Direct Measurement of the ^{7}Be Solar Neutrino Flux with 192 Days of Borexino Data

C. Arpesella,[1,2,a] H. O. Back,[3,b] 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. Dalnoki-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] 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,[6,1,c] D. Franco,[2] B. Freudiger,[16,a] C. Galbiati,[6,2] F. Gatti,[7] S. Gazzana,[1] M. Giammarchi,[2] D. Giugni,[2] M. Goeger-Neff,[17] T. Goldbrunner,[17,d] A. Goretti,[6,2,1] C. Grieb,[3,17,e] C. Hagner,[17,f] W. Hampel,[16] E. Harding,[6,g] S. Hardy,[3] F. X. Hartman,[16] T. Hertrich,[17] G. Heusser,[16] Aldo Ianni,[1,6] Andrea Ianni,[6] M. Joyce,[3] J. Kiko,[16] T. Kirsten,[16] V. Kobychev,[18] G. Korga,[1] G. Korschinek,[17] D. Kryn,[10] V. Lagomarsino,[7] P. Lamarche,[6,1] M. Laubenstein,[1] C. Lendvai,[17] M. Leung,[6] T. Lewke,[17] E. Litvinovich,[14] B. Loer,[6] P. Lombardi,[2] L. Ludhova,[2] I. Machulin,[14] S. Malvezzi,[2] S. Manecki,[3] J. Maneira,[9,2,h] W. Maneschg,[16] I. Manno,[19,2] D. Manuzio,[7,i] G. Manuzio,[7] A. Martemianov,[14,a] F. Masetti,[13] U. Mazzucato,[13] K. McCarty,[6] D. McKinsey,[6,j] Q. Meindl,[17] E. Meroni,[2] L. Miramonti,[2] M. Misiaszek,[20,1] D. Montanari,[1,6] M. E. Monzani,[1,2] V. Muratova,[11] P. Musico,[7] H. Neder,[16] A. Nelson,[6] L. Niedermeier,[17] 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,k] R. S. Raghavan,[3] G. Ranucci,[2] W. Rau,[16,9] A. Razeto,[1] E. Resconi,[7,16] P. Risso,[7] A. Romani,[13] D. Rountree,[3] A. Sabelnikov,[14] R. Saldanha,[6] C. Salvo,[7] D. Schimizzi,[4] S. Schönert,[16] T. Shutt,[6,l] H. Simgen,[16] M. Skorokhvatov,[14] O. Smirnov,[15] A. Sonnenschein,[6,m] A. Sotnikov,[15] S. Sukhotin,[14] Y. Suvorov,[2,14] R. Tartaglia,[1] G. Testera,[7] D. Vignaud,[10] S. Vitale,[7,a] R. B. Vogelaar,[3] F. von Feilitzsch,[17] R. von Hentig,[17,e] T. von Hentig,[17,e] M. Wojcik,[20] M. Wurm,[17] O. Zaimidoroga,[15] S. Zavatarelli,[7] and G. Zuzel[16]

(Borexino Collaboration)

[1]*INFN Laboratori Nazionali del Gran Sasso, SS 17 bis Km 18+910, 67010 Assergi (AQ), Italy*
[2]*Dipartimento di Fisica, Università degli Studi e INFN, 20133 Milano, Italy*
[3]*Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, USA*
[4]*Chemical Engineering Department, Princeton University, Princeton, New Jersey 08544, USA*
[5]*Physics Department, University of Massachusetts, Amherst, Massachusetts 10003, USA*
[6]*Physics Department, Princeton University, Princeton, New Jersey 08544, USA*
[7]*Dipartimento di Fisica, Università e INFN, 16146 Genova, Italy*
[8]*INFN, 27100 Pavia, Italy*
[9]*Physics Department, Queen's University, Kingston, Ontario K7L 3N6, Canada*
[10]*Laboratoire AstroParticule et Cosmologie, 75231 Paris cedex 13, France*
[11]*St. Petersburg Nuclear Physics Institute, 188350 Gatchina, Russia*
[12]*Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[13]*Dipartimento di Chimica, Università e INFN, 06123 Perugia, Italy*
[14]*RRC Kurchatov Institute, 123182 Moscow, Russia*
[15]*Joint Institute for Nuclear Research, 141980 Dubna, Russia*
[16]*Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany*
[17]*Physik Department, Technische Universität Muenchen, 85747 Garching, Germany*
[18]*Kiev Institute for Nuclear Research, 06380 Kiev, Ukraine*
[19]*KFKI-RMKI, 1121 Budapest, Hungary*
[20]*M. Smoluchowski Institute of Physics, Jagiellonian University, 30059 Krakow, Poland*
(Received 9 June 2008; published 29 August 2008)

