Analysis strategies for the 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 have made Borexino an excellent apparatus for geoneutrino measurements. The analysis techniques of the latest geoneutrino results with Borexino were presented using the data obtained from December 2007 to April 2019, corresponding to an exposure of (1.12 $\pm$ 0.05) $\times 10^{32}$ protons $\times$ yr. Enhanced analysis techniques, such as an increased fiducial volume, improved veto for cosmogenic backgrounds, extended energy and coincidence time windows, as well as a more efficient α/β particle discrimination have been adopted in this measurement. The updated statistics and these elaborate resulted in a geoneutrino signal of $47.0^{+8.4}_{-7.7}$ (stat)$^{+2.4}_{-1.9}$ (sys) TNU with $^{+18.3}_{-17.2}$% total precision.

1 Introduction

Geoneutrinos are electron neutrinos and antineutrinos emitted from radioactive decays inside the Earth. Their detection allows to assess the Earth's heat budget, specifically the heat emitted in the radioactive decays, since the total amount of emitted geoneutrinos scales with the total mass of heat producing elements inside the Earth. Geoneutrinos are detected through the *Inverse Beta Decay* (IBD) interaction in *Liquid Scintillator* (LS) detectors ($\bar{\nu}_e + p \rightarrow e^+ + n$). The energy of the antineutrino is directly related to the energy of the prompt event measured via the number of collected photoelectrons (p.e.). 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 located at the Laboratori Nazionali del Gran Sasso, Italy and is one of the two detectors that has measured geoneutrinos so far.

TABLE I. Summary of the optimized selection cuts for IBD candidates: charge cut on the prompt, Q_p and delayed, Q_d, time and space correlation dt and dR, respectively, distance to the IV, d_IV, MLP α/β Particle IDentification parameter cut on delayed, and multiplicity cut.

Cut	Condition
Q_p	> 408 p.e.
Q_d	(700 - 3000) p.e. (860 - 3000) p.e. (WE period)
dt	double cluster: (2.5 - 12.5) μs single cluster: (20 - 1280) μs
dR	1.3 m
Muon veto	2 s or 1.6 s or 2 ms (internal μ) 2 ms (external μ)
d_IV	10 cm (prompt)
PID (α/β)	$\mathrm{MLP_d} > 0.8$
Multiplicity	no $N_{pe} > 400$ p.e. event ± 2 ms around prompt/delayed

2 Analysis techniques

This section briefly describes the improved data selection cuts used when compared to the 2015 analysis [1], different backgrounds and the systematic effects that were included in the analysis [2]. The energy threshold of the prompt event was chosen based on the IBD threshold of 1.8 MeV. Two energy windows were used for the selection of the delayed event in order to include the n-captures on protons and on ^{12}C atoms, corresponding to 2.2 MeV and 4.95 MeV, respectively. In addition, the time difference between the prompt and delayed signals was required to be 5 times the n-capture. Two different time windows namely, 2.5-12.5 μs (double cluster events) and 20-1280 μs (single cluster events) have been used. The distance between the prompt and delayed events was required to be less than 1.3 m. Sophisticated time and spatial vetoes have been applied to eliminate muons and muon daughters (neutrons, ^{9}Li). A time veto of 2 ms has been applied to muons that pass only through the OD. After muons that pass through the ID and OD, three different time vetoes (2 ms, 1.6 s, 2 s) and also a spatial veto

TABLE II. Summary of the expected number of events from non-antineutrino backgrounds in the antineutrino candidate sample (exposure $\mathcal{E}_p$ = (1.29 $\pm$ 0.05) $\times 10^{32}$ protons $\times$ yr). The limits are 95% C.L.

