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Abstract. Borexino is a liquid scintillator detector primary designed to observe solar neutrinos. Due to its low background level as well as its position in a nuclear free country, Italy, Borexino is also sensitive to geo-neutrinos. Borexino is leading this interdisciplinary field of neutrino geoscience by studying electron antineutrinos which are emitted from the decay of radioactive isotopes present in the crust and the mantle of the Earth. With 2056 days of data taken between December 2007 and March 2015, Borexino observed 77 antineutrino candidates. If we assume a chondritic Th/U mass ratio of 3.9, the number of geo-neutrino events is found to be $23.7^{+6.5}_{-5.7}$ (stat) $^{+0.9}_{-0.6}$ (syst). With this measurement, Borexino alone is able to reject the null geo-neutrino signal at $5.9\,\sigma$, to claim a geo-neutrino signal from the mantle at $98\,\%$ C.L. and to restrict the radiogenic heat production for U and Th between 23 and 36 TW.

1. Introduction

Geo-neutrinos are electron antineutrinos which are produced by the decay of radioactive isotopes present in the crust and the mantle of our planet. Since the chemical composition of the Earth is not yet perfectly known, having a new source of information will help to better understand our planet. The idea of using geo-neutrinos as direct messengers was suggested in 1965 by G. Eder [1] and in 1968 by G. Marx [2] before being reviewed by L.M. Krauss, S.L. Glashow and D.N. Schramm in 1984 [3]. So far, only the KamLAND experiment in Japan [4, 5] and the Borexino experiment in Italy [6, 7, 8] have reported geo-neutrino measurements.

2. Geo-neutrino analysis and results

In Borexino, the detection of geo-neutrinos relies on the signature of the inverse β decay (IBD) reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ where the positron, the "prompt" signal, is followed in time by the neutron capture on hydrogen, the "delayed" signal. The prompt and the delayed signals are correlated in space and time, allowing to accurately identify electron antineutrino signal. With an IBD threshold of 1.806 MeV, only geo-neutrinos coming from the decay of ^{238}U and ^{232}Th chains can be detected.

Despite Italy is a nuclear free country, the dominant background remains electron antineutrinos emitted by abroad nuclear reactors. It is nonetheless possible to estimate the

expected number of nuclear reactors events, N_{react}, as follows:

$$N_{\mathrm{react}} = \sum_{r=1}^{R} \sum_{m=1}^{M} \frac{\eta_m}{4\pi L_r^2} P_{rm} \times \int \mathrm{d}E_{\bar{\nu}_e} \sum_{i=1}^{4} \frac{f_i}{E_i} \phi_i(E_{\bar{\nu}_e}) \sigma(E_{\bar{\nu}_e}) P_{ee}(E_{\bar{\nu}_e}, L_r), \tag{1}$$

where r runs over the number of nuclear reactors R considered, m runs over the number of months M considered, η_m stands for the exposure in month m and includes detector efficiency, L_r is the detector-reactor distance, P_{rm} is the effective thermal power of reactor r in month m, i runs over the spectral components of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu, f_i is the power fraction of component i, E_i the average energy released per fission of component i, $\phi_i(E_{\bar{\nu}_e})$ the antineutrino energy spectrum per fission of component i, $\sigma(E_{\bar{\nu}_e})$ the IBD cross section and $P_{ee}(E_{\bar{\nu}_e}, L_r)$ the survival probability of the emitted antineutrinos of energy $E_{\bar{\nu}_e}$ created at distance L_r.

Table 1. Estimated background components in terms of number of events taken from [8]. The combined upper limit is obtained by Monte Carlo.

^{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)

Other backgrounds can mimic an IBD reaction in Borexino, like (α, n) background, accidental coincidences and cosmogenic background such as ^{9}Li-^{8}He. In Borexino, the overall background rate is estimated to be a factor 100 lower than the antineutrino one. The estimated background for each components is reported in table 1.

