Precision measurement of the $^7$Be solar neutrino flux and its day-night asymmetry with Borexino

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On behalf of the Borexino collaboration

Abstract. Borexino measures the $^7$Be solar neutrino flux on 740 live days of data-taking to be $46\pm1.5^{+1.6}_{-1.5}$ events/(day $\cdot$ 100 tons) which corresponds to an equivalent unoscillated flux on Earth of $(3.11\pm0.10^{+0.09}_{-0.06})\cdot10^9$ sec$^{-1}$ cm$^{-2}$. This result excludes the no-oscillation hypothesis at 5 $\sigma$ and provides a precise measurement of the survival probability $P_{ee}$ in the vacuum dominated oscillation regime $P_{ee}=0.51\pm0.07$. Borexino also measures the day-night asymmetry of the $^7$Be neutrino rate with a total error of 1.4% and finds it to be consistent with zero. This result is in agreement with the MSW-LMA hypothesis and disfavours at more than 8.5 $\sigma$ the so-called LOW region of the oscillation parameter space.

1. Introduction
Neutrinos from the Sun have been studied by several experiments in the past 40 years. These studies have led to the discovery of solar neutrino oscillations and to the determination of the oscillation parameters $\Delta m^2 = 7.6 \cdot 10^{-5}$eV$^2$ and $\sin^2 2\theta_{12} = 0.87$ [1]. However, the investigation of the solar neutrino spectrum is far from being complete, especially in the energy region below 1 MeV where experiments can be severely affected by background due to natural radioactivity. The Borexino experiment has been specifically designed to study the low energy solar neutrinos, in particular those coming from the so-called $^7$Be reaction. In order to be able of reducing the energy threshold, the experiment has been built following the most stringent requirements on radiopurity. In this talk I will focus on the recent results published by Borexino on the $^7$Be solar neutrino flux and its day-night asymmetry after 740 days of data-taking. More details can be found in refs [2] and [3].

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The Borexino detector

The Borexino detector is located under the Gran Sasso mountain in the Laboratori Nazionali del Gran Sasso, Italy. It detects solar neutrinos via their elastic scattering on the electrons of 300 tons of liquid scintillator. The scintillator (PC + 1.5 g/l of PPO) is contained in a large spherical nylon vessel (R=4.25m). The scintillation light is viewed by 2214 photomultiplier tubes mounted on a Stainless Steel Sphere (SSS) concentric with the vessel at a radius of 6.85 m (see Fig. 1). In order to reduce external background, 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. Besides keeping external backgrounds at a low level, the key requirement for measuring low energy neutrinos with Borexino is the extreme radiopurity of the scintillator itself. During 15 years of dedicated R&D studies, the Borexino collaboration developed a successful purification strategy which proved to be effective in removing the most dangerous contaminants from the scintillator. In particular, the contamination due to $^{238}\text{U}$ and $^{232}\text{Th}$ was brought to the unprecedented levels of $(1.6 \pm 0.1) \times 10^{-17}$ g/g and $(6.8 \pm 1.5) \times 10^{-18}$ g/g, respectively, one order of magnitude better than the designed goal of $10^{-16}$ g/g. For more details concerning the Borexino detector see [4].

![Figure 1. Schematic view of the Borexino detector](image)

3. Precise measurement of the $^7\text{Be}$ flux

Events in Borexino are collected if they fire at least 25 photomultiplier tubes in a time interval of 99 nsec. The energy and position of each event is obtained from the number of collected photons and from the distribution of their relative arrival times. An extensive calibration campaign has been performed in 2009 to precisely determine the energy scale of the detector and to reduce the systematic error associated to position reconstruction. In our previously published articles ([5] and [6]) the uncertainties on the energy scale and on the fiducial mass estimation were indeed dominating the systematic error of the $^7\text{Be}$ flux measurement. The calibration of the detector was therefore crucial to reduce the total error down to less than 5%.

The scattering of monochromatic $^7\text{Be}$ neutrinos ($E=862$ keV) on the Borexino scintillator produces recoil electrons with a characteristic spectrum. The signature provided by its Compton-like shoulder at $\sim 660$ keV is crucial for disentangling the neutrino signal from residual background by means of a spectral fit. The fit has been performed following two strategies: in the first one, the spectral shapes of signal and backgrounds have been derived by Monte Carlo simulations, in the second one they have been derived analytically. In both fits the weight...
of each relevant component of residual background \((^{85}\text{Kr}, \, ^{210}\text{Bi}, \, ^{210}\text{Po}, \, ^{11}\text{C})\) and signal has been left free to vary. A thorough study of the systematic error associated to the fit procedure has been performed by varying for each fit method several parameters, such as binning, fit intervals and so on. Also, the fits have been performed on spectra built with different energy-related variables, i.e., number of hit PMTs or total charge collected. Finally, the fit has been applied to the spectrum before and after removing the alpha peak due to \(^{210}\text{Po}\) by means of an alpha/beta discrimination technique. Figure 2 shows two examples of the fit: the Monte Carlo-based one applied to the spectrum built without removing the \(^{210}\text{Po}\) peak (left) and the analytical fit performed on the spectrum built after statistically subtracting the \(^{210}\text{Po}\) peak (right). The results of these and all other fits performed varying the fit conditions and the data preparation are consistent: the difference has been included as systematic error of the fit and amounts to 2\%. Our best estimate for the \(^{7}\text{Be}\) flux is \(46 \pm 1.5 \text{ (stat.)} +1.5^{-1.6} \text{ (syst.)} \text{ counts/day \cdot 100 tons}\). Besides the error due to the fit procedure, the systematic uncertainty includes also the error on the fiducial mass \((+0.5\% -1.3\%)\) and on the energy response (2.7\%), both significantly reduced with respect to previously published articles.

