The Borexino impact in the global analysis of neutrino data

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Abstract. The Borexino collaboration has recently published the most precise, direct measurement of $^7$Be solar neutrino rate and the exclusion of a significant day-night asymmetry. These results, combined with the other solar neutrino data, isolate for the first time the Large Mixing Angle solution at $\Delta \chi^2 > 190 \,(2\,\text{d.o.f.})$, without relying on the antineutrino results. We present a phenomenological analysis of neutrino data (the most up-to-date from solar, reactor, atmospheric and accelerator experiments) within the standard scenario of three non-sterile and mixed neutrinos. The aim is to study the implications of Borexino results in neutrino Physics and solar interior astrophysics.

1. Introduction

The Borexino detector, designed and constructed for sub-MeV solar neutrino spectroscopy, is taking data at the Gran Sasso Laboratory (Italy) since May 2007. The detector was designed according to the principle of graded shielding: an onion-like structure allows to protect the inner part from external radiation and from radiation produced in the external shielding layers. The requirements on material radiopurity increase when going toward the innermost region of the detector.

The Borexino collaboration has recently published the most precise, direct measurement of $^7$Be solar neutrino rate [1] and the exclusion of a significant day-night asymmetry [2]:

$^7$Be : $46 \pm 1.5 \,(\text{stat})^{+1.5}_{-1.5} \,(\text{syst}) \,\text{cpd/100 ton ADN} = 0.001 \pm 0.012 \,(\text{stat}) \pm 0.007 \,(\text{syst})$.

These results, combined with the other solar neutrino data, isolate for the first time the Large Mixing Angle solution at $\Delta \chi^2 > 190 \,(2\,\text{d.o.f.})$, without relying on the antineutrino results. Moreover, the $^7$Be result alone provides a precise measurement of the survival probability $P_{ee}$ in the vacuum dominated oscillation regime: $P_{ee} = 0.51 \pm 0.07 \,$ at 862 keV. Thanks to this achievement, the no flavor change hypothesis is ruled out at 5.0$\sigma$.

Direct measurement of sub-MeV solar neutrinos is not only a way through which we can study neutrino oscillations: it is also valuable for solar Physics since it could help in solving the metallicity controversy. The controversy arises because some recent refined calculations showed new (lower) metallicity values in the Sun and in its core, changing the expected fluxes. However, this low-metallicity values lead to solar models which disagree with different helioseismological measurements.

The analysis reported in this proceeding is carried out using the standard solar model [4] (hereafter SHP11) recently published by A. Serenelli, W. Haxton and C. Peña Garay.
This solar model uses newly analyzed nuclear fusion cross sections and, according to the high (GS98 [5]) or low (AGSS09 [6]) metallicity hypothesis, predicts the different solar neutrinos fluxes listed in the table of Fig. 1.

| ν Flux | GS98(SHP11) | AGSS09(SHP11) | Difference % |
|--------|-------------|---------------|--------------|
| pp     | 5.98(1 ± 0.006) | 6.03(1 ± 0.006) | 0.8          |
| pep    | 1.44(1 ± 0.012) | 1.47(1 ± 0.012) | 2.1          |
| hep    | 8.04(1 ± 0.30)  | 8.31(1 ± 0.30)  | 3.4          |
| 7Be    | 5.00(1 ± 0.07)  | 4.56(1 ± 0.07)  | 8.8          |
| 8B     | 5.28(1 ± 0.14)  | 4.59(1 ± 0.14)  | 17.7         |
| 13N    | 2.99(1 ± 0.14)  | 2.17(1 ± 0.14)  | 26.7         |
| 14O    | 2.23(1 ± 0.15)  | 1.56(1 ± 0.15)  | 30.0         |
| 15F    | 5.52(1 ± 0.17)  | 3.40(1 ± 0.16)  | 38.4         |

Neutrino fluxes are given in units of 10^6 cm^-2 s^-1. Asymmetric uncertainties have been averaged.

Figure 1: Neutrino fluxes as predicted by the SHP11 solar model [4] having as input the GS98 high metallicity solution [5] and the AGSS09 low metallicity solution [6]. The percentage difference among the two predictions is indicated.

