New results on solar neutrino fluxes from 192 days of Borexino data

C. Arpesella,¹, ² H.O. Back,³, ⁴ M. Balata,¹ G. Bellini,² J. Benziger,⁴ S. Bonetti,² A. Brigatti,² B. Caccianiga,² L. Cadonati,⁵, ⁶ F. Calaprice,⁶ C. Carraro,⁷ G. Cecchet,⁸ A. Chavarria,⁶ M. Chen,⁹, ⁶ F. Dahmoki-Veress,⁶ D. D’Angelo,² A. de Bari,⁸ A. de Bellefon,¹⁰ H. de Kerret,¹⁰ A. Derbin,¹¹ M. Deutsch,¹² A. di Credico,¹ G. di Pietro,¹, ² R. Eisenstein,⁶ F. Elisei,¹³ A. Etenko,¹⁴ R. Fernholz,⁶ K. Fomenko,¹⁵ R. Ford,⁶, ¹³, ² D. Franco,² B. Freudiger,¹⁶ C. Galiadii,⁵, ² F. Gatti,³ S. Gazzana,¹ M. Giannarchi,² D. Giugni,² M. Goeger-Neff,¹⁷ T. Goldharnn,¹⁷ A. Goretii,², ¹ C. Grieb,³ C. Hagner,¹⁷ W. Hampel,¹⁶ E. Hardine,⁶ S. Hardy,³ F.X. Hartman,¹⁶ T. Hertrich,¹⁷ G. Heusser,¹₆ Aldo Ianni,¹, ² Andrea Ianni,⁶ M. Joyce,³ J. Kiko,¹⁶ T. Kirsten,¹⁶ V. Kobylev,¹⁸ G. Korga,¹ G. Korschinek,¹⁷ D. Krym,¹⁰ V. Lagomarso,⁷ P. Lamarche,¹, ⁶ M. Laubenstein,¹ L. Levdai,¹⁷ M. Leung,¹⁶ T. Lewke,¹⁷ E. Litvinovich,¹⁴ B. Loer,⁶ P. Lombardi,² L. Luddhova,² I. Machulin,¹⁴ S. Malvezzi,² S. Manecki,³ J. Maneira,⁹, ² W. Maneschg,¹⁶ I. Manno,¹⁹, ² D. Manuzio,⁷ G. Manuzio,⁷ A. Martemianov,¹⁴ F. Masetti,¹³ U. Mazzucato,¹³ K. McCarty,⁶ D. McKinsey,⁶ Q. Meindl,¹⁷ E. Meroni,² L. Miramonti,² M. Misiaszek,², ¹¹ D. Montanari,¹, ⁶ M.E. Monzani,³, ² V. Muratovala,¹¹ P. Musico,⁷ H. Neder,¹⁶ A. Nelson,⁶ L. Niedermeier,¹³ L. Oberauer,¹⁷ M. Obolensky,¹⁰ M. Orsini,¹ F. Ortica,¹³ M. Pallavicini,⁷ L. Papp,¹ S. Parmeggiano,² L. Perasso,² A. Pocar,⁶ B.S. Raghavan,³ G. Ranucci,² W. Rau,¹⁶ A. Razeto,¹ E. Resconi,⁷, ¹⁶ P. Risso,⁷ A. Romani,¹³ D. Routree,³ A. Sabelnikov,¹⁴ R. Saldanha,⁶ C. Salvo,⁷ D. Schimizzi,⁴ S. Schönert,¹⁶ T. Slott,⁶ H. Simgen,¹⁶ M. Skorokhvatov,¹⁴ O. Smirnov,¹⁵ A. Sonnenschein,⁶ A. Sotnikov,¹⁵ S. Sukhotin,¹⁴ Y. Suvorov,², ¹⁴ R. Tartaglia,¹ G. Testera,³ D. Vignaud,¹⁰ S. Vitale,⁷ R.B. Vogelaar,³ F. von Feilitzsch,¹⁷ R. von Hentig,¹⁷ T. von Hentig,¹⁷ M. Wojcik,¹⁰ M. Wurm,¹⁷ O. Zaimidoroga,¹⁵ S. Zavatarelli,⁷ and G. Zuzel¹⁶