We report the direct measurement of the ^{7}Be solar neutrino signal rate performed with the Borexino detector at the Laboratori Nazionali del Gran Sasso. The interaction rate of the 0.862 MeV ^{7}Be neutrinos is $49 \pm 3_{\rm stat} \pm 4_{\rm syst}$ counts/(day · 100 ton). The hypothesis of no oscillation for ^{7}Be 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 ν_e in the transition region between matter-enhanced and vacuum-driven oscillations. The measurement improves the experimental determination of the flux of ^{7}Be, pp, and CNO solar ν_e, and the limit on the effective neutrino magnetic moment using solar neutrinos.

DOI: 10.1103/PhysRevLett.101.091302 PACS numbers: 26.65.+t, 13.35.Hb, 14.60.Pq, 95.55.Vj

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 [4] and have been confirmed with observation of reactor $\bar{\nu}_e$ [6] and accelerator neutrinos [7,8]. Borexino is the first experiment to report a real-time observation of low energy solar neutrinos below 4.5 MeV [9], 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 16 May, 2007 to 12 April, 2008, totaling a 41.3 ton $\cdot$ yr fiducial exposure to solar neutrinos.

Solar neutrinos are detected in Borexino through their elastic scattering on electrons in the scintillator. Electron neutrinos (ν_e) interact through charged and neutral currents and in the energy range of interest have a cross section $\sim$5 times larger than ν_μ and ν_τ, 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 monoenergetic 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. [9–11]. 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 μm) nylon vessel [12] and is surrounded by two concentric PC buffers (323 and 567 tons) doped with 5.0 g/l of dimethylphthalate, 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'' PMTs uniformly distributed on the inner surface of the SSS [13,14]. Additional 208 8'' 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 interaction rate of 0.5 counts/(day $\cdot$ 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 [15], and the scintillator and the buffers were purified on site at the time of filling [16,17]. 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 time cluster of PMTs hits, to reject pileup 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 γ background. Additionally, we require the z coordinate of the reconstructed vertex, measured from the center of the detector in the vertical direction, 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 (β^-, $Q =$ 156 keV) intrinsic to the scintillator [18] and the peak at 200 pe is due to ^{210}Po decays (α, $Q = 5.41$ MeV, light yield quenched by $\sim$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 α-emitting contaminants, by use of the pulse shape discrimination made possible by the PC-based scintillator [19]. Prominent features include the Compton-like edge

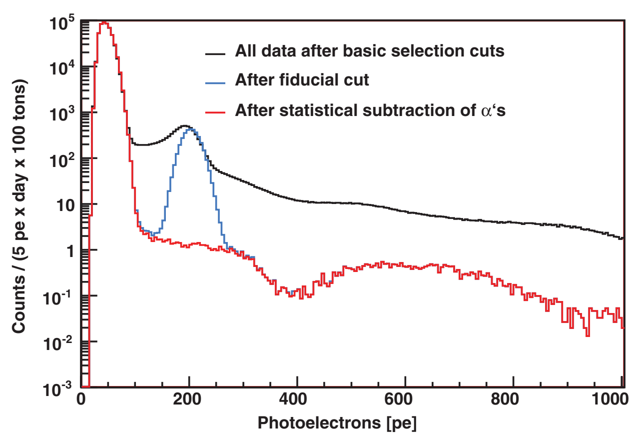

FIG. 1 (color). The raw photoelectron charge spectrum after the basic cuts (i)–(iii) (black), after the fiducial cut (iv) (blue), and after the statistical subtraction of the α-emitting contaminants (red). All curves scaled to the exposure of 100 day $\cdot$ ton. Cuts described in the text.