All solar neutrinos are electron neutrinos produced in the inner part of the Sun. To perform a proper analysis, we first have to study how the survival probability of an electron neutrino propagates in the Sun core, in vacuum (the Sun-Earth path) and in the Earth. If we assume \( P_{\text{e}1'} \) to be the probability that an electron neutrino produced in the Sun becomes a neutrino mass eigenstate \( \nu_1' \) and \( P_{\text{e}2'} \), the probability that a neutrino propagating in vacuum as mass eigenstate is detected on Earth as an electron neutrino, the Survival Probability for an electron neutrino can be written as [7]:

\[
P_{\text{ee}} = \sin^4 \theta_{12} + \cos^4 \theta_{13} \left[ P_{\text{e}1'}^{S} \left(1 - P_{\text{e}2'}^{E}\right) + \left(1 - P_{\text{e}1'}^{S}\right) P_{\text{e}2'}^{E}\right]
\]

For each neutrino source, the probability \( P_{\text{e}1'}^{S} \) is obtained by weighting the \( P_{\text{ee}} \) of each production point for the corresponding distribution. The probability \( P_{\text{e}2'}^{E} \) is computed taking into account the Sun exposure related to Borexino location (LNGS, Italy) and weighted by its livetime (see Fig. 2).

Starting from the survival probability \( P_{\text{ee}} \) and assuming the GS98(SHP11) neutrino fluxes, the theoretical predictions for each Borexino relevant quantity are evaluated as a function of the free parameters of the fit: the oscillation parameters \( \Delta m_{21}^{2} \), \( \tan^2 \theta_{12} \) and \( \sin^2 \theta_{13} \).

2. The global analysis on Borexino data

The constraints on the parameters of the global analysis are obtained by fitting the theoretical prediction to the experimental data through \( \chi^2 \)-method, by finding the minimum of the \( \chi^2 \) function and by tracing the iso-\( \Delta \chi^2 \) contours around it. If \( R_{\text{EXP}}^{i,A} \) is the set of results of the \( i \) measurement actually obtained by the \( A \) experiment, and \( R_{\text{THEO}}^{i,A}(\Delta m_{21}^{2}, \tan^2 \theta_{12}, \sin^2 \theta_{13}, \Phi_{\nu,A}) \) is the corresponding set of theoretical predictions, then:

\[
\chi^2_A = \left[ R_{\text{EXP}}^{i,A} - R_{\text{THEO}}^{i,A}(\Delta m_{21}^{2}, \theta_{12}, \theta_{13}, \Phi_{\nu,A}) \right] \sigma_{ij}^{-1} \left[ R_{\text{EXP}}^{i,A} - R_{\text{THEO}}^{i,A}(\Delta m_{21}^{2}, \theta_{12}, \theta_{13}, \Phi_{\nu,A}) \right]
\]

The error matrix \( \sigma_{ij} \) includes both the theoretical and experimental errors as well as the cross-correlations between errors on the different parameters.

The Borexino measurements included in this global analysis are the \(^7\)Be total count rate [1], the day-night asymmetry [2] and the \(^8\)B total count rate above 3 MeV [3].

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The resulting $\chi^2$ is then minimized for $\Delta m_{21}^2$, $\tan^2 \theta_{12}$ and $\sin^2 \theta_{13}$: in this way we obtain the $\chi^2$-projection for each parameter of the fit. Figure 3 and Fig. 4 show in sequence the effect of including $^7$Be plus $^8$B count rate and $^7$Be day-night asymmetry in the fit. The joint analysis of the $^7$Be and $^8$B count rate is required since the two neutrino fluxes are strictly correlated. Finally, the effect of the day-night measurement is very clear in Fig. 5 where all the Borexino results are fitted together: in the MSW solution, Borexino prefers the LMA region while definitely excludes the LOW region of parameter space.

3. The Borexino impact in the global analysis of neutrino data

The impact of the latest Borexino results [1, 2, 3] can be better understood through a global analysis of all solar neutrino data. This exercise was carried out by adding to the previous Borexino-only analysis the radiochemical data (Homestake [8], SAGE [9], GALLEX/GNO [10]), the Super-KamiokaNDE [11] and the SNO [12] data. In this part of the analysis, we reasonably assumed $\theta_{13} = 0$.

For what concerns solar Physics, the best way to approach to the study of the Standard Solar Model parameters and to look deeper into the low/high metallicity controversy, is to let data decide by leaving $\Phi(^7\text{Be})$ and $\Phi(^8\text{B})$ as free parameters of the fit. To this aim, we define the reduced fluxes as the fluxes normalized to the high metallicity predictions:

$$f_{^7\text{Be}} = \frac{\Phi(^7\text{Be})}{\Phi_{\text{SHP11}}(^7\text{Be})} \quad \text{and} \quad f_{^8\text{B}} = \frac{\Phi(^8\text{B})}{\Phi_{\text{SHP11}}(^8\text{B})}$$

