PROCEEDINGS OF SCIENCE

Improved geoneutrinos observation with Borexino detector

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The comprehensive geo-neutrinos measurement using the Borexino detector, published in Ref. [1], is briefly presented and discussed. Borexino is an ultrapure liquid scintillator detector located at the Gran Sasso National Laboratory in Italy, whose primary scientific goal is the real-time spectroscopy of low energy solar neutrinos. So far, Borexino is the only experiment to achieve an evidence for geo-neutrinos existence beyond a 5σ significance level. In the following, the geo-neutrinos analysis from 3262.74 days data-taking between December 2007 and April 2019, the improved analysis techniques and optimized data selection, and the implications from the geological point of view will be discussed.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

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1. Introduction

Geoneutrinos are electron antineutrinos ($\overline{\nu}_e$) emitted by the β^- decays of isotopes present in the Earth. The three natural chains of interest, starting respectively with ^{238}U, ^{232}Th or ^{40}K, can be globally summarized as follows:

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\mathrm{e}^- + 6\overline{\nu}_\mathrm{e} + 51.7\,\mathrm{MeV} \tag{1}$$
$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4\mathrm{e}^- + 4\overline{\nu}_\mathrm{e} + 42.7\,\mathrm{MeV} \tag{2}$$
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^- + \overline{\nu}_\mathrm{e} + 1.31\,\mathrm{MeV} \tag{3}$$

Geoneutrinos cover a two-fold 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.

On the other side, their flux is correlated to the abundance and spatial distribution of U and Th in the Earth. This information represent a crucial input for several models aiming to describe the geological, geophysical, and geochemical processes occurring inside our planet. Moreover, as we will see later on, the geo-neutrino flux provides information about the radiogenic power of the mantle.

2. Borexino detector

Geo-neutrinos cross almost undisturbed the Earth because of their very low cross section, which is $\sim 10^{-42}\,\mathrm{cm}^2$ at MeV energy for the Inverse Beta Decay reaction (IBD). This elusivity implies a tiny probability to interact in the detectors, and therefore severe experimental requirements in order to measure their flux must be matched: large detector active masses are needed, as well as a very low radioactive background environment. Only two experiments so far have been able to get an evidence of the geo-neutrino flux: Borexino [1, 2] and KamLAND [3].

Borexino [4] is a large volume liquid scintillator detector, whose primary scientific goal is the real-time measurement of low energy solar neutrinos. It is located deep underground in the Hall C of the Gran Sasso National Laboratory, in Italy. The Gran Sasso mountain natural shielding (approximately 3800 m.w.e.), combined with the detector design, allows an extremely high muon flux suppression. The detector design, schematically drawn in Fig. 1, is based on the graded shielding principle. The detection mass is a ultra-pure 278 ton scintillator core, contained in a 125 µm thick spherical nylon Inner Vessel (IV) of approximately 4.25 m radius, and located at the center of concentric shells for passive shielding, with increasing radio-purity from outside towards the inside. The scintillator is a solution of PPO (2,5-diphenyloxazole) in pseudocumene (PC, 1,2,4-trimethylbenzene) at a 2.5 g/l concentration. 2212 internal photo-multipliers (PMTs) are mounted on a Stainless Steel Surface (SSS) to collect scintillation light, allowing the measurement of the position and of the energy for the detected events.

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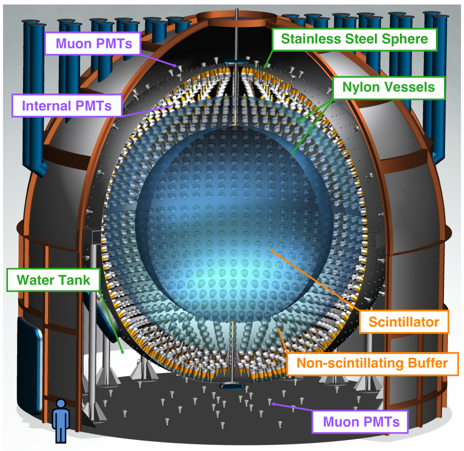

Figure 1: Schematic drawing of the Borexino detector.

