PRECISION MEASUREMENT OF THE BERYLLIUM-7 LINE WITH THE BOREXINO DETECTOR

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Borexino experiment was the first to directly investigate the sub–MeV region of the solar spectrum in real–time. Its search for answers to some fundamental questions in the field of neutrino oscillations was accomplished with a precision measurement of the ^{7}Be line at 5%; Borexino detected $46.0\pm1.5_{\rm stat}{}^{+1.6}_{-1.5}{}_{\rm syst}$ solar neutrino events/day/(100 tons) during Phase I of data taking. Further investigation of the signal led to the determination of day–night asymmetry that resulted in no significant variation; the detected asymmetry of $0.001\pm0.012_{\rm stat}\pm0.007_{\rm syst}$ is consistent with zero within the error. This note presents details of the precision measurement of the ^{7}Be ν's including the first release of the solar neutrino annual flux modulation.

1 Introduction

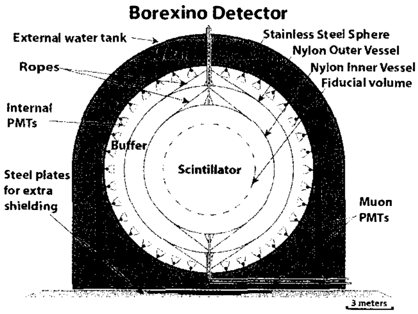
Until late 1990's, only radiochemical experiments would allow us to look into the sub-MeV region of the solar neutrino spectrum. They were however, operating at very low rates, detecting at most one event per day, and it was necessary to build an experiment such as Borexino, that could reach high rates in real–time. One of the most important targets in the low–energy region was the monochromatic line of ^{7}Be neutrinos [a]. The more recent experimental results at the time (from Gallex and Sage), together with the older data (from Homestake and Kamiokande) and the measurement of the solar luminosity indicated a severe suppression of the solar neutrino flux from ^{7}Be reactions, pushing it lower than the neutrino flux from ^{8}B, which paradoxically is a product of the reaction involving ^{7}Be. The deficit of solar neutrinos, explained by the quantum effect of oscillations between their flavors (electron, muon and tau) could be realized in the following two scenarios: oscillations in vacuum, and enhanced oscillations in matter due to charged–current interactions of electron-neutrinos with a dense solar electronic mass. The matter effect is referred to as the Mikheyev–Smirnov–Wolfenstein (MSW) effect.

[a] In fact, two monochromatic lines at 384 and 862 keV

Among many allowed solutions to the problem of missing solar neutrinos, the MSW–Large–Mixing–Angle (LMA) was the favored one[b]. In the (Δm^2, $\sin^2 2\theta$) oscillation parameter space, this corresponds to values of Δm^2=7.6×10^{-5} eV^2 and $\sin^2 2\theta_{12}$=0.87. Borexino's most recent measurement of the ^{7}Be rate of $46.0 \pm 1.5_{\mathrm{stat}}{}^{+1.6}_{-1.5}{}_{\mathrm{syst}}$ counts/(day x 100 ton)[1], is in very good agreement with the expected number from the SSM–MSW-LMA solution of 47.2±3.4 counts/(day x 100ton). The collaboration has also excluded the low neutrino mass squared splitting solution (LOW) with a measurement of absence of the day–night asymmetry, to a precision of 8.5σ [2]. Finally, with the measurement of the annual flux modulation of the low-energy solar neutrinos, the Borexino experiment could test the hypothesis of vacuum oscillations solution (Just-So), where the neutrino mass squared splitting matches the ratio of the energy to the path length from the Sun to Earth.

2 The Borexino Detector

Design Borexino is a calorimetric detector that relies on a concept of graded–shielding as presented in Figure 1 [3]. The very first shield is the overburden of the Gran Sasso mountain chain that provides some 3600 meters of water–equivalent protection from the cosmic rays. The outer layer of the detector contains 2300 m^3 of ultra–pure water (blue-region in Fig. 1) that helps reduce the gamma- and neutron-background from the surrounding rock and serves as a *Ĉerenkov* detector for the crossing muons[c]. 2212 photomultiplier tubes (PMTs) mounted on a 13.7-meter in diameter Stainless–Steel Sphere (SSS) detect light from the active volume. Additionally, 200 PMTs point outwards from the SSS and serve as the outer-detector (OD) muon veto. The inner-buffer (IB, yellow-region in Fig. 1) contains pseudocumene (PC) scintillator that is divided by a transparent, nylon sphere (inner vessel or IV) into two sub–volumes. First is the inactive region that contains PC with dissolved dimethylphthalate (DMP) light-quencher (2 g/L). Second is the inner buffer with 300 m^3 of active PC, including 1.5 g/L 2,5-diphenyloxazole (PPO), fluor and wave–length shifter that guarantees the highest efficiency of light collection by the PMTs.



