Borexino: new results from the high-purity phase-II data

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Abstract. The Borexino experiment has recently celebrated the 10 years of data taking. Among the most relevant results already published, we remind the first direct measurement of $^7$Be and pep neutrinos and the best upper limit on CNO. In 2010-11 six purification were very successful in further reducing the already low backgrounds: a new high-purity Phase II data taking was started in October 2011, aimed to perform high precision measurements and to try to aggression the weakest components of the solar neutrino flux. In this contribution the first results based on the new Phase II data are reviewed.

1. Borexino and solar neutrinos
The Sun is an intense source of neutrinos that can be usefully exploited to better access the physical properties of these elusive particles. Since 2007 Borexino has measured the fluxes of low energy neutrinos, most notably those emitted in the pp chain nuclear fusion reactions in the Sun and the antineutrinos emitted in the beta decays along the natural radioactive chains in the Earth’s rocks. Borexino was the first experiment to make spectroscopic measurements of solar neutrinos with energy lower than 3 MeV, i.e. below the endpoint energy of natural radioactivity [1]. In 2011 thanks to extensive purification campaigns based on water extraction and nitrogen stripping, a record low scintillator contamination of less than $10^{-18}$ g/g was achieved for $^{238}$U and $^{232}$Th; the $^{85}$Kr contamination decreased by a factor 5 and $^{210}$Bi by a factor 2.5. A new Phase II data taking was started and in parallel, a refined Monte Carlo code [2] was developed able to reproduce the energy response of the detector, its uniformity within the fiducial scintillator volume relevant to neutrino physics, and the time distribution of detected photons to better than 1% between 100 keV and several MeV. 

In the following sections, after a brief description of the detector layout, the first results based on the new high-purity Phase II data are presented, namely the first direct measurement of pp-neutrinos, the

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seasonal modulation of the $^7$Be neutrino signal and a new upper limit on the neutrino magnetic moment.

2. The Borexino detector
Borexino, located deep underground (3,800 m water equivalent) in Hall C of the Gran Sasso Laboratory (Italy), measures solar neutrinos via their interactions with a target of 278 ton organic liquid scintillator. The ultrapure liquid scintillator (pseudocumene (1,2,4-trimethylbenzene (PC)) solvent with 1.5 g/l 2,5-diphenyloxazole (PPO) scintillating solute) is contained inside a thin transparent spherical nylon vessel of 8.5 m diameter. Solar neutrinos are detected by measuring the energy and position of electrons scattered by neutrino-electron elastic interactions. As a result of the elastic scattering, electrons gain kinetic energy up to a maximum of $E_\nu/(1 + m_e c^2/2E_\nu)$ where $E_\nu$ is the incoming neutrino energy.

The scintillator promptly converts the kinetic energy of electrons by emitting photons, which are detected and converted into electronic signals (photoelectrons (p.e.)) by 2212 photomultipliers (PMT) mounted on a concentric 13.7 m-diameter stainless steel sphere (SSS). The volume between the nylon vessel and the SSS is filled with 889 ton of ultra pure, non scintillating fluid and acts as a radiation shield for external gamma rays and neutrons. A second, larger nylon sphere (11.5 m diameter) prevents radon and other radioactive contaminants from the PMTs and SSS from diffusing into the central sensitive volume of the detector. The SSS is immersed in a 2100 ton water Cerenkov detector meant to detect residual cosmic muons.

To better disentangle the solar neutrino signals from radioactive backgrounds over a large energy range (from 0.2 to 3 MeV) a new fitting procedure has been developed based on a multivariate approach [3]: the binned likelihood function is built by including the energy spectrum, the distance from the center and the pulse shape distributions of the selected events.

This fitting procedure is repeated by exploiting both MonteCarlo based and analytical model descriptions of the detector energy response [3,4]: the comparison of the results obtained with the two methods is a powerful check for systematics.

3. The measure of pp neutrino flux
At the temperatures typical of the Sun center (~15.7 $10^6$ K) hydrogen is converted into helium predominantly via the pp chain with a release of 26.73 MeV for each conversion of four protons into a helium nuclide.

The highest flux of solar neutrinos comes directly from the first reaction of the chain, the fusion of two protons into a deuteron: $p + p \rightarrow d + e^+ + \nu_e$.

The neutrinos emitted in this reaction are called pp-neutrinos and before Borexino, only the radiochemical gallium experiments [5,6] have been sensitive to this low-energy component ($E < 420$ keV): since the radiochemical experiments measured an integrated flux of all solar electron neutrinos above a given threshold (233 keV for $^{71}$Ga) the pp neutrino signal was inferred only indirectly, by combining the radiochemical measurements with those of other experiments.