Borexino has been taking data since 2007, achieving prominent results for solar neutrino physics: it performed a complete spectroscopy of pp chain solar neutrinos [5] and achieved the first detection of CNO solar neutrinos [6].

The search for $\overline{\nu}_{\rm e}$ in the MeV energy range is allowed by several Borexino unique features: the extremely low intrinsic radioactivity, the cosmic ray passive shielding, the scintillator high photon yield. Borexino is also able to detect $\overline{\nu}_{\rm e}$ exploiting the Inverse Beta Decay reaction $\overline{\nu}_{\rm e} + p \rightarrow n + e^-$. The typical cross section value at the MeV energy range is extremely low ($\sim 10^{-42}\,\mathrm{cm}^2$); consequently, the geo-neutrinos detection is very challenging, in spite of the $10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ expected flux at the Earth surface. The IBD kinematic threshold is $E^{\rm thr}_{\overline{\nu}_e} = 1.806\,\mathrm{MeV}$: only the U and Th chains related $\overline{\nu}_{\rm e}$ can be measured in Borexino, since the ones emitted by the ^{40}K decay chain have a low end-point energy spectrum, 1.31 MeV.

After the IBD reaction has taken place, the produced e^+ immediately comes to rest in the liquid scintillator, annhilated with a scintillator e^- following an emission of two 511 keV γ. The visible energy for this *prompt event* is given by $E_{\rm prompt} = E_{\overline{\nu}_e} - 0.782\,\mathrm{MeV}$. The emitted neutron is captured on scintillator protons in 256 µs mean time, followed by a 2.22 MeV de-excitation γ (*delayed event*). The timing, spatial, and energetic coincidence of the prompt and delayed events allows Borexino to detect geo-neutrinos in an extremely low-background channel.

3. Backgrounds

The data reported in the comprehensive geo-neutrino analysis from Borexino were collected between December 9, 2007 and April 28, 2019 for a total of 3262.74 days before any selection cut [1]. The irreducible and main background for the geo-neutrino analysis is given by the $\overline{\nu}_e$ emitted from the nuclear power plants. The number of reactor antineutrino events is typically kept free in the spectral fit, as we will see in Sec. 5; in any case, one can show that an additional constraint on reactor $\overline{\nu}_{\rm e}$ contribution does not significantly improve the spectral fit and the precision of geoneutrinos flux measurement. On the other side, the non-$\overline{\nu}_{\rm e}$ background can be considered negligible: internal radioactivity of the detector materials (PMTs, IV...), accidental coincidences, and cosmogenic isotopes decays. Their expected contribution is estimated 8.28 ± 1.01 events during the whole data taking.

4. Data selection

In the following, the selection cuts for the geoneutrino comprehensive analysis are briefly summarized [1]. The energy threshold for the prompt event is 1.8 MeV, while the energy windows for delayed events consider the neutron captures on ^{1}H or ^{12}C, and correspond to 2.2 MeV and 4.95 MeV. To guarantee the prompt and delayed coincidence, the time difference between the two events needs to be five times the neutron capture lifetime, while the prompt-delayed distance must be less than 1.3 m, as optimized by the sensitivity studies. For what concerns the rejection of muons and long-lived cosmogenic isotopes, time and spatial vetoes are exploited: a time veto of 2 ms for every muon crossing the outer detector only, three different time vetoes (2 ms, 1.6 s, 2 s) for every muon crossing also the inner detector, and an additional spatial veto according to the type of muon. The external background contribution coming from the Inner Vessel is significantly suppressed by applying a dynamical fiducial volume cut: the prompt event distance from the Inner Vessel must be larger than 10 cm. Particle identification techniques, as the use of Multi-Layer Perceptron variable, are applied to the delayed event in order to perform α/β discrimination. The detection efficiency after the optimized selection cuts for geoneutrinos, determined based on the Monte Carlo simulation of each component, is (87.0 ± 1.5)%. The error is estimated using the calibration data. After the selection cuts, 154 golden candidates are found, for a reduced exposure of $(1.12 \pm 0.05)10^{32}$ protons × year.

