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Updated geoneutrino measurement with Borexino

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***On behalf of the Borexino collaboration**

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Abstract. Borexino is a 280-ton liquid scintillator detector located at the Laboratori Nazionali del Gran Sasso (LNGS), Italy and is one of the two detectors that has measured geoneutrinos so far. The unprecedented radio-purity of the scintillator, the shielding with highly purified water, and the placement of the detector at a 3800 m w.e. depth have resulted in very low background levels and has made Borexino an excellent apparatus for geoneutrino measurements. The new update of the Borexino geoneutrino measurement, using the data obtained from December 2007 to April 2019, has been presented. Enhanced analysis techniques, adopted in this measurement, have been also presented (poster presentation #39 by S. Kumaran). The updated statistics and the new elaborate analysis have led to more than a factor two increase in exposure ($(1.12 \pm 0.05) \times 10^{32}$ protons × yr) when compared to the latest Borexino result from 2015. The resulting geoneutrino signal of $47.0^{+8.4}_{-7.7}$ (stat)$^{+2.4}_{-1.9}$ (sys) TNU has $^{+18.3}_{-17.2}$% total precision. The geological interpretations of this measurement have been discussed. In particular, the 99% C.L. observation of the mantle signal by exploiting the relatively well-known lithospheric contribution, the estimation of the radiogenic heat, as well as the comparison of these results to the predictions based on different geological models. The upper limits on the power of a hypothetical georeactor that might be present at different locations inside the Earth have been set.

1 Introduction

Geoneutrinos are electron (anti)neutrinos emitted from radioactive decays of isotopes with half-lives comparable to, or longer than Earth's age, that are naturally present inside the Earth (^{232}Th, ^{238}U, ^{40}K). Their detection allows us to assess the Earth's heat budget, specifically the radiogenic heat emitted in the radioactive decays of these so called *Heat Producing Elements* (HPEs). The HPEs' distribution inside the Earth affects both the prediction of the geoneutrino signal as well as the geological interpretation of the measurement. Thus, the field of neutrino geoscience is a truly inter-disciplinary one. The Earth shines with a flux of about $10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ geoneutrinos. HPEs are concentrated in the Earth's crust (dominantly in a thick and complex continental crust), while their presence is not expected in the Earth's metallic core due to their chemical affinity to silicates. The key question in the field of geoneutrinos is the estimation of the amount of HPEs, and consequently the amount of the radiogenic heat, originating in the Earth's mantle.

In *Liquid Scintillator* (LS) detectors, geoneutrinos are detected through the *Inverse Beta Decay* (IBD) interaction $\bar{\nu}_e + p \rightarrow e^+ + n$. The positron gives the prompt signal, composed of i) the kinematic energy of the incident antineutrino that was in excess with respect to the 1.8 MeV kinematic threshold of the IBD and ii) energy of the two 0.511 MeV annihilation gammas. The prompt spectrum is thus directly correlated with the energy of the geoneutrinos. The neutron, after some time ($\sim$254.5 μs), is captured on protons or in about 1% of cases on ^{12}C atoms in the LS, to give 2.2 MeV or 4.95 MeV gamma, respectively, which represents the delayed signal. The IBD threshold allows us to detect only geoneutrinos coming from ^{238}U and ^{232}Th decays. Geoneutrino signal is expressed in *Terrestrial Neutrino Units* (TNU), i.e. 1 antineutrino event detected via IBD over 1 year by a detector with 100% detection efficiency containing 10^{32} free target protons (roughly corresponds to 1 kton of LS).

Borexino is a 280-ton liquid scintillator detector (Fig. 1) located at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy at 3800 m water-equivalent depth. With a light yield of about 500 photoelectrons per MeV, the energy resolution of 5% at 1 MeV has been achieved. Borexino has been continuously collecting data since May 2007. The previous Borexino geoneutrino measurement is from 2015 [1], while more details about the results presented here can be found in [2].