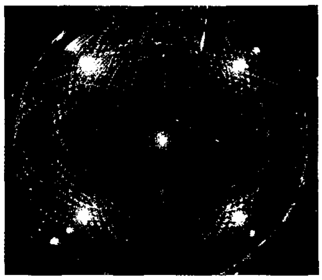


Figure 1: A cross-section of the Borexino detector (left), and a view inside of the stainless–steel sphere from one of the internal CCD-cameras (right).

Finally, a software–defined fiducial volume (FV) cut in the very center provides sufficient reduction of external gamma-rays. Different FV's were chosen for various analyses, e.g. 75 tons for the ^{7}Be ν-rate, 132 tons for the day–night, and 141 tons for the annual modulation search.

Solar neutrinos are detected in Borexino via their elastic scattering off of electrons. This recoil energy is deposited in the scintillator, causing light emission in a uniform direction from

[b] From a combined fit to solar and KamLAND experiments

[c] Thanks to the outer-detector and pulse-shape discrimination, the rejection efficiency of muons in Borexino is better than ~99.99%.

the de-exciting molecules. For every 1 MeV of deposited energy, about 500 photo-electrons are detected by the PMTs. The energy of each event can be defined as a number of hit–PMTs or the total charge collected, whereas the position is determined based on the scintillation–light arrival–time to individual PMTs. The energy and position resolution at 1 MeV in Borexino is on the order of 5%, and about 10-15 cm, respectively.

Due to the nature of neutrino interactions in the Borexino scintillator, the directionality information of the source is lost. This makes the signal indistinguishable from other backgrounds, such as beta- and gamma-radiation, requiring extreme radio–purity of the scintillator. In the end, not only the hardware but mainly the liquids underwent a series of purifications that resulted in unprecedented cleanliness of the system.

Calibration Detailed understanding of the Borexino detector and its response was critical in lowering systematic uncertainties that significantly contributed to the achieved 5% error on the ^{7}Be rate in Phase I. In four campaigns between 2008 and 2009, that took over 35 days of work, multiple configurations of α, β, γ and neutron sources in various energies (from $\sim$100 keV to $\sim$10 MeV) were inserted in about 295 locations throughout the inner vessel. Among the most important radioactive sources used were: ^{222}Rn+^{14}C (α, β, γ: FV, detector uniformity, α/β discrimination), and ^{241}Am^{9}Be (n: energy scale, FV).

One of the most important limitations on the internal calibration campaigns was imposed by the purity of the scintillator. The insertion system had to be thoroughly cleaned, and all the operations were performed through a glove–box filled with a Low Argon and Krypton Nitrogen solution (LAKN). Nevertheless, based on the post–calibration studies of ^{214}BiPo and ^{212}BiPo coincidences, it was determined that no longterm contamination was introduced [4].

3 Solar Neutrino Results

^{7}Be Flux Measurement Precision measurement of the ^{7}Be neutrinos was set as the first goal for the Borexino experiment. Data collection started in May 2007 and soon after, the first results were released, however they carried relatively high systematic errors. Phase I ended in May 2010, and with the information obtained from the calibration campaigns a new number for the ^{7}Be ν-interaction rate was determined, $46\pm1.5_{stat}\pm1.5_{sys}$ counts/(day x 100 ton), which corresponds to a remarkably low error of below 5%. The most significant improvements regarding systematic errors were made for the fiducial mass determination ($^{+0.5\%}_{-1.3\%}$), and energy scale (2.7%).

