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Geo-neutrinos from 1353 days with the Borexino detector

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Abstract

We present a 1353 days measurement of the geo–neutrino flux in Borexino: the signal was found to be 14.3 ± 4.4 events. This result translates into S_{geo} = (38.8 ± 12.0) TNU when a Th/U fixed chondritic mass ratio of 3.9 is assumed. Furthermore Borexino data are compatible with a mantle geo–neutrino signal of (15.4 ± 12.3) TNU.

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1. Introduction

The detection of neutrinos emitted by different natural sources and the study of their properties have been fundamental since ever, not only for elementary particle physics, but also to improve the knowledge of various astrophysical objects. One can think, for instance, of the contribution given by solar neutrino physics to the development of Standard Solar Models [1], or consider the relevant information that Supernova neutrinos carry on the Supernovae explosion mechanism. Since a few years another dream of the neutrino community [2] became true and large volume experiments like KamLAND and Borexino offered for the first time the possibility of studying the interior of the Earth by detecting geo–neutrinos, which are electron antineutrinos ($\bar{\nu}_e$) released in radioactive decays inside the Earth. By measuring the geo–neutrino flux produced mainly in β decays of ^{40}K and several nuclides in the chains of long–lived radioactive isotopes ^{238}U and ^{232}Th, it is in principle possible to deduce the amount of the radiogenic heat produced within the Earth. This information would be very important for geophysical and geochemical models. For a more detailed discussions about the mechanism of geoneutrinos production, their energy spectra and the open geophysical problems to which they are connected, the interested reader can see, for instance, the following paper (and the references contained therein) [3].

Geo-neutrinos measurement from ^{238}U and ^{232}Th was performed by the KamLAND collaboration [4, 5, 6], and Borexino [7] using large volume liquid scintillator detectors located in underground laboratories. Unfortunately these measurements are not able to discriminate among several geological models because of their low statistics and/or systematic errors. As it was shown in [6] and [8], analyses combining the results from different sites have higher prediction power; in fact, several projects which are entering in operation (SNO+ [9]) or are in their design phase (LENA [10] and Hanohano [11]) have geo–neutrinos among their scientific goals.

Borexino measurement of the geo–neutrino signal with 2.4 times higher exposure with respect to [7] has been published in [12]. For the first time, Borexino attempted a measurement of the individual geo–neutrino signals from the ^{238}U and ^{232}Th chains.

2. The Borexino detector and the detection principle

The Borexino detector, installed in the underground hall C of the Laboratori Nazionali del Gran Sasso (LNGS) in the center Italy, is an unsegmented liquid scintillator detector having as main goal the spectral measurement of low–energy solar neutrinos.

It consists of 278 tons of ultra–pure liquid scintillator (pseudocumene (PC) doped with 1.5 g/l of diphenyloxazole) that are confined within a thin spherical nylon vessel (thickness of about 0.1 mm) with a radius of 4.25 m.

The detector's core is shielded from external radiation by 890 tons of buffer liquid, consisting in a solution of PC and 3-5 g/l of dimethylphthalate as light quencher. A second nylon vessel with a 5.75 m radius, divides the buffer in two volumes with the aim to prevent inward radon diffusion. These two nylon vessels are contained in a stainless steel sphere (SSS) with a diameter of 13.7 m on which 2212 8" PMTs detecting the scintillation light are mounted. An external domed water tank (WT) filled with ultra–high purity water, 16.9 m height, acts as a passive shield against gamma rays and neutrons as well as an active muon veto. For furthers information about the Borexino detector see [13, 14].

In order to decrease the systematic errors and to optimize the values of several input parameters of the Monte–Carlo (MC) simulation, several calibration campaigns with radioactive sources [15] were performed.

In Borexino $\bar{\nu}_e$ are detected via the inverse β decay: $\bar{\nu}_e + p \rightarrow e^+ + n$. This reaction has a threshold of 1.806 MeV, above which there are only a small fraction of $\bar{\nu}_e$ from the ^{238}U (6.3%) and ^{232}Th (3.8%) series. The e^+ comes to rest and annihilates while the free n is captured on protons giving a 2.22 MeV de–excitation γ ray that provides a delayed coincidence event. The visible energy of $E_{\text{prompt}} = E_{\bar{\nu}_e} - 0.784$ MeV is detected in a single prompt event.

