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Measurement of geo-neutrinos from 1353 days of Borexino

Borexino Collaboration *

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ABSTRACT

We present a measurement of the geo-neutrino signal obtained from 1353 days of data with the Borexino detector at Laboratori Nazionali del Gran Sasso in Italy. With a fiducial exposure of $(3.69 \pm 0.16) \times 10^{31}$ proton × year after all selection cuts and background subtraction, we detected (14.3 ± 4.4) geo-neutrino events assuming a fixed chondritic mass Th/U ratio of 3.9. This corresponds to a geo-neutrino signal $S_{\text{geo}} = (38.8 \pm 12.0)$ TNU with just a 6×10^{-6} probability for a null geo-neutrino measurement. With U and Th left as free parameters in the fit, the relative signals are $S_{\text{Th}} = (10.6 \pm 12.7)$ TNU and $S_{\text{U}} = (26.5 \pm 19.5)$ TNU. Borexino data alone are compatible with a mantle geo-neutrino signal of

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(15.4 ± 12.3) TNU, while a combined analysis with the KamLAND data allows to extract a mantle signal of (14.1 ± 8.1) TNU. Our measurement of $31.2^{+7.0}_{-6.1}$ reactor anti-neutrino events is in agreement with expectations in the presence of neutrino oscillations.

Geo-neutrinos (geo-$\bar{\nu}_e$) are electron anti-neutrinos ($\bar{\nu}_e$) produced mainly in β decays of ^{40}K and of several nuclides in the chains of long-lived radioactive isotopes ^{238}U and ^{232}Th, which are naturally present in the Earth. By measuring the geo-neutrino flux from all these elements, it is in principle possible to deduce the amount of the radiogenic heat produced within the Earth, an information facing large uncertainty and being of crucial importance for geophysical and geochemical models. The first experimental investigation of geo-neutrinos from ^{238}U and ^{232}Th was performed by the KamLAND Collaboration [1,2], followed by their observation with a high statistical significance of 99.997% C.L. by Borexino [3] and KamLAND[1] [4]. Both these experiments are using large-volume liquid-scintillator detectors placed in underground laboratories shielded against cosmic muons. Due to either low statistics and/or systematic errors, these measurements do not have the power to discriminate among several geological models. Analysis combining the results from different sites have higher prediction power, as it was shown in [4] and [6]. Therefore, new measurements of the geo-neutrino flux are highly awaited by this newly-born inter-disciplinary community. Several projects entering operation such as SNO+ [7] or under the design phase as LENA [8] or Hanohano [9], have geo-neutrinos among their scientific aims. In this work we present a new Borexino measurement of the geo-neutrino signal with 2.4 times higher exposure with respect to [3]. For the first time, Borexino attempts a measurement of the individual geo-neutrino signals from the ^{238}U and ^{232}Th chains. We provide a detailed comparison of our measurement with the predictions of several geological models. In a combined analysis of the Borexino and KamLAND [4] data we provide an estimate of the mantle geo-neutrino signal.

Borexino is an unsegmented liquid-scintillator detector built for the spectral measurement of low-energy solar neutrinos installed in the underground hall C of the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. Several calibration campaigns with radioactive sources [10] allowed us to decrease the systematic errors of our measurements and to optimize the values of several input parameters of the Monte Carlo (MC) simulation. The 278 tons of ultra-pure liquid scintillator (pseudocumene (PC) doped with 1.5 g/l of diphenyloxazole) are confined within a thin spherical nylon vessel with a radius of 4.25 m. The detector core is shielded from external radiation by 890 tons of buffer liquid, a solution of PC and 3–5 g/l of the light quencher dimethylphthalate. The buffer is divided in two volumes by the second nylon vessel with a 5.75 m radius, preventing inward radon diffusion. All this is contained in a 13.7 m diameter stainless steel sphere (SSS) on which are mounted 2212 8″ PMTs detecting the scintillation light, the so-called Inner Detector. An external domed water tank of 9 m radius and 16.9 m height, filled with ultra-high purity water, serves as a passive shield against neutrons and gamma rays as well as an active muon veto. The Cherenkov light radiated by muons passing through the water is measured by 208 8″ external PMTs also mounted on the SSS and define the so-called Outer Detector. A detailed description of the Borexino detector can be found in [11,12].

In liquid-scintillator detectors, $\bar{\nu}_e$ are detected via the inverse neutron β decay,

$$\bar{\nu}_e + p \rightarrow e^+ + n, \qquad (1)$$

with a threshold of 1.806 MeV, above which lies only a small fraction of $\bar{\nu}_e$ from the ^{238}U (6.3%) and ^{232}Th (3.8%) series. Geo-neutrinos emitted in ^{40}K decay cannot be detected by this technique. The positron created in this reaction promptly comes to rest and annihilates. All deposited energy is detected in a single prompt event, with a visible energy of $E_{\mathrm{prompt}} = E_{\bar{\nu}_e} - 0.784$ MeV. The emitted free neutron is typically captured on protons, resulting in the emission of a 2.22 MeV de-excitation γ ray, providing a delayed coincidence event. The mean neutron capture time in Borexino was measured with an AmBe neutron source to be $\tau = (254.5 \pm 1.8)$ μs [13]. The characteristic time and spatial coincidence of prompt and delayed events offers a clean signature of $\bar{\nu}_e$ detection, further suppressing possible background sources.

In this Letter we report the analysis of data collected between December 2007 and August 2012, corresponding to 1352.60 days of live time. The fiducial exposure after all cuts is (613 ± 26) ton × year or $(3.69 \pm 0.16) \times 10^{31}$ proton × year.

The $\bar{\nu}_e$'s from nuclear power plants are the main anti-neutrino background to the geo-neutrino measurement. Since there are no nuclear plants close-by, the LNGS site is well suited for geo-neutrino detection. The expected number of events from reactor $\bar{\nu}_e$'s, N_{react}, is given by:

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

where the index r runs over the number R of reactors considered, the index m runs over the total number of months M for the present data set, η_m is the exposure (in proton × yr) in the mth month including detector efficiency, L_r is the distance of the detector from reactor r, P_{rm} is the effective thermal power of reactor r in month m, the index i stands for the ith spectral component in the set (^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu), f_i is the power fraction of the component i, E_i is the average energy released per fission of the component i, $\phi(E_{\bar{\nu}})$ is the anti-neutrino spectrum per fission of the ith component, $\sigma(E_{\bar{\nu}})$ is the inverse β decay cross section taken from [14], and P_{ee} is the survival probability [6] of the reactor anti-neutrinos of energy $E_{\bar{\nu}}$ traveling the baseline L_r, for mixing parameters $\hat{\theta} = (\delta m^2, \sin^2\theta_{12}, \sin^2\theta_{13})$.

In Eq. (2) we consider the $R = 446$ nuclear cores all over the world, operating in the period of interest. The mean weighted distance of these reactors from the LNGS site is about 1200 km, being the weight $w_{rm} = P_{rm}/L_r^2$. The effective thermal power, P_{rm}, was calculated as a product of the nominal thermal power and the monthly load factor provided for each nuclear core by the International Atomic Energy Agency (IAEA) [15]. For each core the distance, L_r, has been calculated taking into account the geographic coordinates of the center of the Borexino detector (42.4540° latitude and 13.5755° longitude), obtained during the geodesy campaign for a measurement of CNGS muon-neutrino speed [16]. The

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[1] An update of geo-neutrino analysis from KamLAND Collaboration [5] was released after the submission of this Letter and thus it was not considered in the combined analysis presented below.

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