The Compton-like spectrum of the signal and known backgrounds is fitted to their shapes for best agreement. The dominant backgrounds for the ^{7}Be analysis include ^{210}Po, ^{85}Kr, ^{210}Bi, and ^{11}C (all left free in the fit). Along with about fifteen analysis cuts (muon rejection, electronics noise, fiducial mass etc.) an additional cut was used in order to remove alpha-like events. This cut relies on the Gatti parameter which is determined from a difference in the pulse-shapes for alpha- and beta-interactions in PC. The Borexino backgrounds were by far dominated by ^{210}Po, an alpha-emitter whose energy falls into the ^{7}Be window, but thanks to the Gatti–cut, it was possible to remove its contribution with high efficiency. The performance of the spectral fit method was determined by studying a Monte-Carlo (MC) simulated sample and by changing the conditions of the fit parameters in order to understand the effect on the final result. The obtained systematic error of the fitting method was found to be on the order of 2%. Fitted spectra from the data and the Monte-Carlo simulation are shown in Figure 2.

The expected number of un-oscillated ^{7}Be neutrinos in Borexino would be 74 ± 4.0 counts/(day x 100 ton). With the measured $46\pm1.5_{stat}\pm1.5_{sys}$ counts, this number is $5\,\sigma$ away from the expectation, resulting in the survival probability $P_{ee}=0.51\pm0.07$. In the MSW-LMA scenario, the fraction of the predicted to the determined flux with Borexino, $f_{Be}=\Phi(^{7}\mathrm{Be})/\Phi_{SSM}(^{7}\mathrm{Be})$ equals 0.97 ± 0.05. Adding a luminosity constraint, the determined fractions in the global analysis for other species were found to be: $f_{pp}=\Phi(\mathrm{pp})/\Phi_{pp}(^{7}\mathrm{Be})=1.013^{+0.003}_{-0.010}$.

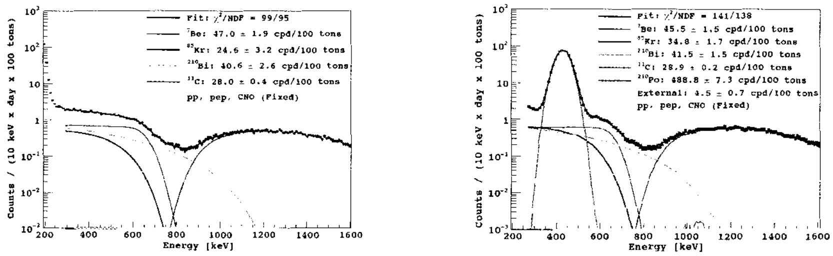


Figure 2: Spectral fit results of the Borexino data in Phase I (left), and its corresponding Monte-Carlo simulation (right). For the data, the alpha-events were statistically removed using Gatti's optimum method.

^{7}Be Day–Night Asymmetry In the scenario of low mass square splitting in the Standard Solar Model, solar neutrinos could regenerate while traversing Earth at night. The expected increase in the number of detected electron–neutrinos would be in this case higher by about 11 to even 80%. In order to test this scenario, the data sample was divided into *day* and *night* subsets and independently analyzed with the same techniques used in the ^{7}Be rate measurement. In fact, two methods were implemented, one that relied on spectral fitting to the individual shapes for *day*-and-*night*, and the other, that used subtracted spectra *night-day* (normalized spectra for both methods are presented in Figure 3). The asymmetry parameter A_{nd}, defined as $2\times(R_n\text{-}R_d)/(R_n+R_d)$, was found to be $0.001\pm0.012_{stat}\pm0.007_{sys}$ with the first method, and $0.007\pm0.073_{stat}$ with the second one; both consistent with zero. No regeneration was identified for the ^{7}Be line, a result that rejects the MSW-LOW solution at more than $8.5\,\sigma$.

