Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Geo-neutrino results with Borexino

To cite this article: R Roncin *et al* 2016 *J. Phys.: Conf. Ser.* **675** 012029

View the article online for updates and enhancements.

Related content

- Nuclear physics inputs needed for geo-neutrino studies
  G Bellini, G Fiorentini, A Ianni et al.
- JUNO PMT system and prototyping
  Zhimin Wang and JUNO Collaboration
- Geo-neutrino flux calculation
  S T Dye

Recent citations

- The fine structure constant and habitable planets
  McCullen Sandora

IOP ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

This content was downloaded from IP address 128.112.172.143 on 06/08/2019 at 14:10

Geo-neutrino results with Borexino

R Roncin[1,2,29], M Agostini[3], S Appel[3], G Bellini[4], J Benziger[5], D Bick[6], G Bonfini[1], D Bravo[7], B Caccianiga[4], F Calaprice[8], A Caminata[9], P Cavalcante[1], A Chepurnov[10], D D'Angelo[4], S Davini[11], A Derbin[11], L Di Noto[9], I Drachnev[11], A Etenko[13], K Fomenko[14], D Franco[2], F Gabriele[1], C Galbiati[8], C Ghiano[9], M Giammarchi[4], M Goeger-Neff[3], A Goretti[8], M Gromov[10], C Hagner[6], E Hungerford[15], Aldo Ianni[1], Andrea Ianni[8], K Jedrzejczak[17], M Kaiser[6], V Kobychev[18], D Korablev[14], G Korga[1], D Kryn[2], M Laubenstein[1], B Lehnert[19], E Litvinovich[13,20], F Lombardi[1], P Lombardi[4], L Ludhova[4], G Lukyanchenko[13,20], I Machulin[13,20], S Manecki[7], W Maneschg[22], S Marcocci[11], E Meroni[4], M Meyer[6], L Miramonti[4], M Misiaszek[17,1], M Montuschi[23], P Mosteiro[8], V Muratova[11], B Neumair[3], L Oberauer[3], M Obolensky[2], F Ortica[24], M Pallavicini[9], L Papp[3], L Perasso[9], A Pocar[26], G Ranucci[4], A Razeto[1], A Re[4], A Romani[24], N Rossi[1], S Schönert[3], D Semenov[11], H Simgen[22], M Skorokhvatov[13,20], O Smirnov[14]A Sotnikov[14], S Sukhotin[13], Y Suvorov[27,13], R Tartaglia[1], G Testera[9], J Thurn[19], M Toropova[13], E Unzhakov[11], A Vishneva[14], R B Vogelaar[7], F von Feilitzsch [3], H Wang[27], S Weinz[28], J Winter[28], M Wojcik[17], M Wurm[28], Z Yokley[7], O Zaimidoroga[14], S Zavatarelli[9], K Zuber[19] and G Zuzel[17](Borexino Collaboration)

[1] INFN Laboratori Nazionali del Gran Sasso, 67010 Assergi (AQ), Italy
[2] AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris Cedex 13, France
[3] Physik-Department and Excellence Cluster Universe, Technische Universität München, 85748 Garching, Germany
[4] Dipartimento di Fisica, Università degli Studi e INFN, 20133 Milano, Italy
[5] Chemical Engineering Department, Princeton University, Princeton, NJ 08544, USA
[6] Institut für Experimentalphysik, Universität, 22761 Hamburg, Germany
[7] Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA
[8] Physics Department, Princeton University, Princeton, NJ 08544, USA
[9] Dipartimento di Fisica, Università degli Studi e INFN, Genova 16146, Italy
[10] Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics, 119234 Moscow, Russia
[11] Gran Sasso Science Institute (INFN), 67100 L'Aquila, Italy
[12] St. Petersburg Nuclear Physics Institute NRC Kurchatov Institute, 188350 Gatchina, Russia
[13] NRC Kurchatov Institute, 123182 Moscow, Russia
[14] Joint Institute for Nuclear Research, 141980 Dubna, Russia
[15] Department of Physics, University of Houston, Houston, TX 77204, USA
[16] Institute for Theoretical and Experimental Physics, 117218 Moscow, Russia

[29] Presenter. To whom any correspondence should be addressed.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

