The Main Results of the Borexino Experiment

A Derbin\textsuperscript{f} and V Muratova\textsuperscript{f} on behalf of the Borexino collaboration:

M Agostini\textsuperscript{c}, K Altenmüller\textsuperscript{r}, S Appel\textsuperscript{a}, G Bellini\textsuperscript{b}, J Benziger\textsuperscript{d}, D Bick\textsuperscript{c}, G Bonfini\textsuperscript{e}, D Bravo\textsuperscript{b}, B Caccianiga\textsuperscript{b}, F Calaprice\textsuperscript{f}, A Caminata\textsuperscript{c}, M Carliti\textsuperscript{c}, P Cavallaro\textsuperscript{c}, A Chepurnov\textsuperscript{g}, D D'Angelo\textsuperscript{b}, S Davini\textsuperscript{m}, A Derbin\textsuperscript{m}, L Di Noto\textsuperscript{c}, I Drachnev\textsuperscript{m}, A Elenko\textsuperscript{b}, K Fomenko\textsuperscript{b}, A Formozov\textsuperscript{b,h}, D Franco\textsuperscript{c}, P Gabriele\textsuperscript{c}, C Galbiati\textsuperscript{b,h}, C Ghiano\textsuperscript{c}, M Giannamarchi\textsuperscript{b}, M Goeger-Neff\textsuperscript{b}, A Goretti\textsuperscript{b,k}, M Gromov\textsuperscript{c}, C Hagner\textsuperscript{c}, E Hungerford\textsuperscript{d}, Aldo Ianni\textsuperscript{e,g}, N. Jedrzejczak\textsuperscript{d}, D Jeschke\textsuperscript{e}, M Kaiser\textsuperscript{c}, V Kobychev\textsuperscript{c}, D Koralev\textsuperscript{c}, G Korga\textsuperscript{c}, D Kryn\textsuperscript{c}, M Laubenbauer\textsuperscript{b,} B Lehnert\textsuperscript{e}, E Litvinovich\textsuperscript{e,g}, F Lombardi\textsuperscript{b}, L Ludhova\textsuperscript{a}, G Lukyanenko\textsuperscript{a}, I Machulin\textsuperscript{a}, S Manecchi\textsuperscript{b}, W Maneschg\textsuperscript{c}, S Marcocci\textsuperscript{m}, E Meroni\textsuperscript{b}, M Meyer\textsuperscript{c}, L Miramonti\textsuperscript{b}, M Misiaszek\textsuperscript{d,e}, M Montuschi\textsuperscript{c}, P Mosteiro\textsuperscript{b}, V Muratova\textsuperscript{m}, R Neumair\textsuperscript{c}, L Oberauer\textsuperscript{c}, M Obolevsky\textsuperscript{b}, F Ortica\textsuperscript{c}, M Pallavicini\textsuperscript{c}, L Papp\textsuperscript{b}, L Perasso\textsuperscript{c}, A Pocar\textsuperscript{g}, G Ramucc\textsuperscript{c}, A Razeto\textsuperscript{c}, A Re\textsuperscript{b}, A Romani\textsuperscript{r}, R Roncin\textsuperscript{b,a}, N Rossi\textsuperscript{b}, S Schöner\textsuperscript{c}, D Semenov\textsuperscript{f}, H Simgen, M Skorokhvatov\textsuperscript{a}, O Smirnoff\textsuperscript{a}, A Sotnikov\textsuperscript{b}, S Sukhotin\textsuperscript{y}, Y Suvorov\textsuperscript{b}, R Tartaglia\textsuperscript{a}, G Testera\textsuperscript{f}, J Thurn\textsuperscript{c}, M Toropova\textsuperscript{c}, E Unzhakov\textsuperscript{c}, A Vishnev\textsuperscript{e}, R B Vogelaar\textsuperscript{a}, F von Feilitzsch\textsuperscript{h}, H Wang\textsuperscript{c}, S Wein\textsuperscript{c}, J Winter\textsuperscript{c}, M Wojcik\textsuperscript{d}, M Wurm\textsuperscript{y}, Z Yokley\textsuperscript{q}, O Zaimidoroga\textsuperscript{b}, S Zavatarelli\textsuperscript{c}, K Zuber\textsuperscript{d}, and G Zuzel\textsuperscript{d}

a) Astroparticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris Cedex 13, France
b) Joint Institute for Nuclear Research, Dubna 141980, Russia
c) Dipartimento di Fisica, Università degli Studi e INFN, Genova 16146, Italy
d) M. Smoluchowski Institute of Physics, Jagellonian University, Krakow, 30059, Poland
e) INFN Laboratori Nazionali del Gran Sasso, Assergi 67010, Italy
f) St. Petersburg Nuclear Physics Institute NRC Kurchatov Institute, Gatchina 188350, Russia
g) NRC Kurchatov Institute, Moscow 123182, Russia
h) Dipartimento di Fisica, Università degli Studi e INFN, Milano 20133, Italy
i) Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
j) Dipartimento di Chimica, Università e INFN, Perugia 06123, Italy
k) Chemical Engineering Department, Princeton University, Princeton, NJ 08544, USA
l) Physics Department, Princeton University, Princeton, NJ 08544, USA
m) Physics Department, Princeton University, Princeton, NJ 08544, USA
n) Gran Sasso Science Institute (INFN), 67100 Aquila, Italy
o) Institute for Nuclear Research, Kiev 03680, Ukraine
p) Physics Department, University of Massachusetts, Amherst MA 01003, USA
q) Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA
r) Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics, Moscow 119234, Russia
s) Institut für Experimentalphysik, Universität, 22761 Hamburg, Germany
t) Department of Physics, University of Houston, Houston, TX 77204, USA
u) Physics and Astronomy Department, University of California Los Angeles (UCLA), Los Angeles, CA 90095, USA
v) Department of Physics, Technische Universität Dresden, 01062 Dresden, Germany
w) Dipartimento di Fisica e Scienze della Terra Università degli Studi di Ferrara e INFN, 44122 Ferrara, Italy
x) Amerist Center for Fundamental Interactions and Physics Department, University of Massachusetts, Amherst, Massachusetts 01003, USA
y) Institute of Physics and Excellence Cluster PRISMA, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany
z) National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Russia

Proceedings of the Third Annual Large Hadron Collider Physics Conference, St. Petersburg, Russia, 2015
Abstract

The main physical results on the registration of solar neutrinos and the search for rare processes obtained by the Borexino collaboration to date are presented.

1. INTRODUCTION

The study of solar neutrinos is at the intersection of elementary particle physics and astrophysics. On one hand these neutrinos allow for the study of neutrino oscillations, and on the other they provide key information for accurate solar modeling. The Borexino first detected and then precisely measured the flux of the $^7$Be solar neutrinos, ruled out any significant day-night asymmetry of their interaction rate, performed the measurement of $^8$B-neutrino with 3 MeV threshold, made the first direct observation of the pep neutrinos, and set the tightest upper limit on the flux of solar neutrinos produced in the CNO cycle.

The uniquely low background level of the Borexino detector made it possible to set new limits on the effective magnetic moment of the neutrino, on the stability of the electron for decay into a neutrino and a photon, on the heavy sterile neutrino mixing in $^8$B-decay, on the possible violation of the Pauli exclusion principle, on the flux of high energy solar axions and on some other rare processes.

2. The Borexino detector

Borexino is a real-time liquid scintillator detector for solar neutrino spectroscopy located at the Gran Sasso Underground Laboratory [1]. Its main goal is to measure low-energy solar neutrinos via $(\nu,e)$-scattering in an ultrapure liquid scintillator. At the same time, the extremely high radiopurity of the detector and its large mass allow it to be used for the study other fundamental questions in particle physics and astrophysics.

Figure 1: Left: the schematic view of the Borexino detector. Right: solar neutrino energy spectrum predicted by standard solar model.

The detector energy and spatial resolution were studied with radioactive sources placed at different positions inside the inner vessel. For high energies
the calibration was performed with a AmBe neutron source [2]. The energy resolution scales approximately as \( \sigma_E / E = 5\% E^{-1/2} \). The position of an event is determined using a photon time of flight reconstruction algorithm. The resolution of the event reconstruction, as measured using the \(^{214}\text{Bi} - ^{214}\text{Po} \) decay sequence, is 13.2 cm.