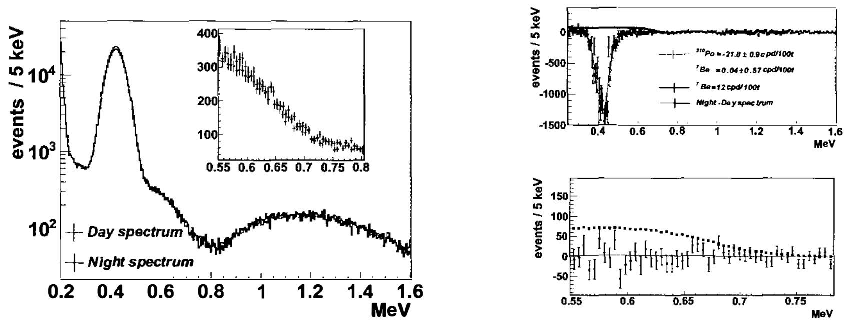


Figure 3: Spectra used in the day–night analysis. The *night-day* subtracted one (left) and separately *day*-and-*night* (right-top panel) with a zoom on the ^{7}Be energy range (right-bottom panel).

^{7}Be Annual Modulation During the 2013 Rencontres de Moriond conference, the Borexino collaboration released its first results for the ^{7}Be ν annual flux modulation. It is expected that in the MSW–LMA solution, all neutrino oscillations take place in the Sun, and the modulation effect is driven purely by the inverse-square-law of the changing Earth-to-Sun distance. This would be referred to as the *normal* effect, and the modulation would be on the order of 7% peak-to-peak. If however, the deficit of solar neutrinos was governed by oscillations in vacuum, between Earth and the Sun, the modulation pattern could differ from a sinusoidal shape. In such a case, we would refer to it as the *anomalous* effect. As a result, the annual modulation measurement can be used to test the Just-So solution of the oscillation parameter space.

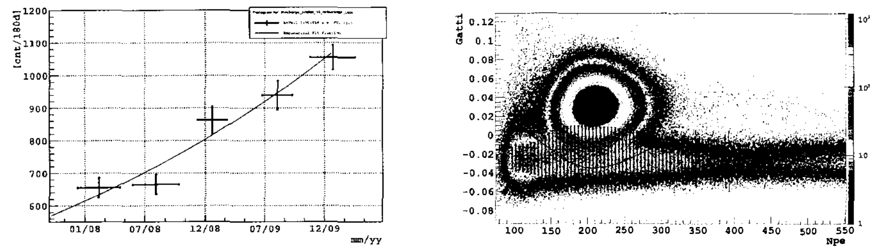


Figure 4: Background trend dominated by ^{210}Bi in the ^{7}Be-^{11}C valley (left), and the Gatti-parameter cut defined to remove all the alpha-like events, at the cost of some beta-events (right).

In this analysis, only rates were investigated as the sub-periods were too short for satisfactory spectral-fit results. With this approach, understanding of the detector's stability and backgrounds became critical. Among multiple factors, the most problematic turned out to be the increasing contribution of ^{210}Bi in the IV volume. The source of this increase is still under investigation, but it is believed that it came from the surface contamination of ^{210}Pb that is adsorbed onto the IV and was washed of by the scintillator currents. The best estimation of the ^{210}Bi trend was found to be exponential (Fig. 4, left), and it was used as the background shape on top of a flat distribution of other species in the [210; 760] keV window; this includes also ^{85}Kr, ^{11}Cand partially the external gamma-background. The contribution of the alpha-events in this region of interest, dominated by ^{210}Po, had to be eliminated by a complete removal of such events, as opposed to the statistical subtraction in the ^{7}Be flux analysis. An energy-dependent cut was defined in the Gatti-parameter space and applied to all the time-bins used in the study. Since the Gatti-separation between alpha- and beta-events is not clean, about 40% of the beta-signal had to be removed along with the alpha-cut (Fig. 4, right).

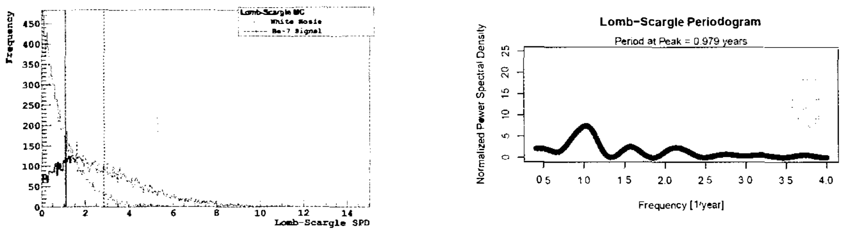


Figure 5: Lomb-Scargle simulation for the annual modulation (left), signal (blue) and white-noise (red). Spectral-Power-Density (SPD) from the Lomb-Scargle frequency analysis for the Borexino data in 10-day bins (right).

