Antineutrino studies with Borexino detector

Oleg Smirnov
141980, Joliot-Curie,6, Dubna, Moscow region, Russia

E-mail: `osmirnov@jinr.ru`

On behalf of the Borexino collaboration

G. Bellini, J. Benziger, D. Bick, S. Bonetti, G. Bonfini, D. Bravo, M. Buizza Avanzini, B. Caccianiga, L. Cadonati, F. Calaprice, C. Carraro, P. Cavalcante, A. Chavarria, D. D'Angelo, S. Davini, A. Derbin, A. Etenko, K. Fomenko, D. Franco, C. Galbiati, S. Gazzana, C. Ghiano, M. Giammarchi, M. Goeger-Neff, A. Goretti, L. Grandi, E. Guardincerri, S. Hardy, Aldo Ianni, Andrea Ianni, D. Korablev, G. Korga, Y. Koshio, D. Kryn, M. Laubenstein, T. Lewke, E. Litvinovich, B. Loer, F. Lombardi, P. Lombardi, L. Ludhova, I. Machulin, S. Manecki, W. Maneschg, G. Manuzio, Q. Meindl, E. Meroni, L. Miramonti, M. Misiaszek, D. Montanari, P. Mosteiro, V. Muratova, L. Oberauer, M. Obolensky, F. Ortica, K. Otis, M. Pallavicini, L. Papp, L. Perasso, S. Perasso, A. Pocar, J. Quirk, R.S. Raghavan, G. Ranucci, A. Razeto, A. Re, A. Romani, A. Sabelnikov, R. Saldanha, C. Salvo, S. Schönert, H. Simgen, M. Skorokhvatov, O. Smirnov, A. Sotnikov, S. Sukhotin, Y. Suvorov, R. Tartaglia, G. Testera, D. Vignaud, R.B. Vogelaar, F. von Feilitzsch, J. Winter, M. Wojcik, A. Wright, M. Wurm, J. Xu, O. Zaimidoroga, S. Zavatarelli, G. Zuzel

Abstract. A very high radiopurity level of its scintillator and detector location far away from the European nuclear reactors makes Borexino a very sensitive tool for antineutrino studies. Spectral contributions corresponding to two known antineutrino sources were reported in a recently published paper [1]: $\bar{\nu}_e$'s produced in European nuclear reactors and geo-neutrinos, produced in β decays of isotopes along the decay chains of long-lived ^{238}U and ^{232}Th distributed within the Earth's interior. A sensitive search for other antineutrino sources has been performed.

1. Geoneutrino

Geo-neutrinos are anti-neutrinos produced in decays of naturally occurring radioactive isotopes. Decays from radioactive elements are believed to contribute a significant but still precisely unknown fraction of the heat generated inside our planet. In 2004 an 1.6σ excess of low-energy antineutrinos above background was reported by KamLAND, and in 2010 the Borexino collaboration reported more than 4σ confirmation for non-zero geoneutrino signal. The total background for the antineutrino studies in Borexino is 100 times lower compared to those of KamLAND due to a lower background from internal radioactivity and lower flux of antineutrinos from nuclear power plants.

Experimental antineutrino spectrum registered by Borexino during 537 days of the data taking is shown in Fig.1a, one can clearly see that the expected background contribution is negligible. The expected spectra from geo- and reactor antineutrino are presented at the same figure normalized to their best fit values. The allowed regions for the number of observed geo- (Ngeo) versus reactor (NReact) antineutrino are shown in Fig.1b. The dashed lines bound the 1σ theoretical ranges (geoneutrino predictions are shown for the so called Bulk Silicate Earth