Background Type	Events
^{9}Li background	3.6 $\pm$ 1.0
Untagged muons	0.023 $\pm$ 0.007
Fast n's (μ in WT)	<0.013
Fast n's (μ in rock)	<1.43
Accidental coincidences	3.846 $\pm$ 0.017
(α, n) in scintillator	0.81 $\pm$ 0.13
(α, n) in buffer	<2.6
(γ, n)	<0.34
Fission in PMTs	<0.057
^{214}Bi-^{214}Po	0.003 $\pm$ 0.001
Total	8.28 $\pm$ 1.01

(whole detector or cylinder of radius 3 m around the muon) have been applied depending on the type of muon. A dynamical fiducial volume cut of 10 cm has been applied which requires that the prompt event is at least 10 cm from the IV. This helps in reducing the background events that might originate from the vessel. The Multi-Layer Perceptron (MLP) variable developed using deep-learning technique was used on the delayed event for α/β discrimination. The delayed event was required to have an MLP value of greater than 0.8. Finally, a multiplicity cut was also applied which requires that there are no high energy events (>400 p.e.) 2 ms before prompt, 2 ms after delayed and in between prompt and delayed events. Summary of the selection cuts is given in Table I. The most important antineutrino background for geoneutrino analysis comes from reactor antineutrinos due to approximately 440 nuclear reactors around the world. Based on the nominal powers obtained form the International Atomic Energy Agency (IAEA), the survival probability and oscillation parameters, the expected number of reactor antineutrino signal at LNGS was calculated as $84.5^{+1.5}_{-1.4}$ TNU and $79.6^{+1.4}_{-1.3}$ TNU, for without and with 5 MeV "excess", respectively. The non-antineutrino backgrounds included in the final spectral fit are: cosmogenic ^{9}Li background caused due to spallation of muons in the LS that remain after the time and spatial vetoes, accidental coincidences that occur due to random events correlated in space and time, and (α,n) background caused due to the small amounts of ^{210}Po in the LS. The total number of expected non-antineutrino backgrounds after including other minor backgrounds was (8.28 ± 1.01) events which is reported in Table II. The systematic effects included for the final results are atmospheric neutrino background, spectral shapes of reactor antineutrinos with and without 5 MeV excess, inner vessel shape, MC efficiency of detection, and position reconstruction of events, as shown in Table III.

3 Results and Conclusions

In the period between December 2007 and April 2019, 154 golden IBD candidates passed the data selection cuts. An unbinned likelihood fit was performed on the charge of the prompt events of the 154 golden candidates. The geoneutrino (Th/U mass ratio fixed to the chondritic value of 3.9) and reactor antineutrino contributions were left free while the non-antineutrino backgrounds were constrained using additional multiplicative Gaussian pull terms. The resulting number of geoneutrinos was $52.6^{+9.4}_{-8.6}$ (stat)$^{+2.7}_{-2.1}$ (sys) (68% interval) corresponding to a signal of $47.0^{+8.4}_{-7.7}$ (stat)$^{+2.4}_{-1.9}$ (sys) TNU. Other geological results such as the extraction of mantle signal, implications on the radiogenic heat, and the test on the georeactor hypothesis are explained in more detail in [2] and in the proceedings of the talk by L.Ludhova in the parallel session neutrino#12.

TABLE III. Summary of the different sources of systematic uncertainty in the geoneutrino and reactor antineutrino measurement. Different contributions are summed up as uncorrelated.

Source	Geo Error [%]	Reactor Error [%]
Atmospheric neutrinos	$^{+0.00}_{-0.38}$	$^{+0.00}_{-3.90}$
Shape of reactor spectrum	$^{+0.00}_{-0.57}$	$^{+0.04}_{-0.00}$
Vessel shape	$^{+3.46}_{-0.00}$	$^{+3.25}_{-0.00}$
Efficiency	1.5	1.5
Position reconstruction	3.6	3.6
Total	$^{+5.2}_{-4.0}$	$^{+5.1}_{-5.5}$

References

[1] M. Agostini *et. al.* 2015 Spectroscopy of geoneutrinos from 2056 days of Borexino data *Phys. Rev.* D92 031101
[2] M. Agostini *et. al.* 2019 Comprehensive geoneutrino analysis with Borexino *arXiv* 1909.02257