First results on $^7$Be solar neutrinos from the Borexino real time detector

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This paper is dedicated to: C Arpesella, M Deutsch, B Freudiger, A Martemianov, S Vitale, members of the Collaboration, now deceased.

Abstract. The Borexino experiment started the data taking may 15th 2007. It is until now the only experiment able to detect in real time neutrino interactions below 2 MeV. This is due to the very high radio-purity reached by the detector, more than one order of magnitude better than the goal of the design. The detector allows the single fluxes of low energy solar neutrinos to be determined from all sources not previously studied: $^7$Be, pep, CNO and hopefully pp. Here the first measurement of the $^7$Be, obtained from the first 47.6 live days of data taking, is presented.
1. A touch of history
In 1990 a group of physicists conceived a project with the goal of studying in real time the solar neutrinos at energies below 2 MeV. For this study, the technology of liquid scintillation has been preferred over water Cherenkov detection, mainly for reasons of higher light yield and greater energy resolution.

The detection in real time of neutrinos below 2 MeV in an underground experiment becomes possible only if the background due to the natural radioactivity is strongly reduced. This is the main reason why the water detectors cannot lower the energy threshold below 5 MeV. A feasibility study revealed that the radioactivity levels of the scintillator should not exceed: $10^{-16}$ g/g for Th and U equivalent, $10^{-14}$ g/g for the natural K and $10^{-18}$ for the ratio $^{14}$C/$^{12}$C; in addition all the construction materials were subjected to a severe selection for radiopurity.

Two years of R&D on the purification showed that the measurements of such low background levels were not possible with the existing detectors. For instance, one of the more sensitive tool available, the plasma source mass spectrometer, was only able to reach $10^{-12}$-$10^{-13}$ g/g. Consequently the Borexino Collaboration constructed and installed a detector at the Gran Sasso underground Laboratory with 4 tons of scintillator (the Counting Test Facility-CTF), which was able to measure radioactivity levels down to $5 \cdot 10^{-16}$ g/g.

In 1995 the CTF measurements showed that, in principle, the Borexino detector was feasible because the design radio-purity goals were reachable [1].

In 1996 the Borexino project has been approved by the Italian INFN and by the German Agencies, and in 1997 by the US NSF. The construction and installation of the detector and the auxiliary plants progressed until August 2002, when the activities have been stopped due to problems between the Gran Sasso Laboratory and the local authorities. Unfortunately, it was only in 2005 that the Collaboration was allowed to resume the operations. A re-commissioning of the set-up was performed and full operations were possible in late spring 2006. The detector was filled with highly purified water by the end of the year.

At the beginning of 2007 the detector has been filled with the scintillator mixture (Pseudocumene plus 1.5 g/l of a fluorescent dye) and with the so-called Buffer liquid (Pseudocumene plus 5.0 g/l of quencher), in addition to the shielding water; all these liquids have been purified before they were inserted into the detector. These operations have been completed on May 15th 2007 and the data taking with the full detector began.

2. The detector
In figure 1 a sketch of the Borexino detector is shown. Borexino is located in the Hall C of the Gran Sasso underground Laboratory, featuring an overburden of $\approx 4000$ m water equivalent. The rate of cosmic muons at the detector location is $= 1/m^2 \cdot h$.

The core of the detector consists of 278 tons of liquid scintillator with two components (Pseudocumene (PC) plus PPO, 2,5-diphenyloxazole) contained in a nylon Inner Vessel (IV; 125 µm thick) with a 4.25 m radius. The IV is surrounded by 890 tons of Pseudocumene loaded to a light quencher (DMP, dimethylphthalate). A stainless steel sphere (SSS, having 6.75 m radius) contains both the liquid scintillator and the quencher Pseudocumene. The aim of the buffer liquid is to shield the IV from the radioactive emissions of the phototubes (PMTs) mounted on the sphere, from the stainless steel of the sphere itself, in addition to the residual external radiations (rock and water). The choice of Pseudocumene as buffer liquid aims to reduce the buoyancy on the IV to a negligible value.

The PMTs are 2214, 1843 of which coupled to an optical concentrator designed to detect only the light emitted by the scintillator; the remaining 371 without optical concentrators capture also the photons produced in the buffer region. Between the IV and the SSS an external nylon vessel functions to stop the radon emitted by the PMTs and by the stainless steel.

The SSS is shielded in all directions by, at least, two meters of ultra-pure water (2100 tons in total) contained in a cylindrical dome. Finally 200 PMTs are mounted on the external surface of the SSS.
(Outer Detector); they point outwards to detect the Cherenkov light produced in the shielding water by cosmic muons crossing the detector.