Published under licence by IOP Publishing Ltd

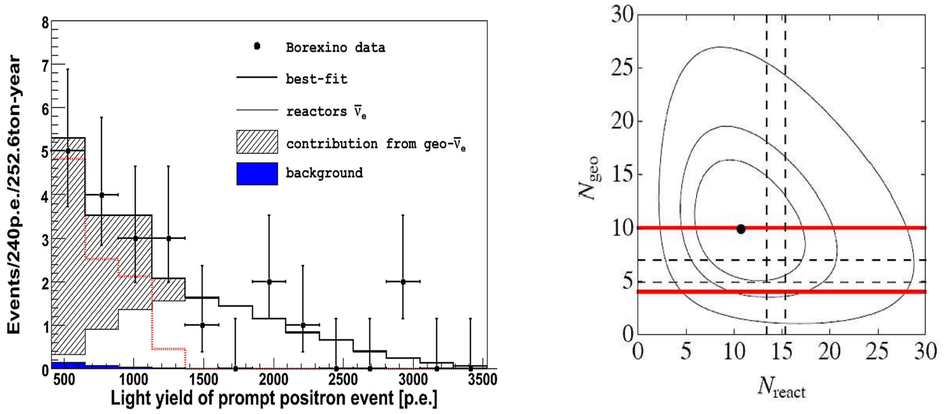

Figure 1. (a)Left figure: experimental antineutrino spectrum registered by Borexino during 537 days of the data taking. (b)Right figure: the allowed regions for the number of observed geo-(Ngeo) versus reactor (NReact) antineutrino for 68%, 90% and 99.73% C.L. correspondingly.

model). Thick (red) horizontal lines mark two extreme models: the so called Minimal Radiogenic Earth model (which considers U and Th from only those Earth layers whose composition has been studied directly) and the Maximal Radiogenic Earth scenario (which assumes that all terrestrial heat is produced exclusively by radioactive decays). As one can see in the above figures, the current observation lacks the precision required to distinguish even the extreme geological models. Nevertheless, the presence of geoneutrinos in the experimental spectrum is confirmed at the very high statistical level (99.997%). Geo-neutrinos were identified at a rate of $3.9^{+1.6(+3.8)}_{-1.3(-3.2)}$ events/(100 ton yr) for 68% (99.73%) C.L. correspondingly.

The definite detection of geo-neutrinos by Borexino confirms that radioactivity contributes a significant fraction, possibly most, of the power. Other sources of thermal power are possible, in particular a powerful natural geo-nuclear reactor at the center of the earth has been suggested as an alternative solution to the heat production problem. The hypothesis of a geo-reactor with a typical power of 3–10 TW at the Earth's core has been examined and an upper limit of 3 TW at 95% C.L. has been established for a reactor with power fractions of ^{235}U:^{238}U=0.75:0.25.

Although radioactivity can account for a significant part of the earth's internal heat, measurements with a global array of geo-neutrino detectors above continental and oceanic crust are needed for a detailed understanding. The techniques developed by Borexino could be applied for the future many tens of kilotones liquid scintillator detectors, with a geoneutrino measurement among other tasks.

2. Reactor antineutrino

The determination of the expected signal from reactor $\bar{\nu}_e$'s required the collection of the detailed information on the time profiles of power and nuclear fuel composition for nearby reactors. The differential reactor anti-neutrino spectrum, in units of MeV^{-1}cm^{-2}, is:

$$\Phi(\mathrm{E}_{\bar{\nu}_e}) = \sum_{\mathrm{r}=1}^{\mathrm{N_{React}}} \sum_{\mathrm{m}=1}^{\mathrm{N_{month}}} \frac{\mathrm{T}_m}{4\pi \mathrm{L}_\mathrm{r}^2} \mathrm{P}_\mathrm{rm} \times \sum_{i=1}^{4} \frac{\mathrm{f}_i}{\mathrm{E}_i} \phi_i(\mathrm{E}_{\bar{\nu}_e}) \mathrm{P}_\mathrm{ee}(\mathrm{E}_{\bar{\nu}_e}; \hat{\Theta}, \mathrm{L}_\mathrm{r}),$$