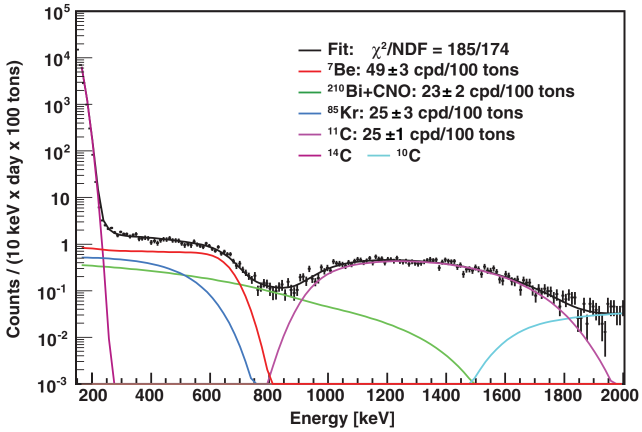

FIG. 2 (color). Spectral fit in the energy region 160–2000 keV. Contributions from ^{214}Pb, pp, and pep neutrinos, not shown, are almost negligible with respect to those in the figure.

due to ^{7}Be solar neutrinos (300–350 pe) and the spectrum of ^{11}C (β^{+}, $Q = 1.98$ MeV, created *in situ* by cosmic ray-induced showers, 400–800 pe).

The study of fast coincidence decays of $^{214}\mathrm{Bi} - {}^{214}\mathrm{Po}$ (from ^{238}U) and $^{212}\mathrm{Bi} - {}^{212}\mathrm{Po}$ (from ^{232}Th) yields, under the assumption of secular equilibrium, contamination for ^{238}U of $(1.6 \pm 0.1) \times 10^{-17}$ g/g and for ^{232}Th of $(6.8 \pm 1.5) \times 10^{-18}$ g/g. The ^{85}Kr content in the scintillator was probed through the rare decay sequence $^{85}\mathrm{Kr} \rightarrow {}^{85\mathrm{m}}\mathrm{Rb} + e^{+} + \nu_e$, $^{85\mathrm{m}}\mathrm{Rb} \rightarrow {}^{85}\mathrm{Rb} + \gamma$ ($\tau = 1.5$ μs, BR 0.43%) that offers a delayed coincidence tag. Our best estimate for the activity of ^{85}Kr is 29 ± 14 counts/(day · 100 ton).

We determined the light yield and the interaction rate of ^{7}Be solar neutrinos by fitting the α-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 β's at the minimum of ionization, and the energy resolution is approximately scaling as $5\%/\sqrt{E[\mathrm{MeV}]}$. 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) [20] and from a recent determination of $\sin^2 2\theta_{12} = 0.87$ and $\Delta m^2_{12} = 7.6 \times 10^{-5}$ eV^2 [6], which correspond to the large mixing angle (LMA) scenario of solar neutrino oscillation via the Mikheyev-Smirnov-Wolfenstein (MSW) effect [21]. The spectra for CNO neutrinos and ^{210}Bi are almost degenerate and cannot be distinguished prior to removal of the ^{11}C background [22,23]: 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 α's subtraction, obtaining consistent results, as shown in Fig. 3.

TABLE I. Fit results [counts/(day · 100 ton)].

^{7}Be	$49 \pm 3_{\mathrm{stat}} \pm 4_{\mathrm{syst}}$
^{85}Kr	$25 \pm 3_{\mathrm{stat}} \pm 2_{\mathrm{syst}}$
^{210}Bi + CNO	$23 \pm 2_{\mathrm{stat}} \pm 2_{\mathrm{syst}}$
^{11}C	$25 \pm 1_{\mathrm{stat}} \pm 2_{\mathrm{syst}}$

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 $\pm 0.2\%$. Not so yet for the fiducial mass, which is defined by a software cut. We estimate the systematic error to be $\pm 6\%$ on the basis of the distribution of reconstructed vertices of uniform background sources (^{14}C, 2.2 MeV γ-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 ($^{212}\mathrm{Bi} - {}^{212}\mathrm{Po}$ coincidences emanating from ^{228}Th contaminations in the nylon of the inner vessel and γ-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 β- and γ-ray energies.