(Borexino Collaboration)

¹INFN Laboratori Nazionali del Gran Sasso, SS 17 bis Km 18+910, 67010 Assergi (AQ), Italy
²Dipartimento di Fisica, Università degli Studi e INFN, 20133 Milano, Italy
³Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA
⁴Chemical Engineering Department, Princeton University, Princeton, NJ 08544, USA
⁵Physics Department, University of Massachusetts, Amherst, MA 01003, USA
⁶Physics Department, Princeton University, Princeton, NJ 08544, USA
⁷Dipartimento di Fisica, Università e INFN, Genova 16146, Italy
⁸INFN, Pavia 27100, Italy
⁹Physics Department, Queen’s University, Kingston ON K7L 3N6, Canada
¹⁰Laboratoire AstroParticule et Cosmologie, 75231 Paris cedex 13, France
¹¹St. Petersburg Nuclear Physics Institute, 188350 Gatchina, Russia
¹²Physics Department, Massachusetts Institute of Technology, Cambridge, MA, 02139 USA
¹³Dipartimento di Chimica, Università e INFN, 06123 Perugia, Italy
¹⁴RRC Kurchatov Institute, 123182 Moscow, Russia
¹⁵Joint Institute for Nuclear Research, 141980 Dubna, Russia
¹⁶Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany
¹⁷Physik Department, Technische Universität München, 85747 Garching, Germany
¹⁸Kiev Institute for Nuclear Research, 06380 Kiev, Ukraine
¹⁹KFKI-RMKI, 1121 Budapest, Hungary
²⁰M. Smoluchowski Institute of Physics, Jagiellonian University, 30059 Krakow, Poland

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We report the direct measurement of the ⁷Be solar neutrino signal rate performed with the Borexino detector at the Laboratori Nazionali del Gran Sasso. The interaction rate of the 0.862 MeV ⁷Be neutrinos is 49±3(stat)±4(syst) counts/(day·100 ton). The hypothesis of no oscillation for ⁷Be solar neutrinos is inconsistent with our measurement at the 4σ C.L.. Our result is the first direct measurement of the survival probability for solar νₑ in the transition region between matter-enhanced and vacuum-driven oscillations. The measurement improves the experimental determination of the flux of ⁷Be, pp, and CN0 solar νₑ, and the limit on the magnetic moment of neutrinos.

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Neutrino oscillations [¹] are the established mechanism to explain the solar neutrino problem, which originated from observations in radiochemical experiments with a sub-MeV threshold [², ³] and from real time observation of high energy neutrinos [⁴, ⁵]. Neutrino oscillations were also observed in atmospheric neutrinos [⁶] and have been confirmed with observation of reactor νₑ [⁶]. Borexino is the first experiment to report a real-time observation...
of low energy solar neutrinos below 4.5 MeV \[7\], which were not accessible so far with the state-of-the-art detector technologies because of natural radioactivity. In this Letter we report the direct measurement of the low energy (0.862 MeV) \(^{7}\)Be solar neutrinos with the Borexino detector from an analysis of 192 live days in the period from May 16, 2007 to April 12, 2008, totaling a 41.3 ton-yr fiducial exposure to solar neutrinos.

Solar neutrinos are detected in Borexino through their elastic scattering on electrons in the scintillator. Electron neutrinos (\(\nu_e\)) interact through charged and neutral currents and in the energy range of interest have a cross section \(~5\) times larger than \(\nu_\mu\) and \(\nu_\tau\), which interact only via the neutral current. The electrons scattered by neutrinos are detected by means of the scintillation light retaining the information on the energy, while information on the direction of the scattered electrons is lost. The basic signature for the mono-energetic 0.862 MeV \(^{7}\)Be neutrinos is the Compton-like edge of the recoil electrons at 665 keV.