In Borexino the mean neutron capture time was measured with an $Am - Be$ neutron source that gave a value of $\tau = (254.5 \pm 1.8)\,\mu$s [16]. The time and spatial coincidence of prompt and delayed events gives a clean signature of $\bar{\nu}_e$ detection, that help for a further suppression of background sources. The Borexino detector was calibrated using several α, β, γ and n sources inserted in the scintillator volume [15]. In order to study the detector response to captured neutrons and to protons recoiling off neutrons the $Am-Be$ neutron source (~10 neutrons/s with energies up to 10 MeV) was deployed in twenty-five different positions.

3. Expected Signal

In paper [12] the dataset consists in 1352.60 days of live time collected between December 2007 and August 2012. After all quality cuts the fiducial exposure is (613 ± 26) ton per year corresponding to (3.69 ± 0.16) · 10^{31} protons per year.

The main anti–neutrino background to the geo–neutrino measurement comes from nuclear power plants; in the analysis 446 nuclear cores, all over the world, have been considered. The mean weighted distance from the Borexino detector (42.4540° latitude and 13.5755° longitude) is about 1200 km.

In order to calculate the expected number of events $N_{\rm react}$ from reactors, the $\sigma(E_{\bar{\nu}})$ of the inverse β decay cross section was taken from [17], while the neutrino oscillation parameters used in the calculation of the P_{ee} survival probability were the ones derived in [19] for normal hierarchy: $\Delta m^2 = (7.54\ ^{+0.26}_{-0.22})\cdot 10^{-5}$ eV^2; $\sin^2\theta_{12} = (3.07\ ^{+0.18}_{-0.16})\cdot 10^{-1}$; $\sin^2\theta_{13} = (2.41 \pm 0.25)\cdot 10^{-2}$. For the effective thermal power calculation, data have been provided, for each nuclear core, by the International Atomic Energy Agency (IAEA) [18].

In the three flavor scenario, a 4.6% decrease in the predicted signal with respect the two neutrino case is expected, but the spectral shape does not change significantly. In the calculations it is also included a +0.6% contribution from matter effects [7].

For the exposure of (613 ± 26) ton per year, after all cuts, the number of expected reactor $\bar{\nu}_e$ candidates is N_{react} = (33.3 ± 2.4) events.

4. Cuts and Backgrounds

In order to select $\bar{\nu}_e$'s candidates several quality cuts have been applied. Naming $Q_{\rm prompt}$ and $Q_{\rm delayed}$ the photomultipliers light yields for the prompt (e^+ candidate) and delayed (n candidate) events, it was set $Q_{\rm prompt} > 408$ p.e. and 860 p.e. $< Q_{\rm delayed} < 1300$ p.e.; the time interval Δt between the prompt and the delayed event was set $20\,\mu$s $< \Delta t < 1280\,\mu$s, and the reconstructed distance $\Delta R < 1$ m. In order to improve the background rejection (discrimination between highly ionizing particles (α, p) from lower specific ionization particles ($\beta^{\pm}$, γ)) a pulse–shape analysis as been performed applying the so–called Gatti parameter G [20]. The total detection efficiency obtained with all these cuts was inferred by Monte–Carlo simulation and it turned out to be 0.84 ± 0.01. The position reconstruction systematic error of $\bar{\nu}_e$ candidates is 3.8% [7]; while the systematic error on the vessel shape is 1.6% and on the cuts efficiency is 1%. Summing up all these systematic errors, we obtain a 4.2% error on the exposure.

Background events which can mimic anti–neutrino interactions can arise from cosmic muons and muon–induced unstable nuclides. Furthermore they can arise from intrinsic contaminations of the scintillator and from all materials surrounding the scintillator, and, last but not least, from the accidental coincidences of non-correlated events. In Table 1 a complete list of all expected backgrounds is presented.

5. Results

The so called golden events, namely the $\bar{\nu}_e$ candidates that satisfied all the selection criteria and have uniform spatial and time distributions are 46. As reported in Table 1, the total number of the events due to the expected background is (0.70 ± 0.18), corresponding to a signal/background ratio of almost 66. For energies greater than $Q_{\rm prompt} > 1300$ p.e., above the end–point of the geo–neutrino spectrum, 21 candidates have been observed. In this energy window, (22.0 ± 1.6) reactor–$\bar{\nu}_e$ events are expected.

An unbinned maximal likelihood fit of the light yield spectrum of the prompt events candidates has been performed. According to the chondritic value of 3.9 [21] the Th/U mass ratio was fixed in order to determine the weights of the geo–neutrino. The reactor $\bar{\nu}_e$ spectral components were left as free fit parameters. All background components were limited at $\pm 1\sigma$ around the expected value. For what concerns the accidental

Table 1. Background faking $\bar{\nu}_e$ interactions (expressed in number of events expected among the 46 golden $\bar{\nu}_e$ candidates). Upper limits are at 90% C.L. Table from [12].