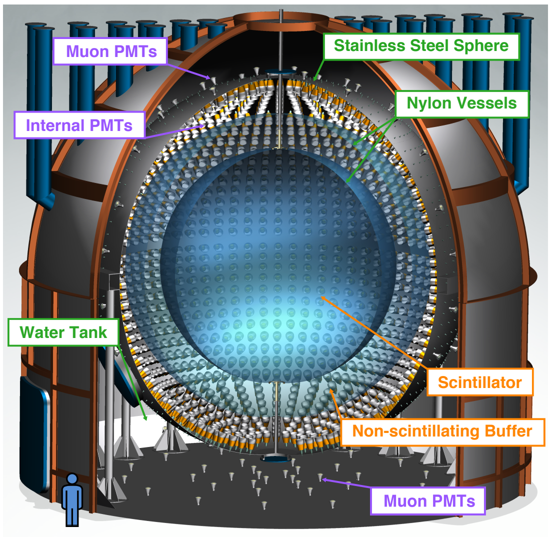
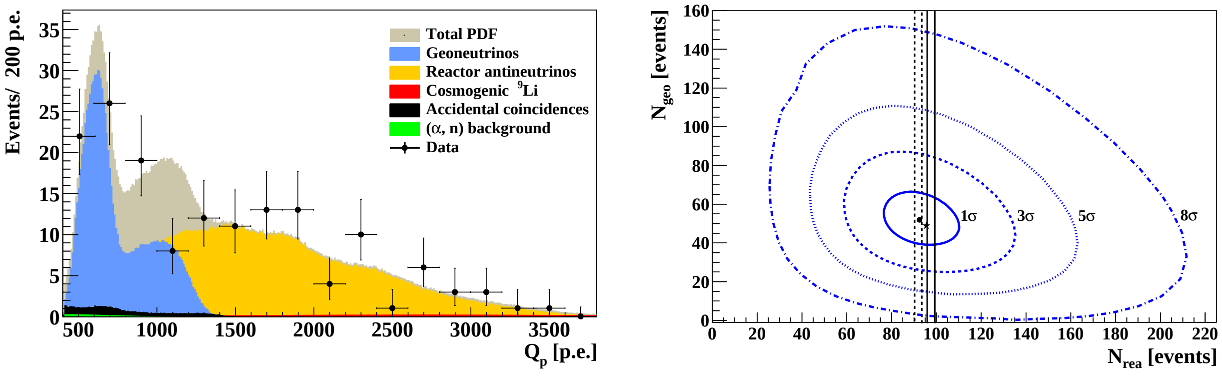


Figure 1. Scheme of the Borexino detector.

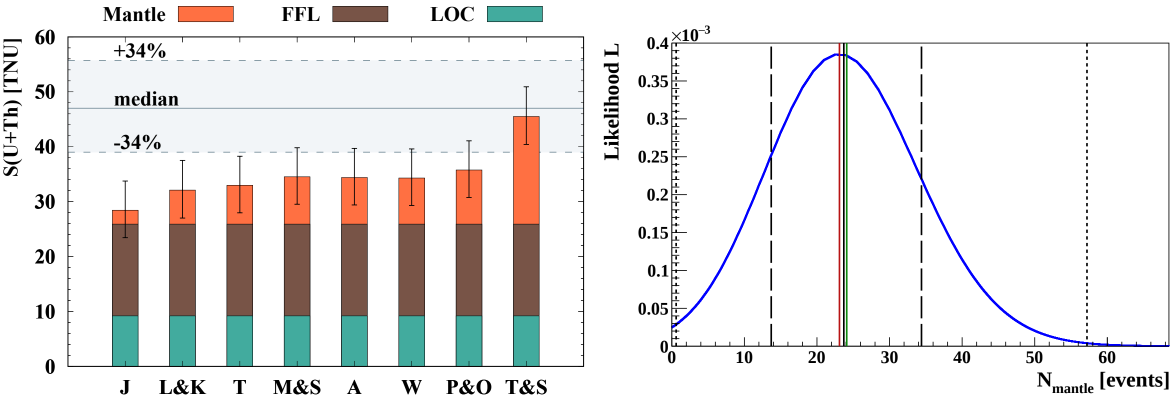
2 Geoneutrino signal at LNGS

In the period between December 9, 2007 and April 28, 2019, corresponding to 3262.74 days of data acquisition, 154 golden IBD candidates were observed to pass the data selection cuts. Their distribution in time and space is compatible with the expectations. The charge spectrum of the prompt candidates was fit (Fig. 2(a)) using the unbinned likelihood approach. The contributions from geoneutrinos and the reactor antineutrino background were left free (Fig. 2(b)). The non-antineutrino backgrounds, dominated by accidental coincidences, decays of cosmogenic ^{9}Li, and (α, n) reactions on ^{13}C triggered by ^{210}Po decays, were constrained in the fit according to the



(a) (b)

Figure 2. (a) Spectral fit of the prompt charge spectrum (500 p.e. ∼1 MeV) assuming the chondritic Th/U ratio. (b) The best fit point (black dot) and the contours for N_{geo} versus N_{rea} assuming Th/U chondritic ratio. The vertical lines mark the 1σ bands of the expected reactor antineutrino signal (solid - without "5 MeV excess", dashed - with "5 MeV excess"). For comparison, the star shows the best fit performed assuming the ^{238}U and ^{232}Th contributions as free and independent fit components.