The key features of the Borexino detector are described in Refs. \[7\] \[8\] \[9\]. Borexino is a scintillator detector with an active mass of 278 tons of pseudocumene (PC, 1,2,4-trimethylbenzene), doped with 1.5 g/liter of PPO (2,5-diphenyloxazole, a fluorescent dye). The scintillator is contained in a thin (125 \(\mu\)m) nylon vessel \[10\] and is surrounded by two concentric PC buffers (323 and 567 tons) doped with 5.0 g/l of dimethylphthalate (DMP), a component quenching the PC scintillation light. The two PC buffers are separated by a second thin nylon membrane to prevent diffusion of radon towards the scintillator. The scintillator and buffers are contained in a Stainless Steel Sphere (SSS) with diameter 13.7 m. The SSS is enclosed in a 18.0-m diameter, 16.9-m high domed Water Tank (WT), containing 2100 tons of ultrapure water as an additional shield. The scintillation light is detected via 2212 \(8^\prime\) PMTs uniformly distributed on the inner surface of the SSS \[11\] \[12\]. Additional 208 \(8^\prime\) PMTs instrument the WT and detect the Cherenkov light radiated by muons in the water shield, serving as a muon veto.

The key requirement in the technology of Borexino is achieving extremely low radioactive contamination, at or below the expected interaction rate of 0.5 counts/(day·ton) expected for \(^{7}\)Be neutrinos. The design of Borexino is based on the principle of graded shielding, with the inner core scintillator at the center of a set of concentric shells of increasing radiopurity. All components were screened and selected for low radioactivity \[13\], and the scintillator and the buffers were purified on site at the time of filling \[14\] \[15\]. Position reconstruction of the events, as obtained from the PMTs timing data via a time-of-flight algorithm, allows to fiducialize the active target: approximately 2/3 of the scintillator serves as an active shield.

Events are selected by means of the following cuts:

i Events must have a unique cluster of PMTs hits, to reject pile-up of multiple events in the same acquisition window.

ii Muons and all events within a time window of 2 ms after a muon are rejected.

iii Decays due to radon daughters occurring before the \(^{214}\)Bi-\(^{214}\)Po delayed coincidences are vetoed. The fraction surviving the veto is accounted for in the analysis.

iv Events must be reconstructed within a spherical fiducial volume corresponding approximately to 1/3 of the scintillator volume in order to reject external \(\gamma\) background. Additionally, we require the \(z\)-coordinate of the reconstructed vertex, measured from the center of the detector, to satisfy \(|z|<1.7\) m in order to remove background near the poles of the inner nylon vessel.

The combined loss of fiducial exposure due to the cuts i-iii is 0.7\%. The fiducial cut iv results in a fiducial mass of 78.5 tons.

The black curve in Fig. 1 is the spectrum of all events surviving the basic cuts i-iii: below 100 photoelectrons (pe) the spectrum is dominated by \(^{14}\)C decays (\(\beta^-, Q=156\) keV) intrinsic to the scintillator \[16\] and the peak at 200 pe is due to \(^{210}\)Po decays (\(\alpha, Q=5.41\) MeV, light yield quenched by \(~13\)), a daughter of \(^{222}\)Rn out of equilibrium with the other isotopes in the sequence. The blue curve is the spectrum after the fiducial cut iv. The red curve is obtained by statistical subtraction of the \(\alpha\)-emitting contaminants, by use of the pulse shape discrimination made possible by the PC-based scintillator \[17\]. Prominent features include the Compton-like edge due to \(^{7}\)Be solar neutrinos (300–350 pe) and the spectrum of \(^{11}\)C (\(\beta^+, Q=1.98\) MeV, created in situ by cosmic ray-induced showers, 400–800 pe).

The study of fast coincidence decays of \(^{214}\)Bi-\(^{214}\)Po (from \(^{238}\)U) and \(^{212}\)Bi-\(^{212}\)Po (from \(^{232}\)Th) yields, under the assumption of secular equilibrium, contamina-

![Figure 1](image-url)
tion for $^{238}$U of $(1.6\pm0.1)\times10^{-17}$ g/g and for $^{232}$Th of $(6.8\pm1.5)\times10^{-18}$ g/g. The $^{85}$Kr content in the scintillator was probed through the rare decay sequence $^{85}$Kr $\rightarrow ^{85m}$Rb$+\gamma$, $^{85m}$Rb $\rightarrow ^{85}$Rb$+\gamma$ ($\tau=1.5$ $\mu$s, BR 0.43%) that offers a delayed coincidence tag. Our best estimate for the activity of $^{85m}$Kr is $29\pm14$ counts/(day-100 ton).

