Understanding the Sun: Borexino

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Abstract. Solar neutrinos have been detected over the past 40 years providing the first evidence of physics beyond the Standard Model for elementary particle interactions. The hypothesis of neutrino oscillations has offered a solution to the long-standing solar neutrino problem (missing solar neutrinos). The Solar Standard Model is a fundamental ingredient in the interpretation of the solar neutrino measurements. New determinations of solar metal abundances caused the Solar Standard Model predictions to be in conflict with helioseismological measurements. The direct measurement of $^7\text{Be}$ solar neutrinos performed by the Borexino experiment at the Gran Sasso Underground Laboratory allows to probe the Solar Standard Model assuming the neutrino oscillation scenario. At present Borexino has measured $^7\text{Be}$ solar neutrinos at the level of 10%. In the near future a measurement at the level of 5-3% could be achieved. This accuracy could allow to determine the metal abundances at the center of the Sun. In this framework solar neutrinos offer an independent method to determine the source of the conflict between Solar Standard Model and helioseismology.

The Borexino results are presented and discussed in the framework of the Solar Standard Model and neutrino oscillations.

1. Solar neutrino measurements, Solar Standard Model and helioseismology

The Sun is a huge source of low energy ($<$15 MeV) electron neutrinos, $\nu_e$. Fig. 1 shows the solar neutrino spectrum at Earth with the different components. The main production process is the fusion of two protons; the average energy is about 0.3 MeV. Detection of these low energy neutrinos is a challenge. In spite of this solar neutrinos have been detected over the past 40 years. In Tab. 1 we summarize results of measurements. Collected data can be understood in the framework of neutrino oscillations [1]: from their origin, in the core of the Sun, to Earth solar electron neutrinos get transformed to other flavours. A fundamental ingredient in the interpretation of solar neutrino measurements is the so-called Solar Standard Model (SSM) [2]. The SSM has been updated with new values of two important astrophysical factors, $S_{34}$ and $S_{14}$ from LUNA [3]. At present, the SSM predicts the $^7\text{Be}(^8\text{B})$ solar neutrino flux at the level of 6% (11%). The SSM can be tested by means of helioseismology [4]. New determination of solar metal abundances [5], [6] caused the SSM predictions to be in conflict with helioseismology. Recently, a new determination of solar abundances has been proposed [6] by using an improved solar atmosphere model and atomic data, and a better selection of spectroscopic lines. In Tab. 2 we report measurements and predictions for the surface helium abundance and the depth of the convective zone. In Fig 2 we plot data against measurements including correlations. From Fig 2 it is evident that at present a strong conflict exists between the prediction of the SSM with new metal abundances (low metallicity, LZ) and observations. On the contrary previous abundances (high metallicity, HZ) were well in agreement with the model. The point we want to make in
this paper is how solar neutrino measurements could help solving this controversy. The impact of new metal abundances with respect to older ones on solar neutrino fluxes is as follows [7], [8]:
1) the flux from $^7\text{Be}$ decreases by 10.6%(8.7%) for LZ05(LZ09); 2) the flux of $^{13}\text{N}$ decreases by 34.4%(26.6%) for LZ05(LZ09); 3) the flux of $^{15}\text{O}$ decreases by 38.3%(29.7%) for LZ05(LZ09).

![Figure 1. Spectrum of solar neutrinos at Earth. Solid lines from left to right: pp, $^{13}\text{N}$, $^{15}\text{O}$, $^{17}\text{F}$ and $^8\text{B}$. Dashed lines from left to right: $^7\text{Be}(0.38 \text{ MeV}), ^7\text{Be}(0.862 \text{ MeV})$ and pep.](image)

![Figure 2. High metallicity against Low metallicity as from data reported in Tab. 2. Solid thick line: data. Dashed thick line: HZ. Solid line: LZ09. Dotted line: LZ05. Contours correspond to 68% and 99% C.L.](image)