Taking into account systematic errors, our best value for the interaction rate of the 0.862 MeV ^{7}Be solar neutrinos is $49 \pm 3_{\mathrm{stat}} \pm 4_{\mathrm{syst}}$ counts/(day · 100 ton). The expected signal for nonoscillated solar ν_e in the high metallicity SSM [20] is 74 ± 4 counts/(day · 100 ton) corresponding to a flux $\Phi(^{7}\mathrm{Be}) = (5.08 \pm 0.25) \times 10^{9}$ cm^{-2} s^{-1}. (We remark that in the absence of a resolution between the

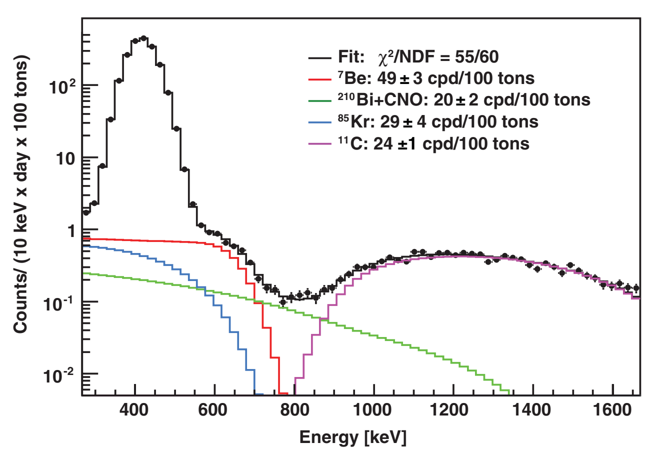

FIG. 3 (color). Spectral fit in the energy region 260–1670 keV prior to statistical α's subtraction.

TABLE II. Estimated systematic uncertainties [%].

Total scintillator mass	0.2
Fiducial mass ratio	6.0
Live time	0.1
Detector response function	6.0
Efficiency of cuts	0.3
Total systematic error	8.5

high-Z abundances reported by Grevesse and Sauval [24] and by Asplund, Grevesse, and Sauval [25], for the purpose of comparison with the SSM, we arbitrarily choose as a reference the latest SSM based on the high-Z abundances reported in Ref. [24]. We remark that the current results from Borexino do not help in solving this important controversy. See Ref. [26] for additional information.) In the MSW-LMA scenario of solar neutrino oscillation, the expected ^{7}Be signal is 48 ± 4 counts/(day $\cdot$ 100 ton), in very good agreement with our measurement.

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

Our best estimate for the cosmogenic ^{11}C activity induced by cosmic rays at Gran Sasso depth (3800 m.w.e., $\bar{E}_\mu = 320$ GeV [27]) is $25 \pm 1_{\rm stat} \pm 2_{\rm syst}$ counts/(day $\cdot$ 100 ton). This is 65% larger than extrapolated from activation on μ beams at the CERN NA54 facility [22] and 45% larger than calculated in Ref. [23].

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 [28]. 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. [28], the lower limit for the magnetic moment is $4 \times 10^{-20}\mu_B$ [29]. Larger values are possible in other extensions of the standard model [30].

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

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

is modified by the addition of an electromagnetic term:

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

where E_ν 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 $(d\sigma/dT)_{\rm EM} \propto 1/T$. The coupling of neutrinos to an electromagnetic field due a neutrino magnetic moment is characterized by a 3×3 matrix. Dirac neutrinos can have both diagonal and off-diagonal (transition) moments; Majorana neutrinos can have only transition moments. The magnetic moment is a combination of matrix elements and depends on the neutrino flavor. In case of measurements performed with solar neutrinos, the magnetic moment in Eq. (2) is an effective quantity which depends on the actual flavor (composition of the physical eigenstates) of the (oscillated) neutrino when scattering inside the detector, after propagation from Sun to Earth. Bounds on the neutrino magnetic moment obtained by using reactor antineutrinos on a short baseline, place a direct limit on the magnetic moment for electron neutrinos.

The Super-KamiokaNDE Collaboration achieved a limit of $1.1 \times 10^{-10}\mu_B$ (90% C.L.) using solar neutrino data above a 5-MeV threshold [31,32]. Reference [33] presented a limit of $8.4 \times 10^{-11}\mu_B$(90% C.L.) from the ^{7}Be solar neutrino spectrum in Ref. [9]. The best limit on magnetic moment from the study of reactor antineutrinos is $5.8 \times 10^{-11}\mu_B$ (90% C.L.) [34].

