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# New results of the Borexino experiment: *pp* solar neutrino detection

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**Summary.** — The Borexino experiment is an ultra-pure liquid scintillator detector, running at Laboratori Nazionali del Gran Sasso (Italy). Borexino has completed the real time spectroscopy of the solar neutrinos generated in the proton-proton chain in the core of the Sun. This article reviews the Borexino experiment and the first direct measurment of *pp* solar neutrinos.

PACS `14.60.Pq` – Neutrino mass and mixing.
PACS `13.15.+g` – Neutrino interactions.

## 1. – Introduction

Borexino is a real-time solar neutrino detector that is designed to detect low energy solar neutrinos, such as the 862 keV mono-energetic $^7$Be solar neutrinos [1,2]. One of the unique features of the Borexino detector is the very low background that allowed the first measurement of the $^7$Be neutrinos immediately after the detector became operational in May 2007 [2]. This result was the first real-time spectroscopic measurement of low energy solar neutrinos, and a technological breakthrough in low background counting.

Borexino is in data taking since May 2007. Borexino Phase I covers the period from May 2007 to May 2010. After the purification of the scintillator performed between May 2010 and August 2011, in November 2011 the Phase II of Borexino started. Borexino Phase II is expected to last at least until 2016.

Borexino-I solar neutrino results, described in detail in [3], include a high-precision measurement of $^7$Be neutrinos [4], the measurement of the absence of day-night asymmetry of $^7$Be neutrinos [5], a measurement of $^8$B solar neutrinos with a threshold recoil electron energy of 3 MeV [6], and the first time measurement of *pep* solar neutrinos and the strongest constraint up to date on CNO solar neutrinos [7]. Other Phase I results include the study of solar and other unknown anti-neutrino fluxes [8], observation of Geo-Neutrinos [9], searches for solar axions [10], and experimental limits on the Pauli-forbidden transitions in $^{12}$C nuclei [11].

The direct real-time measurement of the solar neutrinos from the fundamental *pp* reaction [12] is the greatest achievement of Borexino Phase II.

The motivating goal of low energy solar neutrino detection experiments is to directly probe the nuclear reaction processes in the Sun, and explore neutrino oscillations over a broader range of energies than has been done to date.

One of the features of neutrino oscillations that can be probed with Borexino is the transition from vacuum-dominated oscillation to matter-enhanced oscillations. In the Mikheyev Smirnov Wolfenstein (MSW) Large Mixing Angle (LMA) solution of solar neutrino oscillations [13,14], vacuum-dominated oscillations are expected to dominate at low energies ($\leq 0.5$ MeV), while matter-enhanced oscillations should dominate at higher energies ($\geq 3$ MeV). Accurate measurements of neutrinos with energies below and above the transition region can probe this special aspect of MSW-LMA solution.

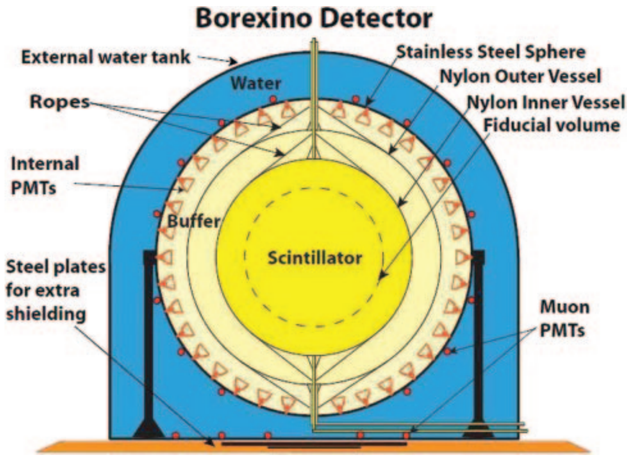


Fig. 1. – Schematic view of the Borexino detector.

## 2. – The Borexino Detector

The main features of the Borexino detector are illustrated schematically in fig. 1. The active detector is 278 tons of two-component liquid scintillator composed of pseudocumene (PC) and 2,5-diphenyloxazole (PPO), a wavelength shifter. The scintillator is contained in a thin nylon vessel, shielded by two PC buffers separated by a second nylon vessel. The scintillator and buffers are contained within a 13.7 m stainless steel sphere that is housed in a 16.9 m domed water tank for additional shielding and muon veto [15].

Neutrinos are detected by their elastic scattering on electrons in the liquid scintillator. The scintillation light is detected with an array of 2200 photomultiplier tubes mounted on the inside surface of the stainless steel sphere. The number of photomultipliers hit is a measure of the energy imparted to the electron, but has no sensitivity to the direction of the neutrino. The position of the scintillation event is determined by a photon time-of-flight method.

The scintillator is shielded from external gamma rays by a combination of high purity water and PC buffer fluids. Additional shielding against gamma rays from the detector peripheral structures is accomplished by selecting an inner fiducial volume (FV). With the external background highly suppressed, the crucial requirement for solar neutrino detection is the internal background in the scintillator. The basic strategy employed for Borexino is to purify the scintillator with a combination of distillation, water extraction, and nitrogen gas stripping [1, 16, 17]. The special procedures for scintillator purification and material fabrication resulted in very low internal backgrounds. The radioactive contaminations of the Borexino scintillator are summarised in table I.

