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Abstract. We review the geoneutrino measurement with Borexino from 2056 days of data taking.

1. Borexino and Geoneutrinos

Borexino is an unsegmented massive liquid scintillator detector installed in the Gran Sasso underground Laboratory (Italy). Borexino has been collecting data since May 2007. The active mass in Borexino consists of 280 tons of organic liquid scintillator, pseudocumene (PC; C_9H_{12}) with the addition of PPO at 1.5 g/l [1]. The liquid scintillator is contained within a 100 μm thick nylon transparent vessel 4.25 m in radius. 2212 8-inch photomultipliers (PMTs) are installed on a Stainless Steel Sphere (SSS) which contains the liquid scintillator and about 900 tons of pseudocumene buffer with the addition of a light quencher (DMP) [2]. The SSS is built inside a water Cherenkov detector for vetoing muons and muon related events [3]. The water tank also serves as shielding against neutrons from the underground environment. For each event inside the active mass the energy and the time distribution of hit PMTs are measured.

Borexino is a high radio purity detector: all materials were carefully selected. A number of purification campaigns were performed to reduce the intrinsic background, namely ^{238}U, ^{232}Th, ^{210}Pb, ^{210}Po, ^{222}Rn and ^{85}Kr. In Borexino calibrations [4] with radioactive sources have been performed. These calibrations allowed to accurately determine the energy scale and to study the uniformity of the light response [5].

Due to the high level of radio purity, Borexino is also an excellent detector for electron anti-neutrinos. These neutrinos are detected by the so-called inverse-beta decay reaction:

$$\bar{\nu}_e + p \rightarrow e^+ + n \tag{1}$$

The threshold of Eq. (1) is equal to 1.806 MeV. The neutron from the capture on hydrogen produces a 2.22 γ-ray. In the Borexino liquid scintillator the capture time is of the order of 260 μs. The visible energy due to the ionization of the positron is related to the $\bar{\nu}_e$ energy by: $E_{vis} = E_\nu - 0.784$MeV. The positron produces a prompt signal. The γ-ray from the neutron capture produces a delayed signal. The space and time correlation between the prompt and delayed signals offers a very powerful tagging for this reaction.

Geoneutrinos are $\bar{\nu}_e$ produced by β decays of long-lived radioactive elements in the Earth's crust and mantle. The main sources of geoneutrinos are: ^{238}U, ^{232}Th and ^{40}K. The energy spectrum of electron anti-neutrinos from these sources is shown in Fig. 1. Only neutrinos from ^{238}U and ^{232}Th can be detected by Eq. (1). These radioactive elements are referred to as Heat Producing Elements (HPE) because they produce an important fraction of the heat radiated by the Earth. At present, geochemical and geodynamical models of the Earth predict that as much as 50% of the total heat radiated by the Earth comes from HPE (radiogenic heat). Geoneutrinos could offer the possibility to make a direct measurement of the radiogenic heat and of the distribution of the HPE in the crust and mantle. On the basis of our understanding the crust contains ppm level of HPE, while the mantle ppb level. However, the amount of HPE in the mantle is model dependent and there is no direct measurement. The observation of geoneutrinos is the method to directly measure the HPE in the mantle. The total flux of geoneutrinos from the Earth is of the order of 10^6 cm^{-2}s^{-1}, which turns to about 50 events/kton/year. Therefore, the measurement of geoneutrinos is difficult and could be limited by statistics. Results from more than one experiment are needed to accurately determine the radiogenic heat and the mantle composition in HPE.