We determined the light yield and the interaction rate of $^7$Be solar neutrinos by fitting the $\alpha$-subtracted spectrum in the region 100–800 pe, accounting for the presence of several possible contaminants. We obtain a light yield of about 500 pe/MeV for $^\beta$'s at the minimum of ionization, and the energy resolution is approximately scaling as 5%/\sqrt{E}$ [MeV]. The weights for $^{14}$C, $^{11}$C, and $^{85}$Kr are left as free parameters in the fit. The $^{214}$Pb surviving cut iii is independently determined and its weight in the fit is fixed. Weights for $pp$ and $pep$ neutrinos are fixed to the values expected from the Standard Solar Model (SSM) [18] and from a recent determination of $\sin^2 2\theta_{12}=0.87$ and $\Delta m^2_{12}=7.6\times10^{-5}$ eV$^2$ [8], which correspond to the Large Mixing Angle (LMA) scenario of solar neutrino oscillation via the MSW effect [19]. The spectra for CNO neutrinos and $^{210}$Bi are almost degenerate and cannot be distinguished prior to removal of the $^{11}$C background [20] [21]: we use a single component whose weight is a free parameter. Two independent analysis codes report consistent spectra and results, shown in Fig. 2 and summarized in Table I. A further check was performed by fitting the spectrum obtained prior to statistical $\alpha$’s subtraction, obtaining consistent results, as shown in Fig. 3.

Several sources, as summarized in Table II, contribute to the systematic error. The total mass of scintillator (315 m$^3$, 278 ton) is known within $\pm0.2\%$. Not so yet

### Table I: Fit Results [counts/(day-100 ton)].

|                 | Counts/(day x 100 tons) |
|-----------------|-------------------------|
| $^7$Be          | 49±3$_{\text{stat}}$    |
| $^{85}$Kr       | 25±3$_{\text{stat}}$    |
| $^{210}$Bi+CNO  | 23±2$_{\text{stat}}$    |
| $^{11}$C        | 25±1$_{\text{stat}}$    |

We estimate the systematic error to be $\pm6\%$ on the basis of the distribution of reconstructed vertexes of uniform background sources ($^{14}$C, 2.2 MeV $\gamma$-rays from capture of cosmogenic neutrons, daughters of Rn introduced during the filling with scintillator) and on the basis of the inner vessel radius determined from the reconstructed position of sources located at the periphery of the active volume ($^{212}$Bi-$^{212}$Po coincidences emanating from $^{228}$Th contaminations in the nylon of the inner vessel and $\gamma$-rays from the buffer volumes). The uncertainty in the detector response function results in a large systematic error, as small variations in the energy response affect the balance of counts attributed by the fit to $^7$Be and $^{85}$Kr. We aim at reducing substantially the global systematic uncertainty with the forthcoming deployment of calibration sources in the detector: this will allow a 3D mapping of the performance of position reconstruction algorithms and an in-depth study of the detector response function as a function of $\beta$- and $\gamma$-ray energies.

Taking into account systematic errors, our best value for the interaction rate of the 0.862 MeV $^7$Be solar neutrinos is $49\pm3_{\text{stat}}\pm4_{\text{syst}}$ counts/(day-100 ton). The expected signal for non-oscillated solar $\nu_e$ in the high metallicity SSM [18] is $74\pm4$ counts/(day-100 ton) corre-
responding to a flux $\Phi(^{7}{\text{Be}}) = (5.08 \pm 0.25) \times 10^{9}$ cm$^{-2}$ s$^{-1}$.
In the MSW-LMA scenario of solar neutrino oscillation, it is 48±4 counts/(day·100 ton), in very good agreement with our measurement.

