Solar neutrino results from Borexino and main future perspectives

Marco Pallavicini

Dipartimento di Fisica, Università di Genova e INFN
Genova, via Dodecaneso, 33 - I-16146, Italy
E-mail: marco.pallavicini@ge.infn.it

on behalf of the Borexino Collaboration

G. Bellini1, J. Benziger2, S. Bonetti2, M. Buizza Avanzini3, B. Cacciapuoti4, L. Cadonati5, F. Calaprice1, C. Caram4, A. Chavarria6, F. Dalnoki-Veress7, D. D’Angelo8, H. de Kerf9, S. Davini6, A. Derbir10, A. Etenko11, K. Fomenko12, D. Franco13, C. Galliari14, S. Gazzana15, M. Giammarchi16, M. Goeger-Neff17, A. Goretta18, C. Grieb19, E. Guardincerri1, S. Hardy20, Aldo Ianni21, Andrea Ianni21, M. Joyce22, V. Kobyrchen23, G. Korgo24, D. Kryl25, M. Laubenheim26, M. Leung26, T. Lewke27, E. Litvinovich1, B. Loer28, P. Lombardi29, L. Ludhova30, I. Machalíř28, S. Manekč31, W. Maneschg32, G. Manuzio33, F. Masetti34, K. McCarty35, Q. Mei46, E. Meroni36, L. Misani1, M. Misiazek37, D. Montanari38, V. Muratori39, L. Oberauer40, M. Obenshain41, F. Ottico42, M. Pallavicini43, L. Papetti44, L. Perasso45, S. Persat3, A. Pocar46, R.S. Raghuvar47, G. Ranucci1, O. Raza35, P. Risso48, A. Roman45, D. Rountree35, A. Sabelnikov2, R. Saldanha29, C. Salvat49, S. Schoner4, H. Simgen50, M. Skorokhvatov51, O. Smirnov51, A. Sotnikov51, S. Sukhotin51, Y. Suvorov51, R. Tartaglia52, D. Vignaud53, R.B. Vogelaar54, F. von Feilitzsch1, M. Wojcik55, M. Warm56, O. Zaimidoroga57, S. Zavatattrell38, G. Zuzel58

1INFN, Laboratori Nazionali del Gran Sasso – Assergi – Italy
2Dipartimento di Fisica dell’Università degli Studi e INFN – Milano – Italy
3Princeton University, Chemical Engineering Department – Princeton, NJ – USA
4Princeton University, Physics Department – Princeton, NJ – USA
5RRC Kurchatov Institute – Moscow – Russia
6Laboratoire AstroParticule et Cosmologie APC – Paris – France
7St. Petersburg Nuclear Physics Institute – Gatchina – Russia
8Massachusetts Institute of Technology, Department of Physics – Cambridge, MA – USA
9Joint Institute for Nuclear Research – Dubna – Russia
10Technische Universität Muenchen – Garching – Germany
11Virginia Tech, Physics Department – Blacksburg, VA – USA
12Dipartimento di Fisica dell’Università e INFN – Genova – Italy
13Dipartimento di Chimica dell’Università e INFN – Pavia – Italy
14Wrocław University
15Max-Planck-Institut für Kernphysik – Heidelberg – Germany
16University of Massachusetts, Amherst, AM01003, USA

Abstract

Borexino is a solar neutrino experiment running at the Laboratori Nazionali del Gran Sasso, Italy. The radioactive background levels in the liquid scintillator target are low enough to achieve design goals, opening unanticipated opportunities. The main results, so far, are the measurement of the $^7$Be solar neutrino flux (the first ever done) and the measurement of the $^8$B neutrino flux performed with electron energy threshold of 2.8 MeV. The short and medium term perspectives are summarized in the conclusions.

Key words: Solar Neutrinos; Neutrino Oscillations; Low Background Detectors; Liquid Scintillators.

1. Introduction

Borexino [1] detects solar neutrinos via their elastic scattering on the electrons of an ultra-pure liquid scintillator target. The main physics goal is the measurement of the flux and of the energy spectrum of solar neutrinos with sub-MeV or few MeV energy. Other goals include geoneutrinos detection, super-nova neutrinos detection and the search for very rare decays [2, 3, 4, 5].

Flavor oscillations of solar neutrinos with MSW effect [6] have been well established by radiochemical experiments [7] and by water Cerenkov detectors [8]. The range of the parameters describing the oscillation phenomenon has been constrained by SNO and KamiKande [8] to lie in the so called LMA (Large Mixing Angle) region of the plane $\theta_{12} \cdot \Delta m_{12}^2$ ($\tan^2(2\theta_{12}) = 0.47^{+0.06}_{-0.05}$ and $\Delta m_{12}^2 = 7.59^{+0.21}_{-0.21} \cdot 10^{-5} \text{eV}^2$).

