amount of information, including the reactor power as a function of time, the component fractions, the reactors-detector distances and the $\overline{\nu}_e$ survival oscillation probability. The number of reactor $\overline{\nu}_e$ is extracted through Monte Carlo simulations and is 5.7 ± 0.3 events / (100 ton yr). The extreme radiopurity of the Borexino detector and the coincidences for IBD events candidates guarantee that the non-$\overline{\nu}_e$ background is almost negligible. The main contributions are due to the internal radioactivity of the detector structural components (PMTs, IV...), to the accidental coincidences, and to the cosmogenic-muon related decays. Neutrons and long-lived cosmogenic radioactivity events have been discarded through time cuts respectively of 2 ms for every muon crossing the outer detector and within 2 s of muons crossing the inner detector. Many additional software cuts have been applied in order to select as possible the $\overline{\nu}_e$ events; the most important ones select the prompt and delayed energy through the amount of scintillation light detected, the correlation distance and time between prompt and delayed signals, the pulse shape discrimination for delayed signals, the dynamical fiducial volume cut. More details about the data selection can be found at Ref. [1]. The combined efficiency of the selection cuts is estimated through Monte Carlo simulations and it is $84.2 \pm 1.5\%$, and a total of 77 candidates have been selected in the considered time period.

Prompt $\overline{\nu}_e$ event candidates spectrum in 2056 days of Borexino data-taking [1], expressed in units of photoelectrons (p.e.), is shown in Fig. 2. An unbinned maximal likelihood fit of the energy spectrum has been performed. The best-fit blue dotted line shows the geo-neutrino and reactor $\overline{\nu}_e$ spectra assuming the Th/U mass ratio fixed to the chondritic model value of 3.9. Blue and light blue areas show respectively the result of the fit with U and Th contributions set as free and independent parameters. The reactor signal (orange area) has been calculated adopting the reactor data from IAEA. Two different fit approaches are shown. Non-$\overline{\nu}_e$ background has been considered in the fit but it is constrained to independent estimations and it is completely negligible for our purposes.

The numbers of detected antineutrinos can be easily converted into fluxes, commonly expressed in Terrestrial Neutrino Units (TNU). This corresponds to the number of antineutrino events detected during one year on a target of 10^{32} protons (i.e. approximately 10^3 ton of liquid scintillator) and 100% detection efficiency. According to the fit choice (Th/U abundance fixed or free parameter) different information can be extracted. The left panel of Fig. 3 shows the best-fit contours for 1σ, 3σ and 5σ regions in the $S_{\rm geo} - S_{\rm react}$ parameters space, extracted through the unbinned likelihood fit with Th/U abundance fixed to che chondritic model value. The absence of geo-neutrinos hypotesis, i.e. $S_{\rm geo} = 0$, is excluded for the first time at more than 5σ (5.9σ discovery). The right panel of Fig. 3 instead shows the best-fit contours for 1σ, 2σ and 3σ regions in the $S_{\rm Th} - S_{\rm U}$ space, for the unbinned likelihood fit with U and Th left as free parameters. The dashed line represents the predictions for the mass ratio Th/U = 3.9 of the chondritic model. The

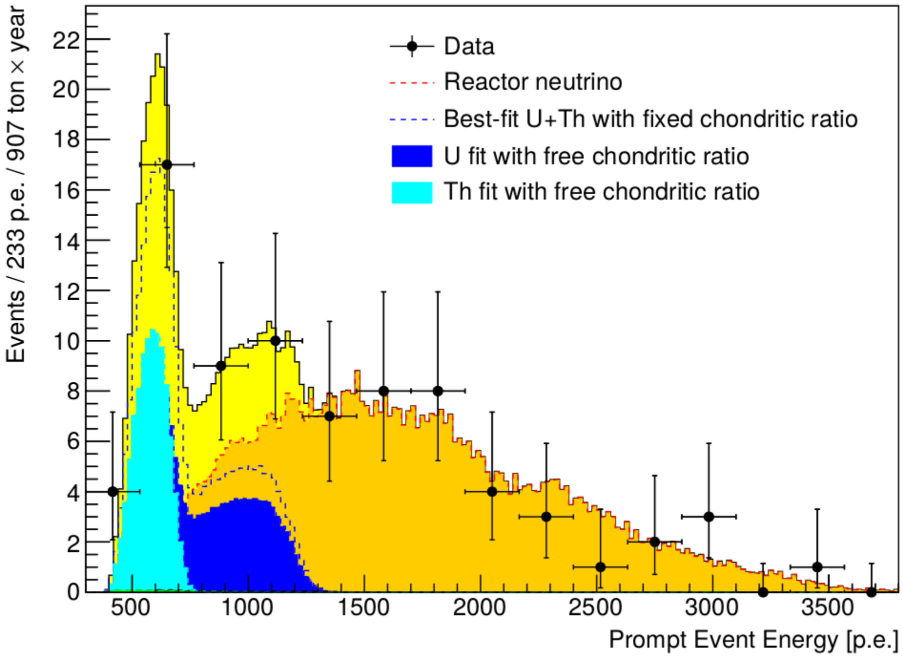

Figure 2: Prompt $\overline{\nu}_e$ event candidates spectrum in 2056 days of Borexino data-taking, expressed in units of photoelectrons (p.e.). The two different fit approaches are shown. The best-fit blue dotted line shows the geo-neutrino and reactor $\overline{\nu}_e$ spectra assuming a fixed chondritic ratio (Th/U $= 3.9$). Blue and light blue areas show respectively the result of fit with U and Th set as free and independent parameters. The orange area represents the reactor $\overline{\nu}_e$ contribution.