Background source	Events
^{9}Li–^{8}He	0.25±0.18
Fast n's (μ's in WT)	<0.07
Fast n's (μ's in rock)	<0.28
Untagged muons	0.080±0.007
Accidental coincidences	0.206±0.004
Time corr. background	0.005±0.012
(γ,n)	<0.04
Spontaneous fission in PMTs	0.022±0.002
(α,n) in scintillator	0.13±0.01
(α,n) in the buffer	<0.43
Total	0.70 ± 0.18

background, the measured spectral shape was used and a Monte–Carlo spectrum was employed for the background induced by (α, n), ^{9}Li and ^{8}He.

The obtained best fit values are $N_{\rm geo}$ = (14.3 ± 4.4) events for geo–neutrinos, corresponding to a signal $S_{\rm geo}$ = (38.8 ± 12.0) TNU[1] and $N_{\rm react} = 31.2^{+7.0}_{-6.1}$ events for the reactors contribution, corresponding to a signal $S_{\rm react} = 84.5^{+19.3}_{-16.9}$ TNU. Considering the cross section of the detection interaction taken from [17], the measured geo–neutrino fluxes are ϕ(U) = (2.4 ± 0.7) × 10^6 cm^{-2} s^{-1} and ϕ(Th) = (2.0 ± 0.6) × 10^6 cm^{-2} s^{-1}. Fig. 1 and Fig. 2 show the data and the best fit of the geo–neutrino and the reactor anti–neutrino signals compared to expectations.

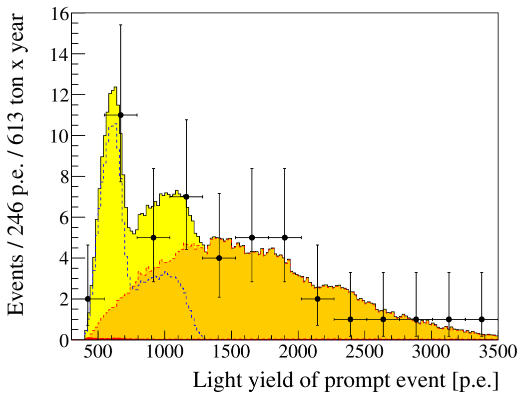

Fig. 1. Spectrum of the 46 prompt $\bar{\nu}_e$ candidates (golden events) and the best fit with the contribution of the geo–$\bar{\nu}_e$ in yellow. The dashed blue line is the geo–$\bar{\nu}_e$ signal resulting from the fit and the dashed red line (orange area) is the reactor–$\bar{\nu}_e$ signal from the fit. The background contribution is almost negligible. In abscissa $Q_{\rm prompt}$ light yield (approximately 500 p.e./MeV). From [12].

The contribution of the local crust (LOC) to the total geo–neutrino signal has been estimated in [22] using a local three dimension geology in the vicinity of the Gran Sasso laboratory, the obtained value being $S_{\rm geo}$(LOC) = (9.7 ± 1.3) TNU. Adding the contribution from the Rest Of the Crust (ROC), evaluated in a recent calculation by Huang et al. [23], the geo–neutrino signal from the crust (LOC+ROC) is $S_{\rm geo}$(Crust) = (23.4 ± 2.8) TNU. The difference between the Borexino geo–neutrino rate and the estimated crustal components give a contribution of the mantle equal to $S_{\rm geo}$(Mantle) = (15.4 ± 12.3) TNU.

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

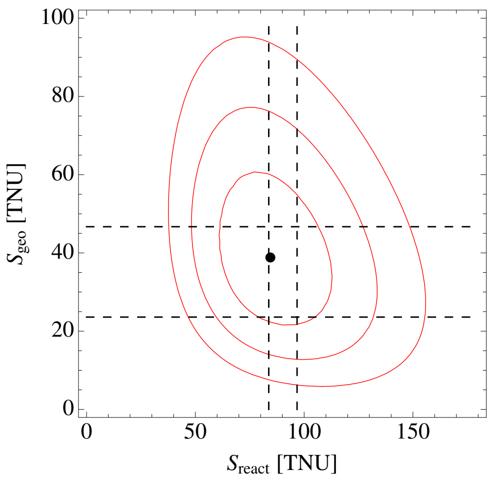

Fig. 2. Contour plots for the geo–neutrino and the reactor anti–neutrino signals in TNU units (at 68.27, 95.45, and 99.73% C.L.). The black horizontal lines are the extremes of the expectations for different BSE models while the back vertical lines are the 1σ expectation band for S_{rea}. From [12].

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