Our best estimate for the $^{85}{\text{Kr}}$ contamination as determined by the fit is 25±3$_{\text{stat}}$±2$_{\text{syst}}$ counts/(day·100 ton). This is consistent with the independent estimate of $^{85}{\text{Kr}}$ activity from coincidence $^{85}{\text{Kr}}$.^{85m}{\text{Rb}}.$

Our best estimate for the cosmogenic $^{11}{\text{C}}$ activity induced by cosmic rays at Gran Sasso depth (3800 m.w.e., $E_{\nu}=$320 GeV $^{[25]}$) is 25±2$_{\text{stat}}$±2$_{\text{syst}}$ counts/(day·100 ton). This is 65% larger than extrapolated from activation on $\mu$ beams at the CERN NA54 facility $^{[20]}$ and 45% larger than calculated in Ref. $^{[24]}$.

A minimal extension of the Electroweak Standard Model with a massive neutrino allows a non zero magnetic moment, with the neutrino magnetic moment proportional to the neutrino mass $^{[24]}$. The experimental evidence from solar and reactor neutrinos has demonstrated that neutrinos are massive, and may thus possess a non-null magnetic moment. In the premises of Ref. $^{[25]}$, the lower limit for the magnetic moment is $4 \times 10^{-20} \mu_B$ $^{[27]}$. Larger values are possible in other extensions of the Standard Model $^{[28]}$.

In case of a non-null neutrino magnetic moment, the electroweak cross section:

$$\frac{d\sigma}{dT} = \frac{2G^2_F m_e}{\pi} \left[ g_L^2 + g_R^2 \left( 1 - \frac{T}{E_\nu} \right)^2 - g_L g_R \frac{m_T}{E_\nu} \right]$$

is modified by the addition of an electromagnetic term:

$$\frac{d\sigma}{dT}_{EM} = \mu^2 \pi \frac{\alpha_{em}}{m_e^2} \left( \frac{1}{T} - \frac{1}{E_\nu} \right)$$

where $E_\nu$ is the neutrino energy and $T$ is the electron kinetic energy. The shape of the solar neutrino spectrum is sensitive to the possible presence of a non-null magnetic moment, and the sensitivity is enhanced at low energy since $\left( \frac{d\sigma}{dT} \right)_{EM} \propto 1/T$. The SuperKamiokaNDE Collaboration achieved a limit of $1.1 \times 10^{-10} \mu_B$ (90% C.L.) using solar neutrino data above a 5-MeV threshold $^{[29]}$ $^{[30]}$. Ref. $^{[31]}$ presented a limit of $8.4 \times 10^{-11} \mu_B$ (90% C.L.) from the $^{7}$Be solar neutrino spectrum in Ref. $^{[7]}$. The best limit on magnetic moment from the study of reactor anti-neutrinos is $5.8 \times 10^{-11} \mu_B$ (90% C.L.) $^{[32]}$.

We had previously reported an upper limit of $5.5 \times 10^{-10}$ using data from the CTF $^{[33]}$. We now derive bounds on the neutrino magnetic moment by analyzing the $\alpha$-subtracted energy spectrum, obtaining an upper limit of $5.4 \times 10^{-11} \mu_B$ (90% C.L.) $^{[34]}$, which is currently the best experimental limit.

In the MSW-LMA scenario, neutrino oscillations are dominated by matter effects above 3 MeV and by vacuum effects below 0.5 MeV $^{[35]}$. The $^{7}$Be neutrinos lie in the lower edge of this transition region. The measured interaction rate of $^{7}$Be neutrinos depends on the solar $\nu_e$ flux and on the survival probability $P_{\nu_e}$ at the energy of 0.862 MeV. At present, the only direct measurement of $P_{\nu_e}$ is in the matter-dominated region by observation of $^{8}$B neutrinos above 5 MeV $^{[5]}$. The measurement of $P_{\nu_e}$ in and below the transition region is an important test of a fundamental feature of the MSW-LMA scenario.