A direct study of pp neutrino is indeed essential to probe our knowledge of stellar modelling and energy production since the pp fusion is by fact the step-maker of the pp chain because of the small weak interaction cross section. By combining neutrino and optical observations it is possible to test the Sun thermodynamic equilibrium over a time scale of the order of $10^6$ years, i.e. the time needed to photons emitted in the Sun’s core to reach the surface after several absorption/reemission and scattering processes with the solar matter.

The pp-neutrino energy spectrum extends up to 420 keV, yielding to a maximal energy of the recoiled electrons of 264 keV: a low energy threshold and high energy resolution detector is mandatory for this measure.

In Borexino, the high scintillator light yield ($\sim 10^4$ photons/MeV) resulting in ~ 500 detected photoelectrons/MeV makes possible to reach a very low energy threshold (50 keV) with a good energy resolution (~ 5% at 1 MeV). Low background is also a key point.
By fact other attempts to measure pp-neutrinos directly over the past 30 years have been hindered by the inability to sufficiently suppress radioactive backgrounds in this low-energy region: particularly relevant is the background due to $^{14}$C, a $\beta$ emitters intrinsic to the organic liquid scintillator whose energy spectrum extends up to 156 keV and its ‘pile-up’.

In spite of its small isotopic fraction in the Borexino scintillator ($^{14}$C/$^{12}$C $\sim$ 2.7 $\cdot$ 10$^{-18}$), $^{14}$C $\beta$-decay is responsible for most of the detector trigger rate (~30 Hz at 50 keV threshold). $^{14}$C and pp-neutrinos exhibit however different energy spectra and they can be therefore disentangled.

To increase the sensitivity, independent and precise data–driven methods have been developed to constrain the irreducible $^{14}$C background and its pile-up [7].

The analysis was done by using the data collected from January 2012 to May 2013 for a total of 408 live days. The pp neutrino rate was extracted by fitting the measured energy spectrum of the selected events in the 165–590 keV energy window with the expected spectra of the signal and background components [7]; the main components of the fit were the solar neutrino signal (the dominant pp component and the low-energy parts of the $^7$Be, pep and CNO components), the $^{14}$C background, its pile-up, and the other relevant radioactive backgrounds ($^{85}$Kr, $^{210}$Bi, $^{210}$Po and $^{214}$Pb).

The solar pp neutrino interaction rate as measured by Borexino was of 144 $\pm$ 13 (stat.) $\pm$ 10 (syst.) counts/(day $\cdot$ 100 t) corresponding to a neutrino flux of $(6.6 \pm 0.7) \cdot 10^{10}$ cm$^{-2}$ s$^{-1}$, in accordance with the oscillation parameters reported in [8]. The survival probability was found to be $P_{\alpha\nu} = 0.64 \pm 0.12$, and it provides a constraint on the Mikheyev–Smirnov–Wolfenstein large-mixing-angle (MSW-LMA) solution in the low-energy vacuum regime.

This measurement demonstrates that about 99% of the energy of the Sun is generated by the pp fusion process.

4. The seasonal modulation of the $^7$Be neutrino signal

In contrast with water Cherenkov detectors, Borexino cannot retain directional information of individual events; a direct solar imaging is therefore not possible. However, the eccentricity of the Earth’s orbit induces a modulation of the detected signal proportional to the solid angle subtended by the Earth with respect the Sun: this effect appears as a 6.7% peak-to-peak seasonal modulation in the measured fluxes.

A search for this signature was already done with Phase I data (collected from May 2007 to May 2010), but because of some backgrounds varying in time, the evidence for such a modulation was poorer [1].

Borexino Phase-II data, in addition to higher statistics and lower background levels, are characterized by the absence of major scintillator handling and thus display a high degree of stability of the detector, crucially important for identifying time dependent signals.

A new attempt to measure this time periodicity in the $^7$Be solar neutrino component was made on the base of the data acquired between December 2011 and December 2015: of particular importance for this study was the reduction thanks to purification campaigns of the $^{85}$Kr and $^{210}$Bi concentrations, both backgrounds in $^7$Be region.

The cuts adopted for this particular analysis are described in [9]. Recoil electrons from the elastic scattering of $^7$Be-$\nu$'s are selected by restricting the analysis to the energy region $\sim$ 215-715 keV. In this range, the major backgrounds are the $\alpha$ decays of $^{210}$Po and the $\beta$ decays of $^{210}$Bi and $^{85}$Kr. The 5.3 MeV $\alpha$’s appear as a peak at $\sim$ 450 keV (after quenching) in the energy spectrum. A major change with respect to Phase I analysis was an enhanced rejection of $^{210}$Po $\alpha$ background, based on MultiLayer Perceptron (MLP) machine learning algorithm: this method uses a neural network based on 13 $\alpha/\beta$ discriminating input variables, that are computed for each event from the pulse time distribution. The MLP provides excellent $\alpha - \beta$ discrimination. With the mlp parameter threshold set at 0.9 to retain $\beta$’s, the $\alpha$ rejection efficiency above 99.98% was achieved for $^{210}$Po candidate events (7.7 MeV).