## 3. – First real time detection of *pp* solar neutrinos

The data used in the analysis of the *pp* neutrinos has been collected between January 2010 and June 2013, for a total of 408 live days. As mentioned before, these data (Borexino Phase II data) are characterised by reduced levels of the most relevant radioactive backgrounds, namely $^{85}$Kr, $^{210}$Po, and $^{210}$Bi.

TABLE I. – *Residual contamination of the Borexino liquid scintillator before and after the purification performed in* 2010–2011. $^{210}$*Po rate is a factor 100 less than at the begining of data daking.* $^{210}$*Bi is a factor* 2 *less than in Phase I.*

| Isotope | Specs for LS | Before purification | After purification |
|---|---|---|---|
| $^{238}$U | $\leq 10^{-16}$ g/g | $(5.3 \pm 0.5) \times 10^{-18}$ g/g | $\leq 8 \times 10^{-20}$ g/g |
| $^{232}$Th | $\leq 10^{-16}$ g/g | $(3.8 \pm 0.8) \times 10^{-18}$ g/g | $\leq 9 \times 10^{-19}$ g/g |
| $^{14}$C/$^{12}$C | $\leq 10^{-18}$ | $(2.69 \pm 0.06) \times 10^{-18}$ | unchanged |
| $^{40}$K | $\leq 10^{-18}$ g/g | $\leq 0.4 \times 10^{-18}$ g/g | unchanged |
| $^{85}$Kr | $\leq 1$ cpd/100t | $(30 \pm 5)$ cpd/100t | $\leq 7$ cpd/100t |
| $^{39}$Ar | $\leq 1$ cpd/100t | $\ll^{85}$Kr | $\ll^{85}$Kr |
| $^{210}$Po | not specified | $\sim 700$ cpd/100t (decaying) | $\sim 90$ cpd/100t (decaying) |
| $^{210}$Bi | not specified | $\sim 20$–70 cpd/100 t | $(25 \pm 2)$ cpd/100t |

Basic data quality cuts of the *pp* analysis are the same of previous Borexino solar neutrino analysis [3] and include cuts to remove muon-correlated events, electronic noise, and $^{214}$Bi-$^{214}$Po in the radon branch in the uranium series. The fiducial volume used in this analysis is a truncated sphere with radius 3.021 m and a vertical cut $|z| \leq 1.67$ m. This fiducial volume corresponds to 75.5 ton of liquid scintillator target.

The main background in the *pp* region of interest is due to $^{14}$C $\beta$-decay, whose endpoint is 156 keV, and its pileup. It is necessary to estimate the $^{14}$C rate independently from the main analysis in order to reliably measure the *pp* neutrino interaction rate. This has been done by looking at at samples of data where the event causing the trigger is followed by a second event within the same data acquisition window (16 $\mu$s long, compared to 100–500 ns of scintillation events). These second events are not subject to the trigger threshold, so scintillation events with energy lower than the trigger threshold can be recorded in this sample. We fit the spectrum of these events against the $^{14}$C spectral shape, obtaining a $^{14}$C rate of $40 \pm 1$ Bq per 100 ton.

It is also necessary to evaluate the contribution due to $^{14}$C-$^{14}$C pileup, whose endpoint is very close to the endpoint of the *pp* induced recoil spectrum. We used an independent data-driven method, which we call *synthetic pileup*. The idea under this method is to artificially overlap real triggered events with random data obtained from the ends of real trigger windows, thus uncorrelated with the triggering event. These synthetic events are then reconstructed using the same software used for real events, and selected using the same analysis cuts, including fiducial volume cut. We generated a number sample of synthetic pile events equivalent to four time of our real data set. With this method, we obtained the true rate and spectral shape of the pileup in Borexino.

Once the $^{14}$C and pileup rates are tightly constrained, we can obtain the *pp* neutrino interaction rate by fitting the data spectrum against the known spectral shapes. In addition to *pp* recoils, $^{14}$C, and pileup, other species included in the fit are $^{7}$Be, *pep* and CNO solar neutrino recoils, $^{85}$Kr, $^{210}$Bi, $^{210}$Po and $^{214}$Pb. The scintillation light yield and two energy resolution parameters are free to vary in the fit. The $^{7}$Be is constrained to the measurement [3], *pep* and CNO are fixed to the value predicted by the latest high-metallicity Solar Standard Model. The $^{214}$Pb rate is fixed to the valued estimated by the $^{214}$Bi-$^{214}$Po coincidences. The energy spectrum after cuts, together with the best fit, is shown in fig. 2.