The fluxes and the energy spectra of solar neutrinos from pp-chain and CNO-cycle are predicted by solar models. Thanks to the unprecedented low background level achieved in the scintillator, Borexino already measured the fluxes and electron recoil spectra of neutrinos coming from the \( pp-, pep-, ^{7}\text{Be} \) -and \(^{8}\text{B}-\) nuclear reactions which take place inside the Sun.

3. \(^{7}\text{Be}-\)neutrinos

Borexino was designed to measure the spectrum of recoil electrons from 862 keV neutrino due to EC-process: \(^{7}\text{Be} + e^- \rightarrow ^{7}\text{Li} + \nu_e\). The measured count rate of \(^{7}\text{Be}\)-neutrino is [3]: \( R(^{7}\text{Be}) = 46.0 \pm 1.5(\text{stat}) \pm 1.6(\text{syst}) \) counts/(d 100 t). Study on a possible asymmetry between day and night \(^{7}\text{Be}\)-neutrino interaction rate gives [3]: \( A_{dn} = 0.001 \pm 0.012(\text{stat}) \pm 0.07(\text{syst}) \). Borexino excluded the LOW region of the MSW parameter space for neutrino without the use of reactor anti-neutrino data and therefore without the assumption of CPT symmetry.

4. \(^{8}\text{B}\)-neutrinos

Borexino reported the first measurement of \(^{8}\text{B}\) solar neutrino rate with 3 MeV threshold [5] \( R(^{8}\text{B}) = 0.22 \pm 0.04(\text{stat}) \pm 0.01(\text{syst}) \) counts/(d 100 t) in good agreement with measurements from SNO and SuperKamiokaNDE.

5. pep- and CNO-neutrino

Standard Solar Model provides an very accurate (1.2%) flux prediction for 1.44 MeV neutrinos emitted in \( p + p + e^- \rightarrow d + \nu_e \) reaction. Borexino performed the first measurement of the pep-neutrino interaction rate and set the strongest
limit on the CNO neutrino interaction rate (at present, it is not sufficient to solve the High/Low metallicity problem) [6]: $R(\text{pep}) = 3.1 \pm 0.6(\text{stat}) \pm 0.3(\text{syst})$ counts/(d 100 t) and $R(\text{CNO}) \leq 7.9$ counts/(d 100 t) at 95% C.L..

Figure 3: Left: energy spectra of the events in the fiducial volume before and after the threefold coincidence veto ($\mu, n, ^{11}\text{C}$ is applied. Right: residual energy spectrum after best-fit rates of all considered backgrounds are subtracted. The $e^{-}$-recoil spectrum from pep-$\nu$ at the best-fit rate is shown for comparison.

6. pp-neutrino

Neutrino produced from the fusion of two protons for the first time has been detected in a real time detector. The unique properties of the Borexino provided an opportunity to extract pp-neutrino spectrum from the background components [7]: $R(pp) = 44 \pm 13(\text{stat}) \pm 10(\text{syst})$ counts/(d 100 t). Assuming LMA-MSW solution this value corresponds to solar pp-neutrino flux $\Phi(pp) = (6.6 \pm 0.7) \times 10^{10}$ cm$^{-2}$s$^{-1}$ which is in good agreement with the prediction of the standard solar model.

Figure 4: Fit of the energy spectrum between 165 and 590 keV. a, The bestfit pp neutrino component is shown in red, the $^{14}\text{C}$ background in dark purple and the synthetic pile-up in light purple. The large green peak is $^{210}\text{Po}$ a-decays. $^{7}\text{Be}$ (dark blue), pep- and CNO (light blue) solar neutrinos, and $^{210}\text{Bi}$ (orange) are almost flat in this energy region. The values of the parameters (in c.p.d. per 100 t) are in the inset above the figure.
7. Electron neutrino survival probability

Survival probability of electron-neutrinos produced by the different nuclear reactions in the Sun. All the numbers are from the Borexino. Because $pp$- and $^8$B-neutrino are emitted with a continuum of energy the reported $P_{ee}$ value refers to the energy range contributing to the measurement. The violet band corresponds to the $\pm 1\sigma$ prediction of the MSW-LMA solution.

![Figure 5](image)

Figure 5: Electron neutrino survival probability obtained by Borexino as a function of energy.