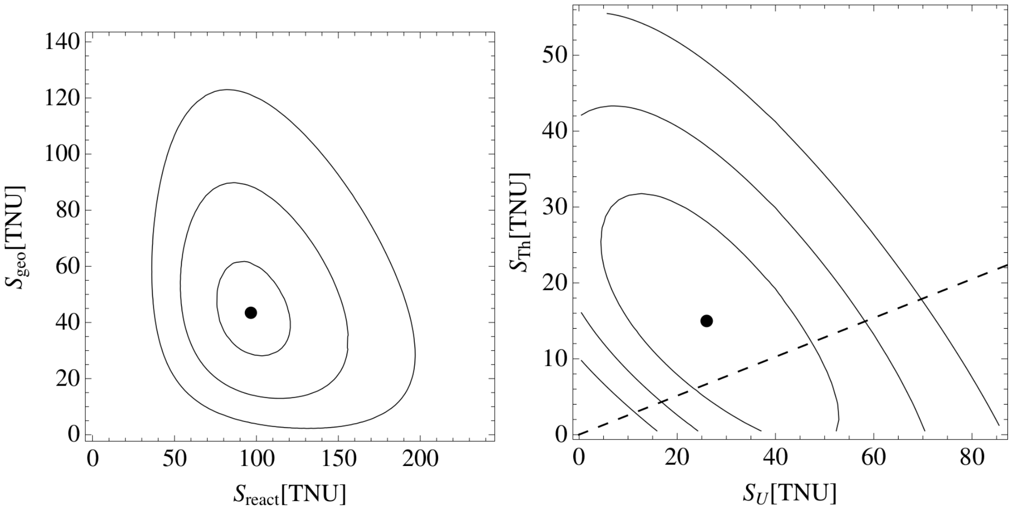

Figure 3: Left panel: best-fit contours for 1σ, 3σ and 5σ in the $S_{geo} - S_{react}$ parameters space, extracted through the unbinned likelihood fit with Th/U mass ratio fixed to che chondritic model value. Right panel: best-fit contours for 1σ, 2σ and 3σ in the $S_{Th} - S_{U}$ for the unbinned likelihood fit with U and Th contributions left as free parameters. Dashed line represents the predictions for the mass ratio Th/U $= 3.9$ of the chondritic model.

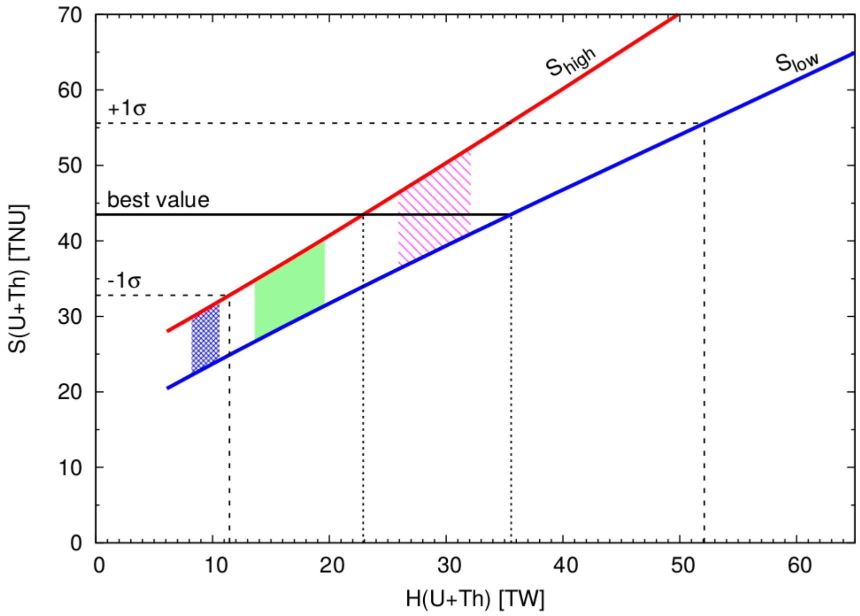

Figure 4: Implications on radiogenic heat: expected geo-neutrino signal in Borexino (TNU units), due to U and Th radioactive decays, as a function of radiogenic heat released. The three blue, green and pink regions represent predictions, from the left to the right, of the cosmochemical, geochemical and geodynamical BSE models [8]. We report the best values from Borexino, along with systematical and statistical errors combined.

central value of the fit is largely compatible with the predictions of the chondritic model. This result show also that Borexino is able to perform a real time spectroscopy of geo-neutrinos, being able to separate the two components of the detectable natural chains.

From the geophysical point of view, the geo-neutrino results have strong implications on our radiogenic heat knowledge: Fig. 4 shows the expected geo-neutrino signal in Borexino, due to U and Th natural radioactive chains, as a function of the radiogenic heat [3].

4. Conclusions

The more recent and complete Borexino results related to geo-neutrinos are reviewed and briefly described. Borexino has been taking $\overline{\nu}_e$ data for 2056 days, thanks to an extremely low background level and to position and energy reconstruction high precision. The main result consists in the geo-neutrinos measurement with 5.9σ significance. We have seen also that Borexino is able to fit separately the two U and Th natural chain contributions, performing a real time geo-neutrino spectroscopy. The study of the Earth's geo-neutrino flux creates a new interdisciplinary field between Geology and Physics [3].

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