![Figure 2](image)

**Figure 2.** Two examples of the spectral fit to extract the \(^{7}\text{Be}\) flux from data: Monte Carlo-based fit (left) and analytical fit (right).

The expected count rate in case of no oscillations (following the latest Standard Solar Model predictions (SSM) [7] and in the high-metallicity hypothesis [8]) would be \(74 \pm 4 \text{ counts/day \cdot 100 tons}\): the observed interaction rate is \(5\sigma\) lower. Under the assumption of oscillations we can extract a precise measurement of the survival probability, \(P_{\text{ee}}\) in the vacuum dominated oscillation regime \(P_{\text{ee}} = 0.51 \pm 0.07\). Figure 3 (left plot) shows the constraints posed on the survival probability of solar \(\nu_e\) by the analysis presented here. The precision measurement of \(^{7}\text{Be}\) neutrinos with Borexino is also a direct probe of the SSM: under the MSW-LMA oscillation assumptions the relative ratio \(f_{\text{Be}} = \Phi(^{7}\text{Be})/\Phi_{\text{SSM}}(^{7}\text{Be})\) is found to be \(0.97\pm0.05\). Furthermore, the inclusion of our result in a global solar neutrino analysis performed with free fluxes (under the luminosity constraint) allows to determine \(f_{\text{pp}} = \Phi(\text{pp})/\Phi_{\text{SSM}}(\text{pp}) = 1.013^{+0.003}_{-0.010}\) and \(f_{\text{CNO}} = \Phi(\text{CNO})/\Phi_{\text{SSM}}(\text{CNO}) < 2.5\) at 95\% C.L.

### 3.1. Day-night asymmetry of the \(^{7}\text{Be}\) solar neutrino flux

For certain values of \(\Delta m^2\) and \(\theta_{12}\) the matter-enhanced oscillation mechanism naturally foresees regeneration of \(\nu_e\) as they travel through the Earth. This would imply a larger rate at night with respect to day. We define the day-night asymmetry as \(A_{dn} = 2 \frac{R_N - R_D}{R_N + R_D}\) where \(R_N\) and \(R_D\) are the \(^{7}\text{Be}\) rate for night and day, respectively. The day-night asymmetry predicted in the LMA region of the parameter space is very small (<0.1\%) while it can be as large as 80\% in other regions (like in the so-called LOW solution). The study of \(A_{dn}\) is therefore important to
Figure 3. (Left plot): survival probability at the $^7$Be energy measured by Borexino (red dot). The grey shaded area shows the 1σ band for MSW-LMA prediction. (Right plot): day (red) and night (black) spectra after the selection cuts.

confirm the LMA scenario and exclude with high statistical significance other regions. Figure 3 (right plot) shows the day and night spectra obtained separately and normalized to the same number of live days. In order to extract the day-night asymmetry we subtract the day spectrum from the night one and fit the difference as the sum of a constant + $^7$Be. This method relies on the assumption that the backgrounds affecting the measurement are equal during day and night and are therefore subtracted away when performing the difference of the two spectra. The fit shows no excess of $^7$Be signal during night which yields to a day-night asymmetry consistent with zero within errors $A_{dn} = 0.001 \pm 0.0012$ (stat) $\pm 0.007$ (sys). This new tight constraint on the day-night effect at the $^7$Be energy is more than 8.5 σ away from the minimum asymmetry foreseen in the LOW region of the parameter space. This region is, for the first time, strongly disfavoured without the use of reactor anti-neutrino data and therefore the assumption of CPT symmetry. Our result is also potentially sensitive to new physics affecting low energy electron neutrino interaction. As an example, we are able of excluding at more than 10 σ the set of parameters chosen in [9] for the mass varying neutrino oscillation scenario.

4. Conclusions and perspectives
The unprecedented levels of radiopurity of Borexino have allowed to perform the precision measurement of the $^7$Be solar neutrino flux and of its day-night asymmetry. Borexino is today the only experiment capable to perform a spectroscopy of solar neutrinos by detecting neutrinos from different reactions in the Sun ($^7$Be, $^8$B, pep). We are currently performing a new purification campaign to reduce even further the internal radioactive background, and therefore open new challenging possibilities, such as the detection of CNO and pp neutrinos.

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