Table 1. Summary of results from solar neutrino measurements. CC = charged-current detection interaction. NC = neutral-current detection interaction. ES = elastic scattering detection interaction.

| Experiment       | $\nu_e$ sources detected                                      | data/model |
|------------------|--------------------------------------------------------------|------------|
| Homestake(CC)    | $^7\text{Be}(13.1\%)$+pep($2.7\%$)+CNO($2.4\%$)+$^8\text{B}(81.8\%)$ | 0.31±0.03  |
| Gallium exps(CC) | pp($55\%$)+$^7\text{Be}(28.3\%)$+pep($2.3\%$)+CNO($3.4\%$)+$^8\text{B}(11\%)$ | 0.53±0.05  |
| Super-Kamiokande(ES) | $^8\text{B}(100\%)$                                           | 0.451±0.017|
| SNO(CC)          | $^8\text{B}(100\%)$                                           | 0.28±0.01  |
| SNO(NC)          | $^8\text{B}(100\%)$                                           | 0.88±0.05  |
| Borexino(ES)     | $^7\text{Be}(100\%)$                                          | 0.65±0.07  |

2. Detecting solar neutrinos and probing the Solar Standard Model with Borexino
Borexino has started taking data in May 2007. For the first time sub-MeV solar neutrinos can be detected in real-time. Borexino is an organic liquid scintillator with a target mass (for solar neutrinos) of 100 tons. Fig 3 shows a sketch of the detector which is based on several layers of
Table 2. The Sun’s $^{4}\text{He}$ surface abundance and depth of the convective zone (in units of solar radius) from Solar Standard Models and from helioseismology. LZ09 is from [7] using metal abundances from [6]. LZ05 makes use of metal abundances from [5]. Correlations are taken from [8].

|       | data     | SSM(HZ)   | SSM(LZ09) | SSM(LZ05) |
|-------|----------|-----------|-----------|-----------|
| $Y_{\text{surf}}$ | 0.2485±0.0035 | 0.242±0.0037 | 0.231±0.0037 | 0.229±0.0037 |
| $R_{\text{CZ}}$  | 0.713±0.001  | 0.713±0.0037 | 0.724±0.0037 | 0.728±0.0037 |

passive shielding material with high radiopurity to reduce external background. More details on the detector can be found in [9].

Figure 3. Sketch of the Borexino detector (taken from [9]).

Figure 4. Spectrum of recoil electrons from solar neutrino interactions in Borexino.

Borexino detects solar neutrinos by elastic scattering. In Fig 4 we show the expected spectrum of recoiled electrons. The main contribution comes from $^7\text{Be}$ solar neutrinos which are monoenergetic. About 74 counts/day/100tons are expected according to the HZ SSM. In Fig 5 we show the measured spectrum of solar neutrinos and backgrounds in Borexino (taken from [10]). For more details on the analysis see [10]. As reported in Tab 1 Borexino measures about 48 counts/day/100tons instead of 74. This is consistent with the hypothesis of neutrino oscillations. At present the $^7\text{Be}$ rate is given with a 10% uncertainty. In Fig 6 we show iso-rate
Figure 5. Borexino data fitted with the solar neutrino signal and backgrounds [10]. When systematic uncertainties are taken into account \( R_{7\text{Be}} = 49 \pm 3 \pm 4 \text{ cpd/100 tons}. \)

Figure 6. Iso-rate, \( R_{7\text{Be}}(\theta_{12}, \delta m^2)/R_{7\text{Be}}^{\text{SM}} \), contours superimposed to the allowed regions at 90% and 99% C.L. from a global analysis of other solar and reactor experiments.

...contours normalized to the SSM(HZ) prediction for Borexino. In the same figure we report the allowed regions from a global analysis of solar (larger region) and solar+reactor (smaller region) data. Due to the fact that at present Borexino reports a value of 0.65\( \pm 0.07 \), no improvements on the oscillation parameters can be extracted from the data. Future results could reach a 5-3% uncertainty due to performed calibration runs which aimed to reduce the systematic errors.