where the index r cycles over the N reactors considered, the index m cycles over the total number of months $\mathrm{N_{month}}$ for the present data set, $\mathrm{T_m}$ is the live time in the m-th month, $\mathrm{L_r}$ is the distance of the detector from reactor r, $\mathrm{P_{rm}}$ is the effective thermal power of reactor r in month m, the index i stands for the i-th 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 anti-neutrino energy per fission of the component i, $\phi(E_{\bar{\nu}})$ is the anti-neutrino flux per fission of the i-th component, and P_{ee} is the survival probability of the reactor anti-neutrinos of energy $E_{\bar{\nu}}$ traveling the baseline L_r, for mixing parameters $\hat{\Theta} = (\Delta m^2_{12}, \sin^2\Theta_{12})$. The main contribution comes from 194 reactors in Europe, while other 245 reactors around the world contribute only 2.5% of the total reactor signal. Typical power fractions for the fuel components are: ^{235}U:^{238}U:^{239}Pu:^{241}Pu $= 0.56 : 0.08 : 0.30 : 0.06$ with a systematic error of 3.2% due to possible differences among the fuels of different cores and the unknown stage of burn-up in each reactor. For the thirty-five European reactors using MOX (Mixed OXide) technology, 30% of their thermal power was considered to have power fractions: ^{235}U:^{238}U:^{239}Pu:^{241}Pu $= 0.000 : 0.080 : 0.708 : 0.212$. Information on the nominal thermal power and monthly load factor for each European reactor originates from IAEA and EDF.

An $\bar{\nu}_e$ rate of $4.3^{+1.7}_{-1.4}$ events/(100 ton yr) was measured from nuclear reactors, consistent with an expected rate of 5.7±0.3 events/(100 ton yr). The oscillations of reactor neutrino are observed for the first time on a baseline of about 1000 km (average distance to the European nuclear reactors), the hypothesis of no oscillations is rejected at 99.60% C.L.

3. Antineutrino from the Sun and neutrino magnetic moment

A weak anti-neutrino flux from the Sun arising from $\nu_e \rightarrow \bar{\nu}_e$ conversion cannot be completely excluded with current experimental data. In particular, the interplay of flavor oscillations and spin flavor precession (SFP) induced by solar magnetic fields on Majorana neutrinos with sizable electric or magnetic transition moments could lead to the appearance of an $\bar{\nu}_e$ admixture in the solar neutrino flux. The limit on the solar anti-neutrino flux of $\phi(\bar{\nu}_e) < 370$ cm^{-2}s^{-1} (90% C.L.) above 8.3 MeV threshold was reported by KamLAND. The Borexino analysis was performed in the energy window from the inverse $\beta-$decay threshold. Assuming the undistorted solar ^{8}B spectrum, the limit on the anti-neutrino flux scaled to the entire energy range is $\phi(\bar{\nu}_e) < 1250$ cm^{-2}s^{-1} (90% C.L.), and a limit on the conversion probability $p_{\nu\rightarrow\bar{\nu}_e} < 1.3 \times 10^{-4}$ (90% C.L.) was set using the ^{8}B theoretical solar neutrino flux of $5.05^{+0.20}_{-0.16} \times 10^6$ cm^{-2}s^{-1}. Though for the moment of publication[4] the limits were the best up to date, recently improvement of limits on $\phi(\bar{\nu}_e)$ and $p_{\nu\rightarrow\bar{\nu}_e}$ by factor 2.5 have been reported by KamLAND collaboration [3].

The limit on solar anti-neutrinos can be used to set limits on the neutrino magnetic moment μ_ν and on the strength and shape of the solar magnetic field.

The higher estimate of the magnetic field in the core of the Sun is 7 MG, which would limits the magnetic moment to $\mu_\nu \leqslant 1.4 \times 10^{-12}\mu_B$.