[17] M. Smoluchowski Institute of Physics, Jagiellonian University, 30059 Krakow, Poland
[18] Kiev Institute for Nuclear Research, 06380 Kiev, Ukraine
[19] Department of Physics, Technische Universität Dresden, 01062 Dresden, Germany
[20] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, Moscow 115409, Russia
[21] Kepler Center for Astro and Particle Physics, Universität Tübingen, 72076 Tübingen, Germany
[22] Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
[23] Dipartimento di Fisica e Scienze della Terra Università degli Studi di Ferrara e INFN, Via Saragat 1-44122, Ferrara, Italy
[24] Dipartimento di Chimica, Università e INFN, 06123 Perugia, Italy
[25] Physics Department, Queen's University, Kingston ON K7L 3N6, Canada
[26] Amherst Center for Fundamental Interactions and Physics Department, University of Massachusetts, Amherst, MA 01003, USA
[27] Physics and Astronomy Department, University of California Los Angeles (UCLA), Los Angeles, California 90095, USA
[28] Institute of Physics and Excellence Cluster PRISMA, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany

E-mail: romain.roncin@lngs.infn.it

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:

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

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 mimick 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:

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

with:

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

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

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

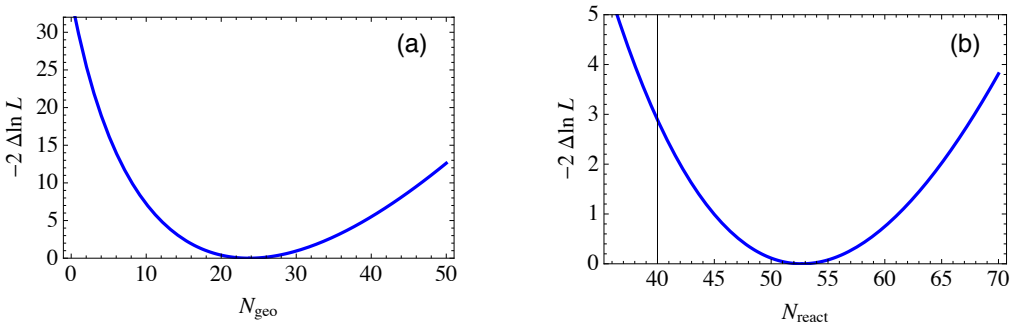

Figure 1. $-2\,\Delta\ln\mathcal{L}$ profiles for $N_{\rm geo}$ (a) and $N_{\rm react}$ (b).

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 $N_{\rm geo} = 23.7^{+6.5}_{-5.7}\,({\rm stat})\,^{+0.9}_{-0.6}\,({\rm syst})$ and $N_{\rm react} = 52.7^{+8.5}_{-7.7}\,({\rm stat})\,^{+0.7}_{-0.9}\,({\rm syst})$ events, which is equivalent to $43.5^{+11.8}_{-10.4}\,({\rm stat})\,^{+2.7}_{-2.4}\,({\rm syst})$ and $96.6^{+15.6}_{-14.2}\,({\rm stat})\,^{+4.9}_{-5.0}\,({\rm syst})$ 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 $N_{\rm geo}$ and $N_{\rm react}$.

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 $^{235}{\rm U}/^{238}{\rm U}$ has been set to 0.75/0.25 while the Pu contribution is set to 0. The

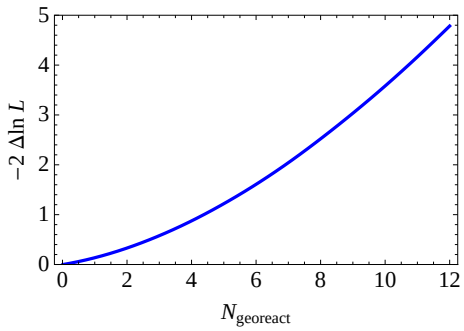

Figure 2. $-2\,\Delta\ln\mathcal{L}$ profile for $N_{\rm georeact}$.

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

[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 × 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

Russian colleagues from MEPhI acknowledge partial support from MEPhI Academic Excellence Project (contract No. 02.a03.21.0005, 27.08.2013).

References

[1] Eder G 1966 *Nucl. Phys.* **78** 657-62
[2] Marx G 1969 *Czech. J. Phys.* B **19** 1471-9
[3] Krauss L M, Glashow S L and Schramm D N 1984 *Nature* **310** 191-8
[4] Araki T *et al.* (KamLAND Collaboration) 2005 *Nature* **436** 499-503
[5] Gando A *et al.* (KamLAND Collaboration) 2013 *Phys. Rev.* D **88** 033001
[6] Bellini G *et al.* (Borexino Collaboration) 2010 *Phys. Lett.* B **687** 299-304
[7] Bellini G *et al.* (Borexino Collaboration) 2013 *Phys. Lett.* B **722** 295-300
[8] Agostini M *et al.* (Borexino Collaboration) 2015 *Phys. Rev.* D **92** 031101
[9] Coltorti M *et al.* 2011 *Geochim. Cosmochim. Acta* **75** 2271
[10] Huang Y *et al.* 2013 *Geochem., Geophys., Geosyst.* **14** 2003-29