Systematic uncertainty in the fit were evaluated by varying the fit conditions. Effects considered include variations in the pileup evaluation method, the definition of the

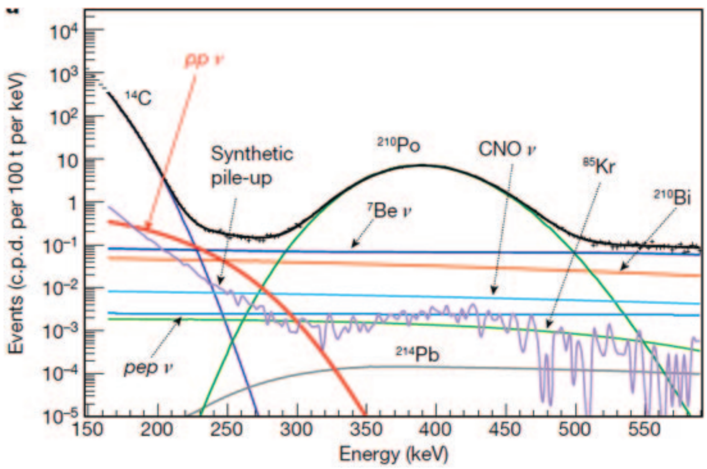


Fig. 2. – The fit result with all components. The fitted *pp* spectrum is shown in red. This figure has been taken from [12].

fiducial volume, the fixed parameters in the fit, and fit start and end points. The effect of the resolution of the position reconstruction algorithm has been included as systematic uncertainty.

The measured *pp* neutrino interaction rate in Borexino is

$$R_{pp} = 144 \pm 13(\mathrm{stat}) \pm 10(\mathrm{syst})\ (\mathrm{days}\ \cdot 100\,\mathrm{ton})^{-1}. \tag{1}$$

Many cross-checks on the stability of the result have been performed, including uncertainties on the spectral shapes of the fit components and adding the $\beta$-decay of $^{87}$Rb to the fit. No significant variations in the result were observed.

The electron neutrino survival probability $\mathrm{P}_{ee}$ is the probability for a electron neutrino produced in the Sun to be detected in the Earth as electron neutrino. We can measure $\mathrm{P}_{ee}$ from our measurement (1), knowing the neutrino interaction cross sections and the electron number density in Borexino and using the prediction of the Solar Standard Model as input. The *pp* neutrino survival probability is

$$P_{ee} = 0.64 \pm 0.12, \tag{2}$$

consistent with the expectation from LMA-MSW oscillation models. The contribution of Borexino to the experimental knowledge of the solar neutrino survival probability is displayed in fig. 3.

Using the neutrino oscillation parameters as input, we can compute the *pp* solar neutrino flux:

$$\phi_{pp} = (6.6 \pm 0.7) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}. \tag{3}$$

The Solar Standard Model prediction is consistent with our measurement.

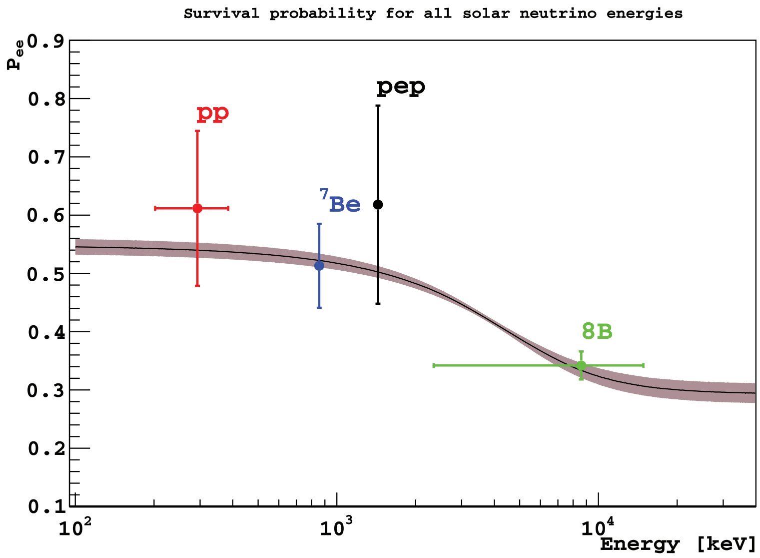


Fig. 3. – Electron neutrino survival probability. All the points in the plot have been measured by the Borexino experiment. In red, the measurement described in this work.

## 4. – Conclusion and outlook

Borexino performed the first direct spectral measurement of the neutrinos from the keystone proton-proton fusion. This observation is a crucial step towards the completion of the spectroscopy of the neutrinos emitted in the *pp* chain, as well as further validation of the LMA-MSW model of neutrino oscillation. The measurement strongly confirms our understanding of the Sun.

The main goals for Borexino Phase II and beyond include the reduction of the uncertainty of the *pep* neutrino flux, the detection of CNO neutrinos, and the reduction of the uncertainty of the $^{7}$Be neutrino flux.

One of the Borexino Phase II aims is also to search for fourth neutrino family (sterile neutrinos) with masses expected to be in the eV regime and the oscillation length of the order of 1 m. The Borexino large size and a good position reconstruction make it an appropriate tool for searching of sterile neutrinos through their short-base oscillation. The search is foreseen to be performed with artificial neutrino sources in the frame of a dedicated project called SOX [18].

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