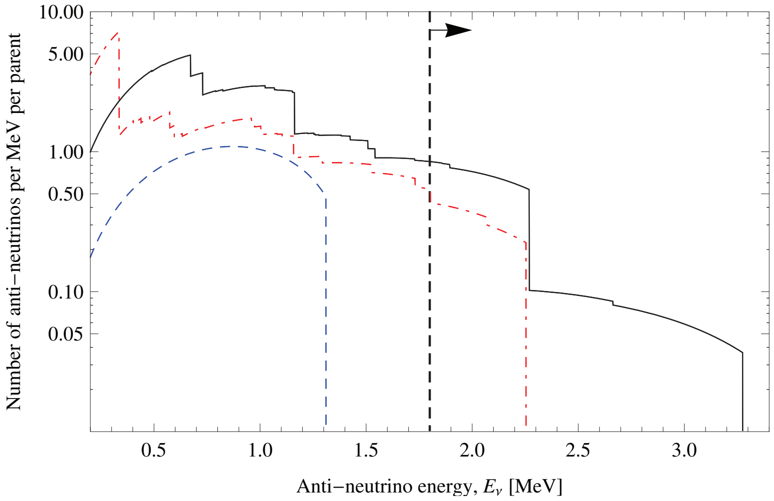

Figure 1. Electron anti-neutrino spectrum from ^{238}U (solid line), ^{232}Th (dashed-dotted line) and ^{40}K (dashed line). The vertical line shows the energy threshold for the inverse-beta decay reaction.

The idea of studying geoneutrinos goes back in time to 1966-1969 [6]. In 1984 a careful study of the geoneutrino signal was published by L.M. Krauss and collaborators [7]. In 1998 the idea of using solar neutrino and reactor neutrino detectors, namely Borexino and KamLAND, for detecting geoneutrinos was put forward [8]. First geoneutrino observations were done by KamLAND [9] and Borexino [10]. The latest geoneutrino results are reported in [11] and [12].

2. High sensitivity measurement of geoneutrino in Borexino

The present measurement of geoneutrinos in Borexino corresponds to 2056 days before any selection cut [12]. These data have been collected in the period December 15, 2007 - March 8, 2015. We discard events occurring within 2 ms of every muon crossing the outer water Cherenkov detector and within 2 s of muons crossing the inner liquid scintillator detector to reject neutrons and long-lived cosmogenic radioactivity, respectively. This cut reduces the live-time to 1841.9 days. For the present data set Table 1 summarizes the estimated backgrounds for $\bar{\nu}_e$ candidates, expressed in number of events. The combined upper limit is obtained by Monte Carlo. The detection efficiency is measured to be (84.2 ± 1.5)%. The total efficiency-corrected exposure for the present data set is 907±44 ton×yr. We have identified 77 $\bar{\nu}_e$ candidates passing all the selection cuts [**?**]. The $\bar{\nu}_e$ signal-to-background ratio is ∼100.

Table 1. Estimated backgrounds for $\bar{\nu}_e$ given in number of events. Upper limits are given for 90% C.L.

^{9}Li-^{8}He	$0.194^{+0.125}_{-0.089}$
Accidental coincidences	0.221±0.004
Time correlated	$0.035^{+0.029}_{-0.028}$
(α,n) in scintillator	0.165±0.010
(α,n) in buffer	<0.51
Fast n's (μ in WT)	<0.01
Fast n's (μ in rock)	< 0.43
untagged muons	0.12±0.01
Fission in PMTs	0.032±0.003
^{214}Bi-^{214}Po	0.009±0.013
Total	$0.78^{+0.13}_{-0.10}$
	< 0.65(combined)