In order to measure the number of geo-neutrinos and antineutrinos from nuclear reactors, we implement an unbinned maximum likelihood fit of the prompt energy spectrum of our antineutrino candidates. We define the log-likelihood function as follows:

$$\ln \mathcal{L}(N_{\mathrm{geo}}, N_{\mathrm{react}}, N_{\mathrm{acc}}, N_{\mathrm{LiHe}}, N_{\alpha n}) = -N_{\mathrm{exp}}(N_{\mathrm{geo}}, N_{\mathrm{react}}, N_{\mathrm{acc}}, N_{\mathrm{LiHe}}, N_{\alpha n})$$
$$+ \sum_{i=1}^{N} \ln \left(f_{\bar{\nu}_e}(E_i, N_{\mathrm{geo}}, N_{\mathrm{react}}) + f_{\mathrm{bg}}(E_i, N_{\mathrm{acc}}, N_{\mathrm{LiHe}}, N_{\alpha n}) \right) - \frac{1}{2} \sum_{\mathrm{bg}} \left(\frac{N_{\mathrm{bg}} - (N_{\mathrm{bg}})_{\mathrm{est}}}{(\delta_{\mathrm{bg}})_{\mathrm{est}}} \right)^2, \tag{2}$$

with:

$$f_{\bar{\nu}_e}(E_i, N_{\mathrm{geo}}, N_{\mathrm{react}}) = f_{\mathrm{geo}}(E_i, N_{\mathrm{geo}}) + f_{\mathrm{react}}(E_i, N_{\mathrm{react}}) \tag{3}$$

$$f_{\mathrm{bg}}(E_i, N_{\mathrm{acc}}, N_{\mathrm{LiHe}}, N_{\alpha n}) = f_{\mathrm{acc}}(E_i, N_{\mathrm{acc}}) + f_{\mathrm{LiHe}}(E_i, N_{\mathrm{LiHe}}) + f_{\alpha n}(E_i, N_{\alpha n}) \tag{4}$$

where N_{exp} corresponds to the expected total number of events and i runs over the $N = 77$ antineutrino candidates. f_{geo}, f_{react}, f_{acc}, f_{LiHe} and $f_{\alpha n}$ are the individual spectra of the geo-neutrinos, the antineutrinos from nuclear reactors, the accidental coincidences, the ^{9}Li-^{8}He events and the (α, n) events. N_{geo} and N_{react} are left as free parameters while the last term
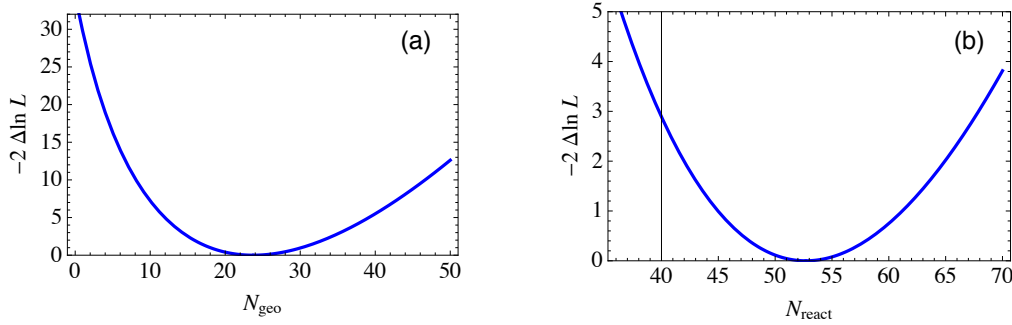
Figure 1. $-2\,\Delta\ln\mathcal{L}$ profiles for N_{geo} (a) and N_{react} (b).

constrains the background components reported in table 1.