8. Neutrino magnetic moment

The shape of the electron recoil spectrum is sensitive to the possible presence of a non-null magnetic moment, and the sensitivity is enhanced at low energy since $E_e^{-1}$. For solar neutrinos we detect the effective magnetic moment, which is composition of magnetic moments for mass or flavor eigenstates. Borexino obtained the upper limit $[8]: \mu_{eff} \leq 5.4 \times 10^{-11}\mu_B$ (90% C.L.).

![Figure 6](image)

Figure 6: The e-recoil spectrum due to magnetic moment equals $5.4 \times 10^{-11}\mu_B$ (blue cycles) in comparison with others components of the Borexino data.

9. Detection of geo- and reactor neutrinos

Geo-neutrinos are electron anti-neutrinos produced by decays of long-lived isotopes, which are naturally present in the interior of the Earth, such as decays...
in the $^{238}\text{U}$ and $^{232}\text{Th}$ chains, and $^{40}\text{K}$. Results from 2056 days of data taking correspond to exposure of $(5.5 \pm 0.3) \times 10^{31}$ proton\text{yr}. Assuming a chondritic Th/U mass ratio of 3.9, Borexino detected $(23.7^{+6.5}_{-5.7})$ geo-neutrino events and $(52.7^{+8.5}_{-7.2})$ reactor (anti)neutrinos [9]. The Borexino reported on the search for anti-neutrinos of yet unknown origin and, in particular, set a new upper limit for a hypothetical solar $\bar{\nu}$ flux of 760 cm$^{-2}$s$^{-1}$, obtained assuming an undistorted solar $^8\text{B}$ energy spectrum [10].

Figure 7: Prompt light yield spectrum, in units of photoelectrons (p.e.), of $\bar{\nu}_e$ candidates and the best-fit. The best-fit shows the geo-neutrino and reactor neutrino spectra (dotted lines) assuming the chondritic ratio. Colored areas show the result of a separate fit with U (blue) and Th (light blue) set as free and independent parameters.

10. Heavy sterile neutrino

The Borexino constrains the mixing of a heavy neutrino with mass $1.5 \text{ MeV} \leq m_H \leq 14 \text{ MeV}$ appearing in $^8\text{B}$-decay to be $|U_{eH}|^2 \leq (10^{-3} - 4 \times 10^{-6})$, respectively [13]. These limits are 10 to 1000-fold stronger than those obtained by experiments searching for $\nu_H \rightarrow \nu_L + e^+ + e^-$ decays at nuclear reactors and 1.5-4 times stronger than those inferred from $\pi \rightarrow e + \nu$ decay.

Figure 8: The Borexino constraints (red) and limits on $|U_{eH}|^2$ versus $m_H$ in the mass range (3 eV – 100 GeV) from different experiments.
11. Test of Pauli Exclusion Principle

Using the unique features of the Borexino detector the following new limits on non-paulian transitions of nucleons from the $1P_{3/2}$-shell to the filled $1S_{1/2}$-shell in $^{12}$C with the emission of $\gamma, n, p$ and $\beta^\pm$ particles have been obtained [11]:

\[ \tau(^{12}\text{C} \rightarrow ^{12}\overline{\text{C}} + \gamma) \geq 5.0 \times 10^{31} \, \text{y}, \quad \tau(^{12}\text{C} \rightarrow ^{11}\overline{\text{B}} + p) \geq 8.9 \times 10^{29} \, \text{y}, \]
\[ \tau(^{12}\text{C} \rightarrow ^{11}\overline{\text{C}} + n) \geq 3.4 \times 10^{30} \, \text{y}, \quad \tau(^{12}\text{C} \rightarrow ^{12}\overline{\text{N}} + e^- + \nu) \geq 3.1 \times 10^{30} \, \text{y} \]
\[ \tau(^{12}\text{C} \rightarrow ^{12}\overline{\text{B}} + e^+ + \overline{\nu}) \geq 2.1 \times 10^{30} \, \text{y}, \] all with 90% C.L. These limits are the best to date.