We had previously reported an upper limit of 5.5×10^{-10} using data from the CTF [35]. We now derive bounds on the neutrino magnetic moment by analyzing the α-subtracted energy spectrum, obtaining an upper limit of $5.4 \times 10^{-11}\mu_B$ (90% C.L.) [36], 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 [37]. 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 ν_e flux and on the survival probability P_{ee} at the energy of 0.862 MeV. At present, the only direct measurement of P_{ee} is in the matter-dominated region by observation of ^{8}B neutrinos above 5 MeV [5]. The measurement of P_{ee} 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 $P_{ee} = 0.56 \pm 0.10$ (1σ) at 0.862 MeV. This is consistent with $P_{ee} = 0.541 \pm 0.017$, as determined from the global fit to all solar (except Borexino) and reactor data [6]. The no oscillation hypothesis, $P_{ee} = 1$, is rejected at 4σ C.L.

Prior to the Borexino measurement the best estimate for $f_{\rm Be}$, the ratio between the measured value and the value predicted by the high metallicity SSM [20] for the ^{7}Be neutrinos flux, was $1.03^{+0.24}_{-1.03}$ [38], 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 $f_{\rm Be} = 1.02 \pm 0.10$. Correspondingly, our best estimate for the flux of ^{7}Be neutrinos is $\Phi(^7{\rm Be}) = (5.18 \pm 0.51) \times 10^9$ cm^{-2} s^{-1}.

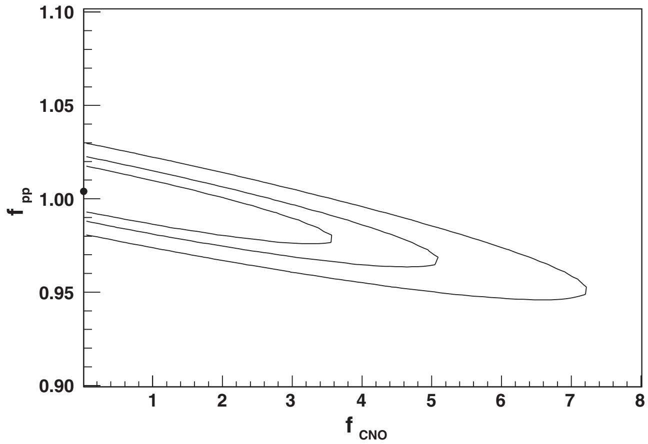

FIG. 4. Determination of flux normalization constants for pp and CNO solar neutrinos, f_{pp} and f_{CNO} (68%, 90%, and 99% C.L.).

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 result of Borexino can be combined with the other solar neutrino measurements to constrain the flux normalization constants of the other fluxes [39]. The expected rate R_l in the chlorine and gallium experiments can be written as

$$R_l = \sum_i R_{l,i} f_i P_{ee}^{l,i}, \tag{3}$$

with $l = \{\mathrm{Ga}, \mathrm{Cl}\}$, $i = \{pp, pep, \mathrm{CNO}, {}^7\mathrm{Be}, {}^8\mathrm{B}\}$, $R_{l,i}$ the rate expected in experiment l for source i at the nominal SSM flux, and $P_{ee}^{l,i}$ the survival probability for the source i above the threshold for experiment l. We use $R_{\mathrm{Cl}} = 2.56 \pm 0.23$ SNU [2], $R_{\mathrm{Ga}} = 68.1 \pm 3.75$ SNU [3], $f_{\mathrm{B}} = 0.83 \pm 0.07$ [5], and $f_{\mathrm{Be}} = 1.02 \pm 0.10$, as determined above.

We determine $f_{pp} = 1.04^{+0.13}_{-0.19}$ (1σ) and $f_{\mathrm{CNO}} < 6.27$ (90% C.L.) by using the 1D χ^2-profile method [40]. The result on f_{pp} represents the best experimental value at present obtained without the luminosity constraint. The result on f_{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 contribution on the order of 0.9%.