5. Methods and results

Once the golden candidates events are selected, the geoneutrino signal is extracted from the spectral fit of the prompt reconstructed energy. The energy variable, named *charge*, is given by the numbers of detected photoelectrons for each event, properly normalized for the number of active PMTs at the event time. An unbinned likelihood fit is employed, since the number of golden candidates is quite small. The spectral shapes of the fit components are constructed via Monte Carlo simulations, except for the accidental background ones, which are measured with sufficient precision. The number of geoneutrino events and the number of reactor $\overline{\nu}_e$ events are free parameters of the fit. The major non-$\overline{\nu}_e$ backgrounds are constrained by means of multiplicative Gaussian pull-terms in the likelihood: the cosmogenic ^{9}Li background, the (α, n) background and the accidental coincidences.

The spectral fit of the data, with the $^{238}\mathrm{U}/^{232}\mathrm{Th}$ ratio fixed to the chondritic value, is shown in Fig. 2 left panel. The resulting number of geoneutrinos is $51.9^{+9.4}_{-8.4}(\mathrm{stat})^{+2.7}_{-2.1}(\mathrm{sys})$. The precision is improved of a factor two, with respect to the previous Borexino 2015 analysis [7]. It is important also to notice that, without any constraints to the number of reactor $\overline{\nu}_e$, the fit returns a value compatible with expectation: this is an important confirmation of the Borexino ability to perform $\overline{\nu}_e$. spectroscopy.

The collected data can be also exploited to extract the mantle signal through the spectral fit, by constraining the bulk litosphere contribution. This has been estimated $28.8^{+5.5}_{-4.6}$ by means of

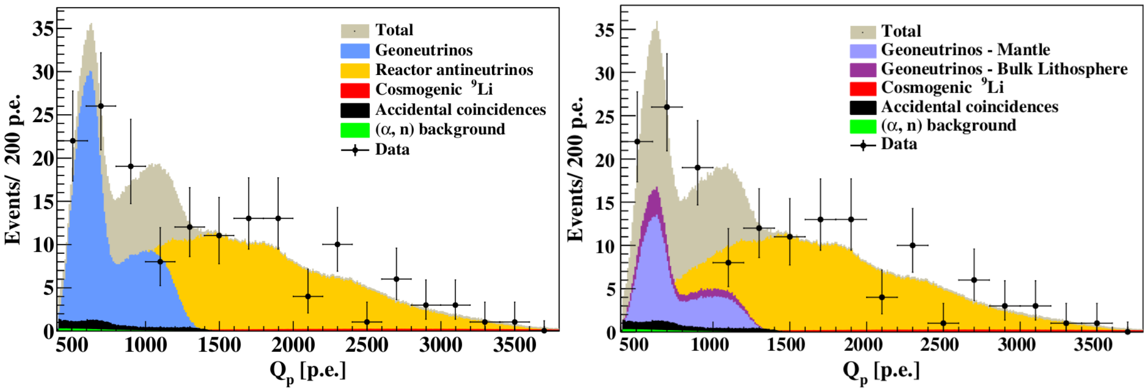

Figure 2: Results of the analysis of 154 golden IBD candidates [1]. Left panel: spectral fit of the data (black points with Poissonian errors) assuming the chondritic Th/U ratio. The total fit function containing all signal and background components is shown in brownish-grey. Geoneutrinos (blue) and reactor antineutrinos (yellow) were kept as free fit parameters. Other non-$\bar{\nu}_e$ backgrounds were constrained in the fit. Right panel: Spectral fit to extract the mantle signal after constraining the contribution of the bulk lithosphere. The grey shaded area shows the summed PDFs of all the signal and background components.

geophysical considerations, thanks to the local knowledge of litosphere [1]. The extracted mantle signal is $21.2^{+9.7}_{-9.0}$ TNU[1]; the null-hypothesis of the mantle signal can be rejected with 99.0% C.L., corresponding to 2.3σ significance.