12. High energy solar axions

A search for 5.5-MeV solar axions produced in $p + d \rightarrow ^3\text{He} + A$ (5.5 MeV) reaction was performed [12]. The Compton conversion of axions to photons - $A + e^- \rightarrow e^- + \gamma$; the axio-electric effect - $A + e^- + Z \rightarrow e^- + Z$; the decay of axions into two photons - $A \rightarrow 2\gamma$; and inverse Primakoff conversion on nuclei - $A + Z \rightarrow Z + \gamma$, are considered. Model independent limits on axion-electron ($g_{Ae}$), axion-photon ($g_{A\gamma}$), and isovector axion-nucleon ($g_{3AN}$) couplings are obtained:

\[ |g_{Ae} \times g_{3AN}| \leq 5.5 \times 10^{13} \text{ and } |g_{A\gamma} \times g_{3AN}| \leq 4.6 \times 10^{11} \text{GeV}^{-1} \text{ at } m_A \leq 1 \text{ MeV (90% c.l.).} \]

13. Test of electron stability

A new limit on the stability of the electron for decay into a neutrino and a single monoenergetic photon $e \rightarrow \nu + \gamma$ was obtained [13]. This new bound, $\tau \geq 6.6 \times 10^{28} \, \text{yr}$ at 90% C.L., is two orders of magnitude better than the previous limit obtained with Borexino prototype CTF.

14. ACKNOWLEDGMENTS

The Borexino program is made possible by funding from INFN (Italy), NSF (USA), BMBF, DFG, and MPG (Germany), RFBR: Grants 15-02-02117 and 14-22-03031, RFBR-ASPERA-13-02-92440 (Russia), RSF: Grant 16-12-10369 (Russia), and NCN Poland (UMO-2012/06/M/ST2/00426). We acknowledge the generous support and hospitality of the Laboratori Nazionali del Gran Sasso (LNGS).

References

[1] G. Bellini et al. (Borexino Collaboration), Final results of Borexino phase-I on low-energy solar neutrino spectroscopy, Phys. Rev. D 89, 112007 (2014)
[2] H. Back et al. (Borexino Collaboration), Borexino calibrations: hardware, methods, and results. JINST7P10018 (2012)
[3] G. Bellini et al. (Borexino Collaboration), Precision measurement of the $^7$Be solar neutrino interaction rate in Borexino, Phys. Rev. Lett. 107, 141302 (2011)
[4] G. Bellini et al. (Borexino Collaboration), Absence of day-night asymmetry of 862 keV Be-7 solar neutrino rate in Borexino and MSW oscillation parameters, Phys. Lett. B 707, 22 (2012)

[5] G. Bellini et al. (Borexino Collaboration), Measurement of the solar 8B neutrino rate with a LS target and 3 MeV energy threshold in the Borexino detector, Phys. Rev. D82:033006 (2010)

[6] G. Bellini et al. (Borexino Collaboration), First evidence of pep solar neutrinos by direct detection in Borexino, Phys. Rev. Lett. 108, 051302 (2012)

[7] G. Bellini et al. (Borexino Collaboration), Neutrinos from the primary proton-proton fusion process in the Sun. Nature, 512:383386, (2014)

[8] C. Arpesella et al. (Borexino Collaboration), New results on solar neutrino fluxes from 192 days of Borexino data, Phys. Rev. Lett. 101:091302, (2008)

[9] M. Agostini et al. (Borexino Collaboration), Spectroscopy of geo-neutrinos from 2056 days of Borexino data, Phys. Rev. D 92, 031101 (2015)

[10] G. Bellini et al. (Borexino Collaboration), Study of solar and other unknown anti-neutrino fluxes with Borexino at LNGS, Phys. Lett. B 696, 191 (2011)

[11] G. Bellini et al. (Borexino Collaboration), New experimental limits on the Pauli forbidden transitions in 12C nuclei obtained with 485 days Borexino data, Phys. Rev. C81:034317 (2010)

[12] G. Bellini et al. (Borexino Collaboration), Search for Solar Axions Produced in p(d,3He)A Reaction with Borexino Detector, Phys. Rev. D 85, 092003 (2012)

[13] G. Bellini et al. (Borexino Collaboration), New limits on heavy sterile neutrino mixing in 8B-decay obtained with the Borexino detector, Phys. Rev. D 88, 072010 (2013)

[14] M. Agostini et al. (Borexino Collaboration), Test of Electric Charge Conservation with Borexino, Phys. Rev. Lett. 115, 231802 (2015)