The main prediction of the LMA-MSW are the energy dependence of the neutrino survival probability $P_{ee}$ and the lack of day-night asymmetry. The $P_{ee}$ decreases with increasing energy. Matter effects dominate at energies above 3 MeV while are absent below 1 MeV. The region in between is called the transition region. While the LMA-MSW predicts a well defined shape for the $P_{ee}$ function in the transition region, current
experimental data do not constraint it at all, and some theoretical models, including non standard interactions, predict survival probability curves with different shape \[\text{[11]}.\]

Borexino is presently the only running experiment that measured the signal rate due to the 0.862 MeV $^7$Be neutrinos \[\text{[12][13]}\] and the one due to $^8B$ \[\text{[14]}\] with a energy threshold (2.8 MeV), lower than any previous experiment. Besides, a measurement of a null day night difference of the $^7$Be flux provides a further new confirmation of the LMA-MSW solution.

Interest of this measurement is also related to the possibility to accommodate quite large effects in some alternative oscillation scenario based on the mass varying model \[\text{[17]}\].

The neutrino interaction rate measured by Borexino depends on the solar neutrino flux and on the oscillation parameters. A scientific debate about high and low metallicity solar models and the related flux calculations \[\text{[16]}\] is in progress. The relevance of the measurements of the various components of the solar neutrino measurements in Borexino is then twofold: from one side they can increase the confidence in the oscillation scenario and from the other side, assuming the knowledge of the oscillation parameters, they provide a measurement of the absolute solar neutrino flux. The precision of the actual data about solar neutrinos does not allow to distinguish between high and low metallicity models \[\text{[16]}\] but future high precision measurements of the $^7$Be might give useful constraints.

Besides, the experimental determination of the flux of the CNO components is of strategical importance being the CNO flux prediction different by more than 30% in the two classes of models.

2. The $^7$Be signal

The $^7$Be signal rate in Borexino is obtained by fitting the energy spectrum which is a superposition of the neutrino signal events and the background. Event selection is described in \[\text{[13]}\]. The resulting energy spectrum corresponding to a live time of 192 days is shown in figure \[\text{[1]}\].

The energy calibration is obtained by studying the $\beta$ decay of $^{14}C$ with 156 KeV end point (not shown) and through the spectral fit itself. The expected $^7$Be spectral signature is a electron recoil spectrum with a Compton like shape and its features are visible in figure \[\text{[1]}\]. The large peak in the same figure is due to the 5.3 MeV $\alpha$ decay of $^{210}Po$, a daughter of $^{222}Rn$ out of equilibrium. The ionization quenching of the scintillator reduces the visible energy by a factor about 13 and brings the $\alpha$ peak in the energy region of the $^7$Be signal. A positive side effect of this large background is its use to study the yield stability and the energy resolution of the detector. The $^{210}Po$ count rate decreases with time consistently with its mean life of 200 days.

The study of the time correlated events belonging to the $^{238}U$ and $^{232}Th$ radioactive chains yields, under the hypothesis of secular equilibrium, an internal contamination for $^{238}U$ of $1.6 \pm 0.1 \cdot 10^{-17}$g/g and for $^{232}Th$ of $6.8 \pm 1.5 \cdot 10^{-18}$g/g. The concentration of these contaminants is more than an order of magnitude lower than the design value of $\approx 10^{-16}$g/g and it is not therefore the main issue of the $^7$Be analysis. On the contrary, the most important background is due to the $\beta$ decay of $^{85}Kr$ with 687 KeV end point having a rate of the same order of magnitude of the $^7$Be signal and a spectral shape not too different.

The analysis of the rare decays of $^{85}Kr$ into $^{85}Rb$ (branching ration 0.43 % but taggable due to the presence of time correlated events) yields 28.7 counts/(days 100 t) after a live time of more than 1 year. Additional background is identified as $^{210}Bi$ and as $^{11}C$. The last one is produced by the interaction of muons in the scintillator.

![Borexino energy spectrum](image_url)

Figure 1: The Borexino energy spectrum (192 days of live time) and its fit. A similar fit procedure in which the $^{210}Po$ is statistically subtracted by exploiting the $\alpha-\beta$ separation capability of the detector gives consistent results.

The energy spectrum is fitted by two procedures \[\text{[12][13]}\]: one of the them includes the $^{210}Po$ $\alpha$ peak and in the second one a statistical subtraction of this peak is applied. The two results are mutually consistent and they give the value of the 0.862 $^7$Be solar neutrino interaction rate of $49 \pm 3_{\text{stat}} \pm 4_{\text{syst}}$ ev/(day 100 t) after 192 days of live time. Assuming the flux of the Standard Solar Model with high metallicity the expected
rate without oscillations is $74 \pm 4 \text{ ev/(day100r)}$ which should reduce to $48 \pm 4 \text{ ev/(day 100t)}$ using the LMA-MSW oscillation parameters. The $^7$Be measurement of Borexino confirms the prediction at low energy of the LMA oscillation model.