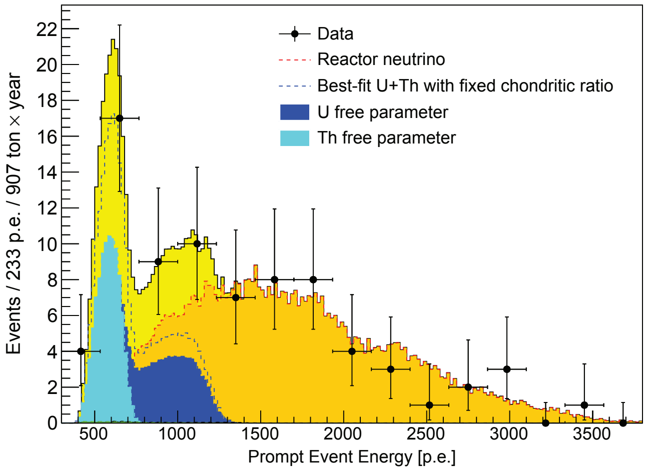

Figure 2. Prompt light yield spectrum, in units of photoelectrons (p.e.), of antineutrino candidates and best-fit. The best-fit shows the total contribution of geoneutrino, reactor neutrino and background (yellow colored area) and reactor neutrino (orange colored area) assuming the chondritic ratio. The result of a separate fit with U (blue colored area) and Th (light-blue colored area) set as free and independent parameters is also shown.

An unbinned likelihood fit of the energy spectrum of selected prompt $\bar{\nu}_e$ candidate events has been performed. In Fig. 2 the selected candidates and the fit result are shown. Using the chondritic ratio, $m(Th)/m(U) = 3.9$, our best fit yields $S_{geo} = 23.7^{+6.5}_{-5.7}(stat)^{+0.9}_{-0.6}(sys)$ events $[43.5^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(sys)$ TNU[1]] and $S_{react} =$

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[1] 1TNU=1event/year/10^{32}protons

$52.7^{+8.5}_{-7.7}(stat)^{+0.7}_{-0.9}(sys)$ events [$96.6^{+15.6}_{-14.2}(stat)^{+4.9}_{-5.0}(sys)$ TNU]. In Fig. 3 we show the 1, 3 and 5σ contours from the log-likelihood fit. Borexino alone observes geoneutrinos with 5.9σ significance (Fig. 3). The null hypothesis for geoneutrino observation has a probability equal to 3.6×10^{-9}.

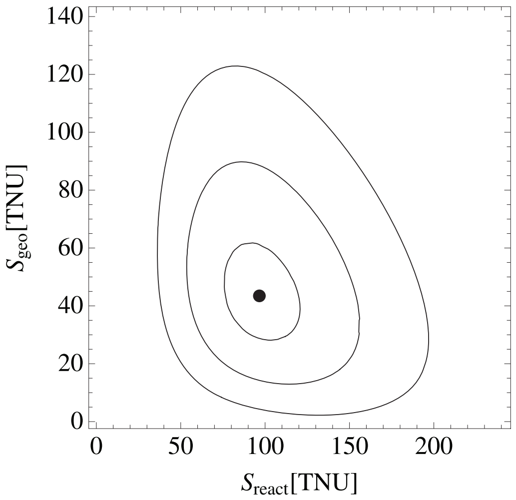

Figure 3. Best-fit contours for 1, 3 and 5σ for the statistics reported in this paper.

From the present data set we can infer the signal from the mantle. Using a detailed computation of the contribution from the crust [13] it turns out that the corresponding geoneutrino signal is $S_{geo}(\mathrm{crust}) = (23.4 \pm 2.8)$ TNU. The signal from Borexino is $S_{geo} = 43.5^{+12.1}_{-10.7}$ TNU. Considering the experimental likelihood profile for S_{geo} and a gaussian profile for S_{crust}: $S_{mantle} = S_{geo} - S_{crust} = 20.1^{+15.1}_{10.3}$ TNU. The hypothesis $S_{mantle} = 0$ is rejected at 98% C.L.

Understanding the Earth's energy budget is a fundamental question for plate tectonics and mantle convection. The present geoneutrino data from Borexino for the radiogenic heat corresponds to 23-36 TW for the best fit. Adopting the chondritic mass ratio above and a potassium-to-uranium mass ratio $m(K)/m(U) = 10^4$, the total measured terrestrial radiogenic power is $P(U + Th + K) = 33^{+28}_{-20}$ TW, to be compared with the global terrestrial power output $P_{tot} = 47 \pm 2$ TW [14].

In conclusion, Borexino-only data measure geoneutrinos with 5.9σ significance. The background level in Borexino allows to perform a real time spectroscopy of geoneutrinos and probe the contribution due to the mantle.

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