Due to Earth’s orbital eccentricity ($e = 0.0167$), the total count rate is expected to vary as:

$$ R(t) = R_0 + R_\alpha \left[ 1 + \epsilon \cdot \cos \frac{2\pi}{T} (t - \varphi) \right] $$

(1)
where $T$ is the period (one year), $\varphi$ is the phase relative to the perihelion, $R_A$ is the average neutrino interaction rate and $R_0$ is the time independent background rate. This formalism is consistent with the MSW solution predicting no additional time modulations at the $^7$Be energies. The event rate $R(t_k)$ of a series of time bins of equal length $t_k$ was obtained as the ratio of the number of selected events and the corrected life time (subtracted of the muon veto dead time and any down-time between consecutive runs).

The time bins are too short to allow extracting a value of the $^7$Be neutrino interaction rate via a spectral fit. The raw $\beta$-event rate was used instead, which include background contributions.

In a first approach the event rate as a function of the time was fit with the function defined in Eq. (2). To extract the modulation parameters, a $\chi^2$ fit of the data with 30.43-day bins was performed without folding multiple years on top of each other. Fig. 2 shows the event rate (in cpd/100 ton) along with the best fit. The best-fit eccentricity is $\epsilon = 0.0174 \pm 0.0045$, which corresponds to an amplitude of the modulation of $(7.1 \pm 1.9)\%$, and the best-fit period is $T = 367 \pm 10$ days [9]. Both values are in agreement with the expected values of 6.7% and of $T = 365.25$ days. The fit returns a phase of $\varphi = -18 \pm 24$ days.

We note that this result does represent a measurement of the astronomical year with solar neutrinos. The reliability of the method has been tested by following other two different analysis approaches: the Lomb-Scargle method, an extension of the Fourier Transform approach and the Empirical Mode decomposition (EMD) method, that makes no assumption about the functional form of the signal, in contrast to the Fourier analysis, and can therefore extract any time variation embedded in the data set. These alternative approaches provided perfectly consistent results. The no modulation hypothesis was excluded at 3.9 $\sigma$ by comparing the $\chi^2$ obtained with and without an annual periodicity [9].

5. A new upper limit on neutrino magnetic moment

When the standard model (SM) is extended to include neutrino masses, a neutrino magnetic moment is predicted, directly proportional to the neutrino mass: the known upper limit on neutrino mass $m$, lead to $\mu$, less that $10^{-18}$ $\mu_B$, which is roughly 8 orders of magnitude lower than the exiting experimental limits. The most stringent laboratory bound on $\mu$, is $2.9 \times 10^{-11}$ $\mu_B$ (90% C.L.) and has been obtained with reactor antineutrinos [10]. Other competitive limits come from astrophysical observations [11].

Though experimental bounds on $\mu$ are far from the values by extended SM, there are more general models with right-handed bosons or with an extended sector of scalar particles predicting magnetic moments proportional to the masses of charged leptons: these values are closer to the experimental bounds, therefore they justify further experimental investigations.

In the SM the scattering of a neutrino with a not zero magnetic moment is determined by both a weak interaction and a single photon exchange term. Since the latter changes the neutrino helicity, the amplitude on the two terms does not interfere and the total cross section is at the first order is the sum of the two. The coupling of the neutrino mass eigenstates to an electromagnetic field is characterized
by a 3 x 3 matrix of the magnetic and electric dipole moments. The contribution to the neutrino-electron scattering cross section is proportional to the square of the effective magnetic moment:

\[ \frac{d\sigma_{\text{EM}}}{dT_e} (T_e, E_\nu) = \pi r_0^2 \mu_{\text{eff}}^2 \left( \frac{1}{T_e} - \frac{1}{E_\nu} \right) \]  
\[ \mu_{\text{eff}}^2 = \sum_j |\sum_k \mu_{jk} A_k (E_\nu, L)|^2 \]  

where \( T_e \) is the electron recoil energy and \( r_0 \) is the classical electron radius. Since neutrinos are a mixture of mass eigenstates, the effective magnetic moment for neutrino-electron scattering \( \mu_{\text{eff}} \) depends on the components of the neutrino moment matrix \( \mu_{ij} \) and on the amplitude of the k-mass state at the point of scattering, \( A_k (E_\nu, L) \).