A big effort is now in progress to reduce the errors associated to the measurement of the $^7$Be signal rate: the main contributions are the imperfect knowledge of the fiducial volume and of the detector response function (each one of them gives a contribution to the systematic error of 6% ). We are planning to reduce these errors through the detector calibration: three calibration campaigns have been already completed, and the results are under analysis.

3. Day night asymmetry

Several different radioactive sources ($^{14}$C source, Rn loaded scintillator source, $\gamma$-sources, neutron sources) have been inserted in the inner vessel center and along the vertical axis (first calibration campaign) and in more than 100 positions off axis (second and third calibration campaign) to verify the accuracy of the event position reconstruction (see figure 2), which is used to define the fiducial volume, to check the absolute energy calibration and to study the dependence of the energy response on the scintillation position.

Figure 2: As preliminary example of calibration data the distribution of the measured x positions of the scintillation events due to a $^{214}$Po $\alpha$ decay from a Radon source placed off axis is shown. The vertical axis in Borexino is z. The x coordinate is reconstructed with a Gaussian distribution having a standard deviation of 11 cm. The accuracy of the reconstruction of the absolute position is under study.

Particular care has been devoted to the design of the source insertion system, to the selection of its materials and to the definition of the insertion procedure in order to minimize the risk of introduction of any radioactive contaminants in the detector that would spoil the exceptional performances of Borexino. The post calibration data indicate that the source insertion operations did not introduce important changes of the background.

Eight $\gamma$-sources with energies ranging from 150 keV up to 2.2 MeV and the neutron source with its 4.4 MeV capture line on $^{12}$C have been chosen in order to study the energy response in the whole region of interest for solar neutrino physics.

The true source position can be determined within 2 cm accuracy through the use of a red led light (mounted on the source support) and a system of CCD camera. The goal is to reduce the error associated to the $^7$Be signal rate to few percent.

A preliminary analysis of the day and night spectra provides a further confirmation of the prediction of the LMA model through the absence of a significant day-night asymmetry in the $^7$Be flux. For each event, from the absolute time we compute the value of the Sun zenith angle at the Laboratori Nazionali del G. Sasso latitude. Figure 3 shows the day and night spectra corresponding to a total live time of 422.12 days with 212.87 days and 209.25 night. The horizontal axis represents the number of hits detected by the photomultipliers which is closely connected to the energy of the events. Events are selected as described in [12] the only difference concerns the choice of the fiducial volume being here only the spatial cut $r<3$ m applied. The day-night asymmetry $A_{dn}$ is defined as $A_{dn} = \frac{C_d - C_n}{C_d + C_n}$ where $C_d$ and $C_n$ are the counts during day and the night time. $A_{dn}$ has

Figure 3: Day (red) and night (blue) spectra of the selected events normalized to the night live time and in the energy region outside the $^{210}$Po peak.
Figure 4: Binned day night asymmetry as a function of nhits and the zoom in the region where the contribution of the $^7$Be signal is maximum. The fit is performed with a constant function. The reduced Chi squared is 66.5/72.

been evaluated for every bin (see figure 4) in the region from nhits $>$ 250 to nhits $<$ 700 as shown in figure. Here below nhits=350 the signal to background ratio is maximum while for nhits$>$350 the background (due to $^{11}$C) is dominant. The binned day night asymmetry well fit with a constant function providing $A_{fit}^{dn} = 0.007 \pm 0.008$ in the region (250,700) nhits and $A_{fit}^{fit} = 0.014 \pm 0.013$ in the region (250,350) nhits. This last value is consistent with $A_{fit}^{fit} = 0.011 \pm 0.014$ obtained using the integrated counts in the region with nhits (250,350). The absence of significant difference between the day and night signals in the high energy region is a check of the consistency of the data while the results about $A_{fit}^{fit}$ and $A_{fit}^{fit}$ in the region (250,350) nhits show that the day night asymmetry of the $^7$Be solar neutrino signal is zero within one standard deviation. This result is independent on the precision of the definition of the fiducial volume and on the knowledge of the detector response function.

The day night asymmetry in the region nhits (250,350) here discussed includes the contribution both of the signal and of the background. Considering the statistical precision of the $^7$Be flux determination in the day and night periods we get the contribution of the signal alone $A_{fit}^{fit} = 0.02 \pm 0.04_{stat}$. This is our preliminary result confirming the expectation of the LMA-MSW scenario. Further analysis and the evaluation of the contribution of possible systematic errors due to the selection of the data sample are in progress.