The Lomb–Scargle (LS) periodogram search method was used in the first analysis approach. This method is similar to the common Fast–Fourier–Transform used in frequency studies, but was tuned for unevenly distributed data–samples and, as a result, is more suitable for the solar neutrino study. The LS method is sometimes referred to as simply the Least–Square spectral analysis as it relies on a least–squares fit of sinusoids to data samples. Unfortunately, a rather low sensitivity for a significant result was determined from a Monte-Carlo simulation for the expected neutrino rate in Borexino, even though the available statistics was doubled using an increased fiducial mass of 141 tons. Figure 5 (left), shows the MC–simulated distribution of the Spectral–Power–Density (SPD) at 1-year for signal (blue–line) and white–noise (red–region). The vertical lines show the 1, 2 and $3\,\sigma$ confidence levels that correspond to a detection sensitivity of 81.62, 43.54 and 11.68% respectively [d]. From the analyzed data in Phase I, that was divided into 10-day bins, a significant peak was identified at 0.98–year, with a Lomb-Scargle SPD equal to 7.96, which corresponds to a $3\,\sigma$ confidence level derived from MC.

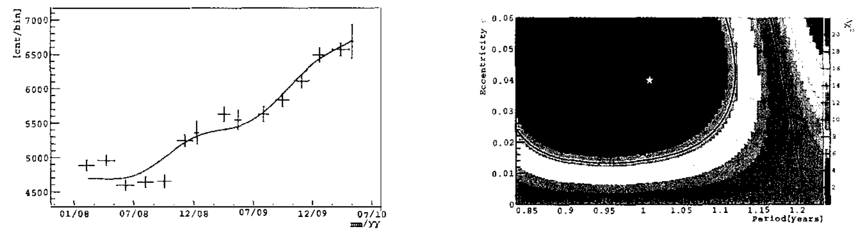


Figure 6: The expected annual modulation and its background function from Eq. 1 (left). 2 d.o.f. $\Delta\chi^2$ scatter plot for eccentricity on the vertical axis, and period (right), black lines show the 1, 2 and $3\,\sigma$ confidence contours.

In the second approach, the data was divided into 60-day bins and fitted with a sinusoidal function of the expected annual modulation and the background shape:

$$R(t) = B + \bar{R}\left[1 + 2\epsilon\cos\left(\frac{2\pi t}{T} - \phi\right)\right] \tag{1}$$

where, B is the background (dominated by the ^{210}Bi exponential factor) $C{+}e^{St}$, $\bar{R}$ the average neutrino rate, ϵ the eccentricity parameter, T period, and ϕ phase. The data–sample in comparison with the expected modulation is shown Figure 6 (left).

The resulting $\chi^2{=}1.27$ from the fit was satisfactory, and the eccentricity parameter ϵ was found to be 0.0398±0.0102. The fit–result can be seen as a yellow–star in the $\Delta\chi^2$ scatter plot in Figure 6 (right), where the expected values for eccentricity and period are indicated with a black-star, within a $2\,\sigma$ contour.

4 Conclusions

Borexino has completed Phase I of the solar neutrino program and performed a detailed analysis of its main target, the ^{7}Be ν-spectrum. The three major measurements, the overall rate of $46{\pm}1.5_{stat}{\pm}1.5_{sys}$ (5% error), the (absence of) day–night asymmetry and the annual–modulation of the ^{7}Be neutrinos, consistent with the *normal* effect, all deliver a clear confirmation of the MSW–Large–Mixing–Angle solution in the Standard Solar Model.

Phase II of data-acquisition started in October 2011 after a refined and successful purification campaign that helped significantly reduce the most important backgrounds for the detector: ^{85}Kr (consistent with 0 counts/(day x 100 ton)), ^{210}Bi (reduced by a factor of 2 with respect to Phase I), and ^{238}U and ^{232}Th chains (by an order of magnitude lower than in Phase I).

Borexino continuous its solar program and with the current status, it is expected to deliver even more precise and exciting physics in the near future.

References

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[d] If for instance, all the blue region was found above the $3\,\sigma$ line, we would say that there is a 100% probability of finding the evidence for the *normal* effect of the annual modulation.