Figure 4 shows the 2D correlation of f_{pp} and f_{CNO} when adding the luminosity constraint. Under the same hypothesis, we obtain $f_{pp} = 1.005^{+0.008}_{-0.020}$ (1σ) and $f_{\mathrm{CNO}} < 3.80$ (90% C.L.) by using the 1D χ^2-profile method. This result on f_{pp} represents the best determination of the pp solar neutrinos flux obtained with the assumption of the luminosity constraint. The result on f_{CNO} translates into a CNO contribution to the solar neutrino luminosity <3.3% (90% C.L.).

The Borexino program was made possible by funding from INFN (Italy), NSF (U.S.), BMBF, DFG and MPG (Germany), Rosnauka (Russia), and MNiSW (Poland). We acknowledge the generous support of the Laboratori Nazionali del Gran Sasso (LNGS). This work has been supported by the ILIAS integrating activity (Contract No. RII3-CT-2004-506222) as part of the EU FP6 programme. O. Smirnov aknowledges the support of Fondazione Cariplo.

[a]Deceased.
[b]Present address: North Carolina State University, Raleigh, NC, USA.
[c]Present address: SNOLab, Sudbury, ON, Canada.
[d]Present address: Booz & Company, Münich, Germany.
[e]Present address: European Patent Office, Münich, Germany.
[f]Present address: Universität Hamburg, Hamburg, Germany.
[g]Present address: Lockheed Martin Space Systems Company, Sunnyvale, CA, USA.
[h]Present address: Laboratório de Instrumentacão e Física Experimental de Partícula, Lisboa, Portugal.
[i]Present address: Carestream Health Technology and Innovation Center, Genova, Italy.
[j]Present address: Yale University, New Haven, CT, USA.
[k]Present address: Stanford University, Stanford, CA, USA.
[l]Present address: Case Western Reserve University, Cleveland, OH, USA.
[m]Present address: Fermi National Accelerator Laboratory, Batavia, IL, USA.

[1] V. Gribov and B. Pontecorvo, Phys. Lett. B **28**, 493 (1969); J. N. Bahcall and R. Davis, Science **191**, 264 (1976); J. N. Bahcall, *Neutrino Astrophysics* (Cambridge University Press, Cambridge, U.K., 1989); Astrophys. J. **467**, 475 (1996).
[2] B. T. Cleveland *et al.*, Astrophys. J. **496**, 505 (1998); K. Lande and P. Wildenhain, Nucl. Phys. B, Proc. Suppl. **118**, 49 (2003); R. Davis, Nobel Prize in Physics in 2002.
[3] W. Hampel *et al.* (GALLEX Collaboration), Phys. Lett. B **447**, 127 (1999); J. N. Abdurashitov *et al.* (SAGE Collaboration), Phys. Rev. Lett. **83**, 4686 (1999); M. Altmann *et al.* (GNO Collaboration), Phys. Lett. B **616**, 174 (2005).
[4] K. S. Hirata *et al.* (KamiokaNDE Collaboration), Phys. Rev. Lett. **63**, 16 (1989); Y. Fukuda *et al.* (Super-Kamiokande Collaboration), Phys. Rev. Lett. **81**, 1562 (1998); J. P. Cravens *et al.* (SuperKamiokaNDE Collaboration), arXiv:0803.4312v1 [Phys. Rev. D (to be published)].
[5] Q. R. Ahmad *et al.* (SNO Collaboration), Phys. Rev. Lett. **87**, 071301 (2001); B. Aharmim *et al.* (SNO Collaboration), Phys. Rev. C **75**, 045502 (2007).
[6] S. Abe *et al.* (KamLAND Collaboration), Phys. Rev. Lett. **100**, 221803 (2008).
[7] M. H. Ahn *et al.* (K2K Collaboration), Phys. Rev. D **74**, 072003 (2006).