With these definitions, the high-metallicity SHP11(GS98) hypothesis corresponds to:

$$f_{^7\text{Be}} = 1.00 \pm 0.07 \quad \text{and} \quad f_{^8\text{B}} = 1.00 \pm 0.14,$$

while the low-metallicity SHP11(AGSS09) hypothesis corresponds to:

$$f_{^7\text{Be}} = 0.91 \pm 0.07 \quad \text{and} \quad f_{^8\text{B}} = 0.82 \pm 0.11.$$  

Under the light form of the luminosity constraint, $f_{^7\text{Be}} = 1.08 - 0.08f_{^7\text{Be}}$, we leave the reduced fluxes $f_{^7\text{Be}}$ and $f_{^8\text{B}}$ free to vary. Figure 6 shows the allowed region for $f_{^7\text{Be}}$ and $f_{^8\text{B}}$ after marginalization over $\Delta m_{21}^2$ and $\tan^2 \theta_{12}$. It is clear that, at present, solar neutrino data cannot
Figure 6: 1σ theoretical range of high (red, [5]) and low (blue, [6]) metallicity model compared to the 1σ, 2σ and 3σ allowed regions predicted by all solar neutrino data.

Figure 7: 1σ, 2σ and 3σ allowed regions by the solar neutrino data without (left panel) and including (right panel) the Borexino [1, 2, 3] data.

discriminate between the low or high metallicity hypothesis in the solar model: either the 1σ theoretical range of low and high metallicity model envelops the 3σ allowed region by the current solar data.

For what concerns neutrino Physics, in particular the neutrino oscillations parameter estimation, the left panel of Fig. 7 shows the 1, 2, 3σ allowed regions for the mixing parameters $\Delta m^2_{21}$ and $\tan^2 \theta_{12}$ by all solar neutrino data without Borexino. The best fit point
( $\Delta m^2_{21} = 5.2 \times 10^{-5}$ eV$^2$, $\tan^2 \theta_{12} = 0.47$) is in the LMA region and a small portion of LOW region is still allowed at $\Delta \chi^2 = 11.83$. The right panel shows the same allowed regions once the Borexino [1, 2, 3] data are included in the analysis. The LMA region is only slightly modified ($\Delta m^2_{21} = 5.2 \times 10^{-5}$ eV$^2$, $\tan^2 \theta_{12} = 0.46$) but the LOW region is now strongly excluded at $\Delta \chi^2 > 190$. Therefore, after the inclusion of the Borexino data, solar neutrino data alone can single out the LMA solution with very high confidence (see Fig. 8). The origin of this powerful result is mainly ascribable to the goodness of Borexino day-night asymmetry measurement [2]. In fact, the measured asymmetry, in agreement with the prediction of MSW-LMA neutrino oscillations, disfavours at more than 8.5$\sigma$ MSW oscillations with mixing parameters in the LOW region: for the first time, this region is strongly disfavoured without using Kamland data, that is without the assumption of CPT symmetry.

![Figure 8: Results of the global fit: $\chi^2$-profile of $\Delta m^2_{21}$ for all solar data without Borexino (left) and after the inclusion of the Borexino results (right).](image)

References

[1] G. Bellini et al., *Phys. Rev. Lett.*, 107, 141302 (2011).
[2] G. Bellini et al., *Phys. Lett. B*, 707, 22 (2012).
[3] G. Bellini et al., *Phys. Rev. D*, 82, 033006 (2010).
[4] A. Serenelli, W. Haxton and C. Peña Garay, *Astrophys. J.*, 743, 24 (2011).
[5] N. Grevesse and A. Sauval, *Space Sci. Rev.*, 85, 161-174 (1998).
[6] A. Serenelli, S. Basu, J. Ferguson and M. Asplund, *Astrophys. J.*, 705, L123-L127 (2009).
[7] M. Gonzalez-Garcia and C. Peña Garay, *Nucl. Phys. B Proc. Suppl.*, 91, 8088 (2001).
[8] B. Cleveland et al., *Astrophys. J.*, 496, 505 (1998)
[9] J. Abdurashitov et al., *Phys. Rev. C*, 80, 015807 (2009).
[10] F. Kaether et al., *Phys. Lett. B*, 685, 47 (2010)
[11] J. Hosaka et al., *Phys. Rev. D*, 73, 025503 (2006); K. Abe et al., *Phys. Rev. D*, 83, 052010 (2011).
[12] B. Aharmim et al., *Phys. Rev. C*, 81, 055504 (2010); B. Aharmim et al., *Phys. Rev. Lett.*, 101, 111301 (2008).