Present Borexino data however already give important results on SSM parameters, when we make a comparison with previous (that is prior to Borexino) analyses. As a matter of fact, using SNO and Super-Kamiokande data it is possible to determine the flux of \( ^8\text{B} \) solar neutrinos without using the SSM. This is shown in Fig 7. The \( ^8\text{B} \) flux normalized to SSM(HZ) is found to be 0.90\( \pm 0.05 \). Using this result and data from other solar neutrino experiments (see Tab 1) and assuming neutrino oscillations one can determine the flux of pp and CNO neutrinos with and without the luminosity constraint [11]. This is shown in Fig 8. In particular, it can be found that the pp flux normalized to the SSM(HZ) is 1.04\( +0.16 \)\(-0.19 \) (1.02\( \pm 0.10 \) without) with the luminosity constraint. This is a great improvement with respect to the result before Borexino. More can be done by using the correlation between \( ^8\text{B} \) and \(^7\text{Be} \) solar neutrinos as suggested by C. Pena-Garay [12]. In Fig 9 we show data against predictions: in particular, for the data we report \( f_B \) from SNO (lower value) and from SNO+Super-Kamiokande; for predictions we report the SSM(LZ05) lower left ellipse and the SSM(HZ) upper right ellipse at 68\% C.L. From this figure it is evident that: 1) the \( ^8\text{B} \) solar neutrino flux measurement sits in between the two models; 2) uncertainties are too large at present too try to disentangle the two models with this method. In the future this method can be used with improved results from SNO (after the low threshold analysis will be completed) and with smaller errors from Borexino. Other possibilities using CNO neutrinos have been proposed [13].

By assuming the SSM(HZ) fluxes the Borexino data can be used to determine the solar electron neutrino survival probability at Earth. Due to the high radiopurity achieved Borexino has been able to detect \( ^8\text{B} \) neutrinos above 3 MeV [14]. In Fig 10 we report the survival...
Figure 7. Measurement of the $^8$B solar neutrino flux with SNO and Super-Kamiokande. $f_B$ is the $^8$B solar neutrino flux normalized to the SSM(HZ); $P_{ee}$ is the electron neutrino survival probability at Earth. Contours are given at 68%, 90% and 99% C.L.

Figure 8. Measurement of the pp vs CNO solar neutrino fluxes with Borexino with and without the luminosity constraint. Contours are given at 68%, 90% and 99% C.L.

probability from Borexino and SNO together with the one which can be calculated for pp neutrinos. This figure shows also the Large Mixing Angle prediction (solid line). The plot shows the agreement between data and model for neutrino oscillations. Future Borexino measurements of $^7$Be and $^8$B solar neutrinos will confirm better this agreement or show possible sub-leading effects.

3. Conclusions
First results from Borexino on $^7$Be and $^8$B solar neutrinos, with less than one year of livetime, have already shown a great potentiality for understanding the Sun and the hypothesis of neutrino oscillations (see Fig 8, 10). At present important results have been obtained for the indirect measurement of the pp solar neutrino flux, a fundamental astrophysical parameter, and for the electron neutrino survival probability. Without a calibration campaign with external sources (in order to not contaminate the liquid scintillator) Borexino has performed a 10% measurement of the $^7$Be(0.862 MeV) solar neutrino flux. Future measurements with reduced systematics (5-3%), after a full calibration campaign with sources deployed inside the liquid scintillator, will allow to probe better the SSM helping to solve the solar abundance problem.

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Figure 9. $^7$Be against $^8$B from Borexino and SNO/Super-Kamiokande. Upper(lower) ellipse is for the high(low 2005 [5]) metallicity model. 68% C.L. are shown. Left experimental point is from SNO only; right point is from SNO+Super-Kamiokande.

Figure 10. Survival probability for $\nu_e$ at Earth assuming the SSM(HZ).

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