For \( T_e \ll E_\nu \), the ratio between the magnetic and weak scattering cross section is proportional to \( 1/T_e \) and sensitivity of an experiment strongly increases at low energies. This makes the low-energy threshold of Borexino perfectly suitable for a neutrino magnetic moment study: the effects of a non null neutrino magnetic moment can be investigated by looking for a distortion in the shape of the electron recoil energy spectrum.

A renewed search has been performed using data collected during the Borexino Phase II campaign from December 2011 to May 2016 with a live time of 1291.5 days. Events are selected within a fiducial volume corresponding to approximately 1/4 of the scintillator volume in order to increase the shielding against external backgrounds.

The analytical model used to describe the energy spectrum is an improved version of the one reported in [7] with the goal of enlarging the fitting energy range. The most relevant changes concern as improved treatment of the energy scale nonlinearities and the addition of a resolution parameter to better reproduce the low energy region. In the fitting procedure the minor components of pep, \(^7\)Be and CNO solar neutrino were kept fixed according to the standard solar model predictions. For CNO both high and low metallicity variant was tested since the predicted rates are significantly different and the induced uncertainty added to the systematics.

Special care was taken to describe the pileup events: a “synthetic” spectrum was constructed by overlapping real events with randomly sampled data of the same time length. Including the electromagnetic component as described in (2) in the fit leads to a decrease of the pp-neutrino component as a consequence of the larger total cross section: this correlation can be mitigated by applying the constraint coming from the result of radiochemical experiments, which are independent of the neutrino electromagnetic properties, to the sum of the neutrino fluxes detected in Borexino. If this constrain is added to the fit as a penalty term, the analysis of the likelihood profile gives a limit of \( \mu_{\text{eff}} < 2.8 \times 10^{-11} \) \( \mu_B \) at 90% C.L., already including the systematics [12].

In case of Majorana neutrinos only the transition moments of the electromagnetic matrix are non-zero, while the diagonal elements are null because of CPT. For the Dirac neutrinos all the elements may have non-zero values. The effective magnetic moment can be expanded both in terms of the mass eigenstates and of the flavour eigenstates. In the last case, the effective magnetic moment for the LMA-MSW solution is given by:

\[ \mu_{\text{eff}}^2 = \mu_e^2 + (1 - P^{2\nu}) (\cos^2 \theta_{23} \cdot \mu_\mu^2 + \sin^2 \theta_{23} \cdot \mu_\tau^2) \]  

where \( P^{2\nu} = \sin^4 \theta_{13} + \cos^4 \theta_{13} \cdot P^{2\nu} \) is the \( \nu_e \) survival probability with \( P^{2\nu} \) calculated in the standard 2-neutrino scheme; \( \theta_{13} \) and \( \theta_{23} \) are the corresponding mixing angles. The individual contributions in eq. (3) are positive therefore this expression can be used to compute limits on the single flavour magnetic moments.

In the approximation that the survival probability is the same for pp and \(^7\)Be neutrinos and equal to \( P^{2\nu} = 0.55 \), from eq. (3) the following limits can be quoted at 90% C.L. [12]:

\[ \mu_e < 2.8 \times 10^{-11} \]
• $\mu_e < 3.9 \times 10^{-11} \mu_B$  \hspace{1cm} (5)
• $\mu_\mu < 5.8 \times 10^{-11} \mu_B$  \hspace{1cm} (6)
• $\mu_\tau < 5.8 \times 10^{-11} \mu_B$  \hspace{1cm} (7)

Because the mass hierarchy is still unknown, the values above were calculated for the choice of hierarchy providing the most conservative limits, i.e. the inverted one.

In conclusion a new model independent limit of $\mu_{\text{eff}} < 2.8 \times 10^{-11} \mu_B$ was obtained at 90% C.L. including systematics, that slightly improves the previous best limit from GEMMA [9]. This limit was obtained by constraining the sum of the solar neutrino fluxes using the results form the gallium experiment and is free from uncertainty associated with prediction from the SSM flux and systematics from the detector fiducial volume mass.

![Figure 3](image.png)

**Figure 3.** Spectral fit with the neutrino magnetic moment equal to $\mu_{\text{eff}} = 2.8 \times 10^{-11} \mu_B$

6. Conclusions

The first results based on the new Borexino high-purity Phase II data have been reviewed, namely the first direct measurement of pp-neutrinos, the seasonal modulation of the $^7$Be neutrino signal and a new and improved upper limit on the neutrino magnetic moment. New preliminary and more precise neutrino fluxes measurements obtained with a simultaneous fit of pp, pep and $^7$Be components have been presented at this conference and they will be published soon.

7. References

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