Under the assumption of the constraint coming from the high metallicity SSM (6% uncertainty on $^{7}$Be neutrinos flux), we combine in quadrature systematic and statistical error and we obtain $P_{\nu_e} = 0.56\pm0.10$ (1\$\sigma$) at 0.862 MeV. This is consistent with $P_{\nu_e} = 0.54\pm0.017$, as determined from the global fit to all solar (except Borexino) and reactor data $^{[6]}$. The no oscillation hypothesis, $P_{\nu_e} = 1$, is rejected at 4\$\sigma$ C.L.

Prior to the Borexino measurement the best estimate for $f_{^{7}{\text{Be}}}$, the ratio between the measured value and the value predicted by the high metallicity SSM $^{[18]}$ for the $^{7}$Be neutrinos flux, was $1.03^{+0.24}_{-1.03}$ $^{[36]}$, as determined through a global fit on all solar (except Borexino) and reactor data, with the assumption of the constraint on solar luminosity. From our measurement, under the assumption of the constraint from the high metallicity SSM and of the MSW-LMA scenario, we obtain $f_{^{7}{\text{Be}}} = 1.02\pm0.10$. Correspondingly, our best estimate for the flux of $^{7}$Be neutrinos is $\Phi(^{7}{\text{Be}}) = (5.18\pm0.51) \times 10^{9}$ cm$^{-2}$ s$^{-1}$.

We then explore the constraint on the flux normalization constants $f_{pp}$ and $f_{CNO}$ - also defined as the ratio between the measured and predicted values of the respective fluxes - due to the measurement of the $^{7}$Be interaction rate reported in this Letter: the Borexino measured rate can be combined with the other solar neutrino measurements to constrain the flux normalization constants of the other fluxes $^{[37]}$. The expected rate $R_l$ in the Chlorine and Gallium experiments can be written as:

$$R_l = \sum_i R_{l,i} f_{P}^{i}\nu_{ee}$$

with $l = \{\text{Ga},\text{Cl}\}$, $i = \{\text{pp, pep, CNO, }^{7}\text{Be, }^{8}\text{B}\}$, $R_{l,i}$ the rate expected in experiment $l$ for source $i$ at the nominal SSM flux, and $f_{\nu_{ee}}^{i}$ the survival probability for the source $i$ above the threshold for experiment $l$. We use $R_{\text{Cl}} = 2.56\pm0.23$ SNU $^{[2]}$, $R_{\text{Ga}} = 68.1\pm3.75$ SNU $^{[3]}$, $f_{\text{B}} = 0.83\pm0.07$ $^{[5]}$, and $f_{\nu_{ee}} = 1.02\pm0.10$, as determined above.

We determine $f_{pp} = 1.04^{+0.13}_{-0.19}$ (1\$\sigma$) and $f_{CNO} < 6.27$ (90% C.L.) by using the 1-D $\chi^2$-profile method $^{[38]}$. The result on $f_{pp}$ represents the best experimental value at present obtained without the
same hypothesis, we obtain $f_{\text{CNO}}$ when adding the luminosity constraint. Under the contribution on the order of 0.9%.

The result on $f_{\text{CNO}}$ translates into a CNO contribution to the solar luminosity <5.4% (90% C.L.) which is also at present the best limit. We remark that the SSM we use predicts a CNO luminosity constraint. The result on $f_{\text{CNO}}$ represents the best determination of the $pp$ solar neutrinos flux obtained with the assumption of the luminosity constraint. The result on $f_{\text{CNO}}$ translates into a CNO contribution to the solar neutrino luminosity <3.3% (90% C.L.).

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4. Determination of flux normalization constants for $pp$ and CNO solar neutrinos, $f_{pp}$ and $f_{\text{CNO}}$ (68%, 90%, and 99% C.L.).

The result on $f_{\text{CNO}}$ translates into a CNO contribution to the solar luminosity constraint. The result on $f_{\text{CNO}}$ represents the best determination of the $pp$ solar neutrinos flux obtained with the assumption of the luminosity constraint. The result on $f_{\text{CNO}}$ translates into a CNO contribution to the solar neutrino luminosity <3.3% (90% C.L.).
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