If we assume a chondritic Th/U mass ratio of 3.9, our best fit values are $N_{\text{geo}} = 23.7^{+6.5}_{-5.7}\,(\text{stat})\,^{+0.9}_{-0.6}\,(\text{syst})$ and $N_{\text{react}} = 52.7^{+8.5}_{-7.7}\,(\text{stat})\,^{+0.7}_{-0.9}\,(\text{syst})$ events, which is equivalent to $43.5^{+11.8}_{-10.4}\,(\text{stat})\,^{+2.7}_{-2.4}\,(\text{syst})$ and $96.6^{+15.6}_{-14.2}\,(\text{stat})\,^{+4.9}_{-5.0}\,(\text{syst})$ TNU[30] respectively. This result allows to reject the null geo-neutrino signal at $5.9\,\sigma$. Figure 1 shows the $-2\,\Delta\ln\mathcal{L}$ profiles for N_{geo} and N_{react}.

A signal from the mantle can then be assessed by retrieving the crust signal (investigated in [9] and [10]) to the total signal measured in Borexino. Using the geo-neutrino log-likelihood profile and assuming a Gaussian approximation for the crust contribution, one can extract a signal from the mantle equal to $20.9^{+15.1}_{-10.3}$, leading to a $98\,\%$ C.L. geo-neutrino signal from the mantle. Finally, a fit where both U and Th spectra are left as free parameters has also been performed, restricting the radiogenic heat production from these isotopes between 23 and 36 TW.

3. Investigation on a possible georeactor
In addition to the standard geo-neutrino analysis, we report an investigation on a possible natural nuclear reactor, called georeactor, standing inside the Earth. We assume this reactor to release a constant power for the whole data taking period. The Monte Carlo spectrum is built such that $^{235}\text{U}/^{238}\text{U}$ has been set to 0.75/0.25 while the Pu contribution is set to 0. The
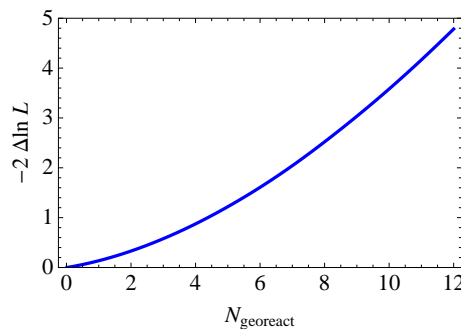

Figure 2. $-2\,\Delta\ln\mathcal{L}$ profile for N_{georeact}.

fit has been done in the energy range above 1510 p.e. in order to get rid of the geo-neutrino spectrum. The background components have been normalized to the [1510, 5000 p.e.] energy

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[30] One TNU corresponds to one event detected over one year exposure of 10^{32} target protons at $100\,\%$ efficiency.

range of interest and the reactor component has been constrained to the theoretical value and error of 56 ± 2 (30 ± 1 in the [1510, 5000 p.e.] energy range of interest).

Figure 2 shows the $-2\,\Delta\ln\mathcal{L}$ profile for N_{georeact}. The best fit value is 0 and the upper limit in terms of number of events is 8.4 (10.5) at 90 % C.L. (95 % C.L.). This limit is usually expressed in terms of TW. On the whole energy range, 1 TW is found to be equal to 4.4 events with an exposure of 5.5×10^{31} proton $\times$ year, oscillation through core and mantle taken into account. It corresponds to 2.5 events in the [1510, 5000 p.e.] energy range of interest, which leads to an upper limit of 3.4 TW (4.2 TW) at 90 % C.L. (95 % C.L.).

4. Conclusion

From 2056 days of data taking, Borexino alone is able to reject the null geo-neutrino signal at $5.9\,\sigma$, to claim a geo-neutrino signal from the mantle at 98 % C.L. and to restrict the radiogenic heat production for U and Th between 23 and 36 TW. With a signal-to-background ratio of the order of 100, Borexino provides a real time spectroscopy of geo-neutrinos. Finally, we have investigated the hypothesis of a georeactor and we have set an upper limit for a 3.4 TW georeactor (4.2 TW) at 90 % C.L. (95 % C.L.).

Acknowledgments

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