[8] P. Adamson *et al.* (MINOS Collaboration) arXiv:0806.2237 [Phys. Rev. Lett. (to be published)].
[9] C. Arpesella *et al.* (Borexino Collaboration), Phys. Lett. B **658**, 101 (2008).
[10] G. Alimonti *et al.* (Borexino Collaboration), Astropart. Phys. **16**, 205 (2002).
[11] G. Alimonti *et al.* (Borexino Collaboration), arXiv:0806.2400v1.
[12] J. Benziger *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **582**, 509 (2007).
[13] A. Ianni *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **537**, 683 (2005); A. Brigatti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **537**, 521 (2005).
[14] L. Oberauer *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **530**, 453 (2004).
[15] C. Arpesella *et al.* (Borexino Collaboration), Astropart. Phys. **18**, 1 (2002).
[16] J. Benziger *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **587**, 277 (2008).
[17] H. Simgen and G. Zuzel, in *Topical Workshop on Low Radioactivity Techniques: LRT 2006, Aussois, France*, edited by P. Loaiza, AIP Conference Proceedings No. 897 (AIP, New York, 2007), pp. 45–50.
[18] G. Alimonti *et al.* (Borexino Collaboration), Phys. Lett. B **422**, 349 (1998).
[19] H. O. Back *et al.* (Borexino Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **584**, 98 (2008).
[20] J. N. Bahcall, A. M. Serenelli, and S. Basu, Astrophys. J. Suppl. Ser. **165**, 400 (2006); C. Peña-Garay, in *Proceedings of the XII International Workshop on Neutrino Telescopes, Venice, 2007*, neutrino.pd.infn.it/conference2007/; A. Serenelli (private communication).
[21] S. P. Mikheyev and A. Yu. Smirnov, Sov. J. Nucl. Phys. **42**, 913 (1985); L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978); P.C. de Holanda and A. Yu. Smirnov, J. Cosmol. Astropart. Phys. 02 (2003) 001.
[22] T. Hagner *et al.*, Astropart. Phys. **14**, 33 (2000); H. Back *et al.* (Borexino Collaboration), Phys. Rev. C **74**, 045805 (2006).
[23] C. Galbiati *et al.*, Phys. Rev. C **71**, 055805 (2005).
[24] N. Grevesse and A. J. Sauval, Space Sci. Rev. **85**, 161 (1998).
[25] M. Asplund, N. Grevesse, and A. J. Sauval, in *Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis*, edited by T. G. Barnes III and F. N. Bash, ASP Conf. Ser. 336 (ASP, San Francisco, 2004).
[26] J. N. Bahcall, S. Basu, and A. M. Serenelli, Astrophys. J. **631**, 1281 (2005).
[27] M. Ambrosio *et al.* (MACRO Collaboration), Astropart. Phys. **10**, 11 (1999).
[28] W. J. Marciano and A. I. Sanda, Phys. Lett. B **67**, 303 (1977); B. W. Lee and R. E. Shrock, Phys. Rev. D **16**, 1444 (1977); K. Fujikawa and R. E. Shrock, Phys. Rev. Lett. **45**, 963 (1980).
[29] A. B. Balantekin, arXiv:hep-ph/0601113v1.
[30] H. Georgi and L. Randall, Phys. Lett. B **244**, 196 (1990); N. F. Bell, V. Cirigliano, M. J. Ramsey-Musolf, P. Vogel, and M. B. Wise, Phys. Rev. Lett. **95**, 151802 (2005).
[31] J. F. Beacom and P. Vogel, Phys. Rev. Lett. **83**, 5222 (1999).
[32] D. W. Liu *et al.* (Super-KamiokaNDE Collaboration), Phys. Rev. Lett. **93**, 021802 (2004).
[33] D. Montanino, M. Picariello, and J. Pulido, Phys. Rev. D **77**, 093011 (2008).
[34] A. G. Beda *et al.*, arXiv:0705.4576.
[35] H. O. Back *et al.* (Borexino Collaboration), Phys. Lett. B **563**, 35 (2003).
[36] Borexino Collaboration (unpublished).
[37] A. Yu. Smirnov, arXiv:hep-ph/0305106v1; A. Friedland, C. Lunardini, and C. Peña-Garay, Phys. Lett. B **594**, 347 (2004).
[38] M. C. Gonzalez-Garcia and M. Maltoni, Phys. Rep. **460**, 1 (2008).
[39] We acknowledge an analysis aimed to determine f_{CNO} from the first Borexino results performed by F. Villante, B. Ricci, and collaborators. See F. Mancini, Diploma thesis, University of Ferrara, 2007.
[40] W.-M. Yao *et al.*, J. Phys. G **33**, 306 (2006).