4. The low energy threshold $^8$B signal

The excellent radiopurity levels obtained by Borexino made possible a measurement of the $^8$B solar neutrino flux with the unprecedented energy threshold of 2.8 MeV [14]. This value is mainly determined by the need to cut the residual $\gamma$ background due to the Thallium decay in the PMT materials. The expected signal rate, including neutrino oscillations, is $0.26 \pm 0.03$ counts/day in 100 t. Data selection procedure (see [14] for details) includes the removal (with 99.7% efficiency) of short lived ($\tau < 2$ sec cosmogenic isotopes by vetoing the detector for 5 sec after each muon crossing the scintillator, the removal of $^{10}$C by the triple coincidence with the parent muon and the neutron capture on proton and the statistical subtraction of the Thallium spectrum due to the internal radioactivity. The resulting $^8$B neutrinos signal rate is $0.26 \pm 0.04_{stat} \pm 0.02_{sys}$ counts/(days 100 t) after 246 days of live time. This measurement confirms flavor oscillations at 4.2 $\sigma$ level.

The neutrino survival probability at an average energy of 8.6 MeV is $P_{ee}^{^8B} = 0.35 \pm 0.10$ while the one of the $^7$Be neutrinos is $P_{ee}^{^7Be} = 0.56 \pm 0.10$. Eliminating the common sources of systematic errors the ratio between the two probabilities is 1.6 $\pm$ 0.33 confirming the expectation of the LMA-MSW oscillation scenario at 93% C.L. (see figure 5).

Figure 5: The electron neutrino survival probability of the LMA-MSW model and the experimental results including the new data of Borexino

5. Conclusions and future programs

Borexino has completed the first real time measurements of $^7$Be and the low threshold $^8$B signal rate. A preliminary re-
sult about the day night asymmetry has also been obtained. All results confirm the current LMA-MSW scenario. Annual modulation analysis is underway.

A calibration campaign is in progress. The results are expected to contribute to a significant reduction of the errors on the fiducial volume and on the detector response function, yielding a $^7\text{Be}$ signal rate measurement with few percent accuracy and of the reduction of the systematic errors of the $^8\text{B}$ measurement.

The possibility to purify the scintillator to reduce the background due to $^{85}\text{Kr}$ and to $^{210}\text{Bi}$ is under consideration. If successful, Borexino might attempt the direct detection of pep and pp, and CNO neutrinos.

6. Acknowledgments

This work has been funded by: INFN (Italy), NSF (USA), BMBF, DFG and MPG (Germany), Rosnauka (Russia), MNiSW (Poland).

References

[1] H. O. Back et al. (Borexino Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 584, 98 (2008)
[2] H. O. Back et al. (Borexino Collaboration), Phys. Lett. B, Vol. 563 (23), 2003
[3] H. O. Back et al. (Borexino Collaboration), Phys. Lett. B, Vol. 525 (29), 2002
[4] H. O. Back et al. (Borexino Collaboration), Eur. Phys. J. C, Vol. 37 (421), 2004
[5] H. O. Back et al. (Borexino Collaboration), Phys. Lett. B, Vol. 563 (35), 2003
[6] B. T. Cleveland et al., Astrophys. J. 496, 505 (1998); 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).
[7] 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. (Super-Kamiokande Collaboration), [arXiv:0803.4312v1](http://arxiv.org/abs/0803.4312v1) 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)
[8] S. Abe et al. (KamLAND Collaboration), Phys. Rev. Lett. 100, 221803 (2008).
[9] S. P. Mikhayev and A. Yu. Smirnov, Sov. J. Nucl. Phys. 42, 913 (1985); L. Wolfenstein, Phys. Rev. D 17, 2369 (1978).
[10] A. Yu. Smirnov [arXiv:hep-ph/0305106v1](http://arxiv.org/abs/hep-ph/0305106v1)
[11] Barger et al., Phys. Rev. Lett. 95 211802 (2005); A.Friedland et al., Phys. Lett. B 594 (2004) 347
[12] C. Arpesella et al. (Borexino Collaboration) Phys. Rev. Lett. 101 9 (2008)
[13] C. Arpesella et al. (Borexino Collaboration) Phys. Lett. B 658, 101 (2008)
[14] G. Bellini et al. (Borexino Collaboration) arXiv:0808.2865v1(2008)
[15] A. de Gouvea, A. Friedland, H. Murayama Phys. Rev. D 60 (1999) 093011[http://arxiv.org/abs/hep-ph/9910289v2](http://arxiv.org/abs/hep-ph/9910289v2)
[16] C. Pena Garay, A. Serenelli [arXiv:0811.2424v1](http://arxiv.org/abs/0811.2424v1)
[17] P. C. de Holanda, [arXiv:0811.0567v1](http://arxiv.org/abs/0811.0567v1) (nov 2008)
[18] J.N.Bahcall and P.N. Krastev Phys. Rev. C 56 5 2839 (1997)