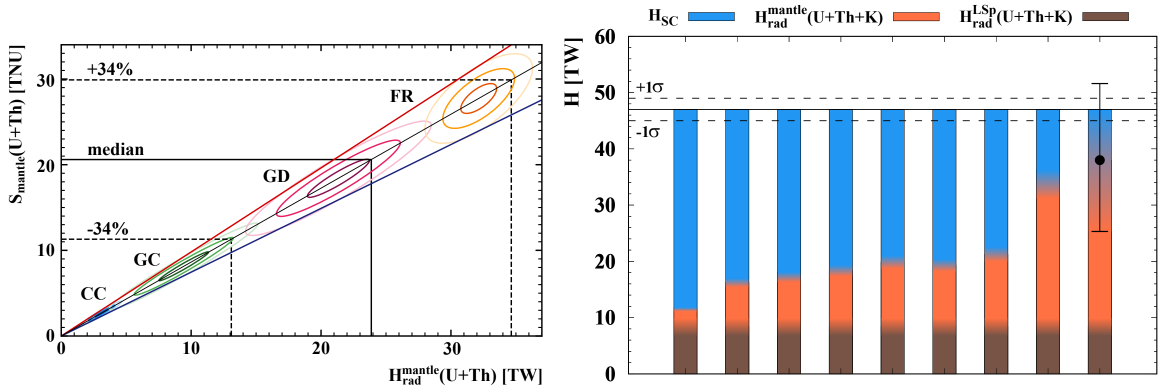
(a) (b)

Figure 3. (a) Comparison of the expected geoneutrino signal S_{geo}(U+Th) at LNGS (different bars calculated according to different Bulk Silicate Earth models) with the Borexino measurement (horizontal lines). FFL = Far Field Lithosphere, LOC = LOcal Crust. (b) The likelihood profile for the number of mantle geoneutrino events.

expectations (total of about 8 events). By observing $52.6^{+9.4}_{-8.6}$ (stat)$^{+2.7}_{-2.1}$ (sys) geoneutrinos (68% interval) from ^{238}U and ^{232}Th, a geoneutrino signal of $47.0^{+8.4}_{-7.7}$ (stat)$^{+2.4}_{-1.9}$ (sys) TNU with $^{+18.3}_{-17.2}$% total precision was obtained. Figure 3(a) compares the observed signal with he expectations according to different geological models.

3 Mantle signal and radiogenic heat

The mantle signal (Fig. 3(b)) was extracted from the spectral fit by constraining the contribution from the bulk lithosphere according to the expectation based on a detailed geological study of the area around LNGS to $28.8^{+5.5}_{-4.6}$ events. The resulting mantle signal is $21.2^{+9.6}_{-9.0}$ (stat)$^{+1.1}_{-0.9}$ (sys) TNU



(a)

(b)

Figure 4. (a) Mantle geoneutrino signal expected in Borexino as a function of U and Th mantle radiogenic heat: the area between the red and blue lines denotes the region constrained by assumptions on HPEs distribution in the mantle. The black horizontal lines represent the mantle signal measured by Borexino. (b) Decomposition of the Earth's total surface heat flux $H_{\text{tot}} = (47 \pm 2)$ TW (horizontal black lines) into its three major contributions - lithospheric (brown) and mantle (orange) radiogenic heat $H_{\text{rad}}^{\text{LSp}}$ and $H_{\text{rad}}^{\text{mantle}}$, respectively, and secular cooling H_{SC} (blue). Different bars represent different geological models, while the last bar (BX) represents the Borexino estimate inferred from the extracted mantle signal.

and its null-hypothesis is excluded at a 99% C.L. The mantle signal corresponds to the production of a radiogenic heat of $24.6^{+11.1}_{-10.4}$ TW (68% interval) from ^{238}U and ^{232}Th in the mantle (Fig. 4(a)). Even though Borexino results are compatible with different Earth models, there is a $\sim 2.4\sigma$ tension with those Earth models which predict the lowest concentration of heat-producing elements in the mantle. Assuming 18% contribution of ^{40}K in the mantle and $8.1^{+1.9}_{-1.4}$ TW of total radiogenic heat of the lithosphere, the Borexino estimate of the total radiogenic heat of the Earth is $38.2^{+13.6}_{-12.7}$ TW. The comparison of this result with different geological models is in Fig. 4(b). In addition, Borexino geoneutrino measurement has constrained at 90% C.L. the mantle composition to $a_{\text{mantle}}(\text{U}) > 13$ ppb and $a_{\text{mantle}}(\text{Th}) > 48$ ppb, the mantle radiogenic heat power to $H_{\text{rad}}^{\text{mantle}}(\text{U+Th}) > 10$ TW and $H_{\text{rad}}^{\text{mantle}}(\text{U+Th+K}) > 12.2$ TW, as well as the convective Urey ratio to $UR_{CV} > 0.13$.

4 Georeactor

With the application of a constraint on the number of expected reactor antineutrino events, Borexino has placed an upper limit on the number of events from a hypothetical georeactor inside the Earth. We exclude the existence of a georeactor with a power greater than 0.5/2.4/5.7 TW at 95% C.L., assuming its location at 2900/6371/9842 km distance from the detector.

References

[1] Agostini M et al. (Borexino Collaboration) 2015 *Phys. Rev. D* **92** 031101(R).
[2] Agostini M et al. (Borexino Collaboration) 2019 *arXiv:1909.02257*, accepted for publication in *Phys. Rev. D.*