Currently, the best limit on the neutrino magnetic moment, $\mu_\nu < 3\times10^{-12}\mu_B$, is obtained by imposing astrophysical constraints that avoid excessive energy losses by globular-cluster stars. The best direct limit is obtained with reactor neutrinos, $\mu_{\bar{\nu}_e} < 3.2 \times 10^{-11}\mu_B$ [5]. The direct limits on neutrino magnetic moment has been established with Borexino data searching for the deviations of the electrons recoil spectrum from the standard electroweak shape [6]. No deviations has been found at 90% C.L. for the effective magnetic moment of solar neutrino down to 5.4×10^{-11} Bohrs magneton at 90% C.L.. These experimental limits on the neutrino magnetic moments, together with reasonable assumptions on the distribution of turbulent magnetic fields in the Sun, corresponds to a conversion probability $p_{\nu\rightarrow\bar{\nu}} \sim 10^{-6}$ far of the reach (two orders of magnitude) of present experiments.

The study of the antineutrino using inverse β-decay is naturally limited by the reaction threshold of 1.8 MeV. Below the threshold the only possible reaction for antineutrino detection in Borexino is elastic scattering. The spectrum of recoil electrons for antineutrino scattering differs from the one for neutrino, this allows to discriminate between neutrino and antineutrino. The low total cross section for antineutrino (about factor 5 lower than for neutrino) considerably limits

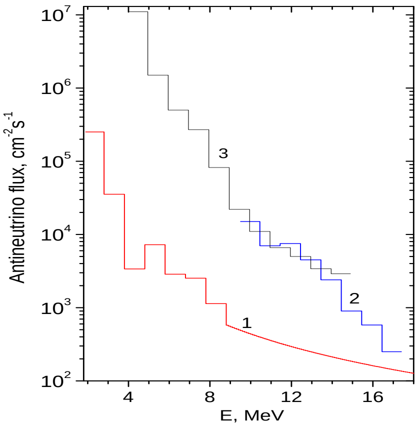

Figure 2. Model independent limits on antineutrino fluxes established by Borexino (1) compared with SuperKamiokaNDE (2) and SNO (3) data.

the sensitivity of such search. In order to estimate the sensitivity of Borexino to antineutrinos from the conversion of solar neutrinos below 1.8 MeV we studied the monoenergetic ^{7}Be solar neutrino's, allowing its partial conversion to antineutrino and adding antineutrinos with ^{7}Be energy (862 keV) to the standard fit of Borexino spectrum. Following the changes in χ^2 profile with respect to the antineutrino fraction we established a limit on this hypothetical addition of no more than 30% of the original ^{7}Be neutrino flux at 90% C.L. [6].

4. Other antineutrino sources

These include the search for unspecified and model independent $\bar{\nu_e}$ fluxes. The case of an undistorted ^{8}B anti-neutrino spectrum is a special case of $\nu_e \rightarrow \bar{\nu_e}$ conversion for energy-independent conversion probability. A model independent search for unknown anti-neutrino fluxes was performed in 1 MeV energy bins for 1.8 $<E_\nu<$17.8 MeV. The analysis consisted in setting the limits on any contribution of unknown origin in the anti-neutrino spectrum registered by Borexino. In order to obtain conservative limits, the minimal expected number of events in every bin has been calculated separately for reactor and geo-neutrinos. For geo-neutrinos we considered the Minimal Radiogenic Earth model, which only includes the radioactivity from U and Th in the Earth crust which can be directly measured in rock-samples. The 90% C.L. upper limits were calculated in Feldman- Cousins approach using observed number of events in every bin and (minimal) expected background. Model independent limits on antineutrino fluxes are shown in Fig.3 compared with SuperKamiokaNDE and SNO data. New limits on unknown antineutrino sources were established in the energy range 1.8-17.8 MeV, some orders of magnitude stronger than existing ones.

References

[1] G.Bellini, et al., Borexino Collaboration, Phys. Lett. B 687 (2010) 299-304.
[2] K. Eguchi, et al., KamLAND Collaboration, Phys. Rev. Lett. 92 (2004) 071301;
[3] A. Gando, et al., KamLAND Collaboration, arXiv:1105.3516;
[4] G.Bellini, et al., Borexino Collaboration, Phys.Lett. B 696 (2011) 191;
[5] A.G.Beda et al., arXiv:1005.2736v2 [hep-ex]
[6] C. Arpesella, et al., Borexino Collaboration, Phys.Rev.Lett. 101 (2008) 091302