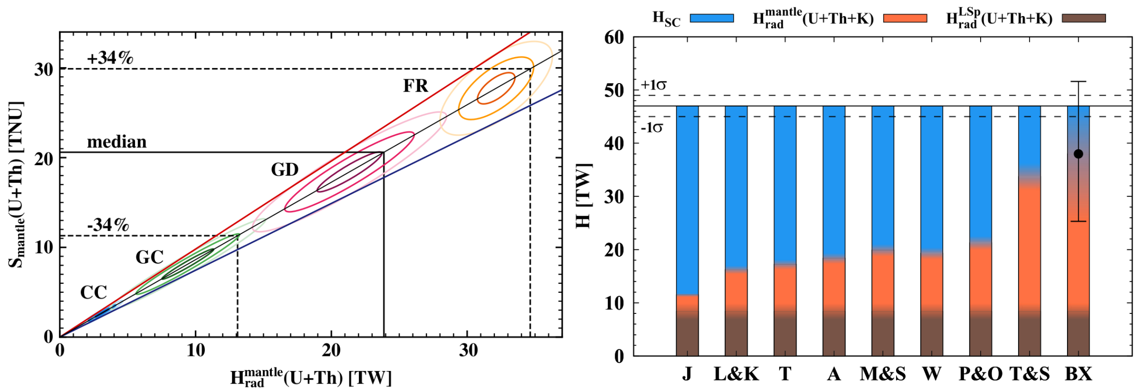

Figure 3: Left panel: mantle geoneutrino signal as a function of U and Th mantle radiogenic heat [1]. The mantle signal measured by Borexino is reported as the black horizontal lines: the median mantle signal is given by the solid line, while the 68% coverage interval is displayed as dashed lines. The blue, green, red, and yellow ellipses are calculated with the following U and Th mantle radiogenic power H mantle according to different BSE models: CC model, GC model GD model, and FR model. For each model, darker to lighter shades of respective colors represent 1σ, 2σ, and 3σ significance contours. Right panel: the Earth total surface heat flux (solid black line) and its three major contributions according to different BSE models: litospheric (brown), mantle (orange), secular cooling (blue). The right bar represent the Borexino results.

The mantle geoneutrino signal expected in Borexino as a function of U and Th mantle radiogenic heat is reported in left panel of Fig. 3. The mantle signal measured by Borexino is reported as

[1]A TNU (terrestrial neutrino unit) is equal to 1 antineutrino event detected via IBD over 1 year by a detector with 100% detection efficiency containing 10^{32} free target protons

the black horizontal lines: the median mantle signal is given by the solid line, while the 68% coverage interval is displayed as dashed lines. The blue, green, red, and yellow ellipses are calculated with the following U and Th mantle radiogenic power H mantle according to different BSE models: cosmochemical model (CC), geochemical model (GC), geodynamical model (GD), and fully radiogenic model (FR). For each model, darker to lighter shades of respective colors represent 1σ, 2σ, and 3σ significance contours. Right panel of Fig. 3 shows the Earth total surface heat flux (solid black line) and its three major contributions according to different BSE models: litospheric (brown), mantle (orange), secular cooling (blue). The right bar represent the Borexino results: it is compatible with the all the models predictions. No model can be excluded at 3σ level, with a mild preference for models with relatively high radiogenic power. This implies a cool initial environment at early Earth's formation stages and small values of the current heat coming from the secular cooling [1]. Nevertheless, this result shows a 2.4σ tension with the cosmochemical model (CC).

6. Conclusions

The comprehensive geoneutrino analysis with Borexino has been briefly reviewed, based on 3262.74 days data-taking extending from December 2007 to April 2019. The data selection improvements, the analysis strategy and the main results are described. The geoneutrino flux is measured with precision improved of a factor two with respect to the 2015 analysis, while the flux contribution from the mantle is isolated for the first time. In a nutshell, Borexino has been able to confirm again the feasibility of geoneutrino measurements, and the validity of geological models predicting the U and Th abundances in the Earth. This reinforces the strict interdisciplinarity of physics and geosciences.

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