In Borexino the $\nu$–$e$ scattering is studied.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{Borexino_Design.png}
\caption{Schematic drawing of the Borexino detector.}
\end{figure}

3. Tools for a success

The set-up includes a relevant number of subsystems to store the PC, purify the PC, a concentrated solution of PC plus PPO (master solution), and the water, to fill the detector with the scintillator and with buffer liquid, and to perform precise cleaning of all the plants. In addition several safety installations have been integrated into the system.

But even more important are the methods, the procedures, the precautions adopted to construct and install the detector and the auxiliary systems [2]. Here the most important of them are listed:

i) The scintillator was cleaned before the filling of the detector: the PC and separately the master solution were purified via water extraction, distillation (at 80 mbar of pressure and 90-95 $^\circ$C of temperature), nitrogen stripping, ultra-fine filtration. The master solution has been added to the pure PC during the filling. The Nitrogen used for the stripping has been purified and selected to obtain the following upper limits: $\text{Rn}<8 \, \mu\text{Bq/m}^3$, $\text{Ar}<0.012 \, \text{ppm}$, $\text{Kr}<0.02 \, \text{ppt}$.

ii) Any water used in the installation has been purified to reduce the contaminants down to: $\text{U/Th equivalent}<10^{-14} \, \text{g/g}$, $\text{Rn}<1 \, \text{mBq/m}^3$, $\text{226Ra}<0.8 \, \text{mBq/m}^3$.

iii) All construction components: concrete, stainless-steel, gaskets, PMT glass and ceramics, sealing materials, etc. have been subjected to a rigorous solution process to keep the radioactive contents at minimum levels.

iv) All the critical stainless-steel subsystems were electro-polished. Their tightness was tested to be better than $10^{-8} \, \text{bar} \cdot \text{cm}^2 \cdot \text{s}$. This is particularly important because the Rn content in the underground air ranges between 40 and 120 Bq/m$^3$.

v) All operations concerning the detector have been carried out in cleans rooms at classes: 10, 100, 1000, depending on the operation conditions. During the installation the detector itself was a clean room of class 10000. All operations on the auxiliary plants have been made in N$_2$ atmosphere, whenever possible.

vi) A precision cleaning was applied to the detector, storage vessels, piping and plant components. The cleaning involved acid solutions, detergent and ultra-pure water.

vii) Special care was taken during the PC procurement: a dedicated loading station was constructed at the producer plant (Polimeri Europa in Sardinia), which allowed the loading of
clean isotanks in a N\textsubscript{2} atmosphere. The isotanks were then shipped to Gran Sasso and unloaded using a dedicated pumping station.

viii) Extreme precaution was taken in the fabrication and assembly of the nylon vessels. The raw material was selected and the film was extruded in controlled areas. Finally the nylon vessels were constructed in a clean room equipped with a dedicated Rn control system.

4. Data acquisition

The first tests of the electronics and DAQ have been carried out with the detector filled with N\textsubscript{2} and water. The data taking with the detector fully filled with scintillator, buffer liquid and water, started may 15\textsuperscript{th}, 2007. An initial period of time was devoted to the tuning of the electronics. Here the results of the first 47.4 live days of data acquisition are reported.

The main trigger fires when $\geq$ 30 PMTs detect one photo-electron, at least, within 60 ns. The energy threshold is about 60 keV. Time and charge of each PMT, detected in 7.2 $\mu$s, are recorded by means a TDC ($\approx$ 0.5 ns of resolution) and by an 8 bits ADC, respectively. The typical triggering rate is $\approx$ 11 cps (dominated by the $^{14}$C decays).

The Outer Detector gives a muon signal when $\geq$ 6 PMTs fire (99.8\% of probability of muon rejection). In addition, all events within 2 ms after a $\mu$ crossing the PC are rejected to discard muon induced activity. The muon rate on the IV is 0.0055$\pm$0.0002 s$^{-1}$.

In the Borexino detector the time and the total charge of each event are measured. The event location is reconstructed from the PMT timing. The absolute time is also provided via a GPS link.

The number of hits and the total collected charge are more or less equivalent because the detector is designed in such a way that, at energies lower than few MeV, in most of the cases the charge of the PMTs corresponds to one photoelectron.

Two fully independent analyses with two independent codes have been carried out. The reconstruction programs as used in the analysis, we are referring to here, have not yet been calibrated with external radioactive sources. The calibrations at present are based upon internal signals.

5. Detector performances

A fiducial volume (FV) is defined within the IV, in order to have a further shielding of 1.25m against the radiations emitted by the vessel nylon and the residual background from the PMTs.

The nominal IV radius is 4.25 m, corresponding to a content of 278 tons of scintillator. The effective IV radius has been reconstructed by means of various methods: the spatial distribution of the $^{14}$C decays, the decay of the Thoron ($\tau$=80 s) emitted by the IV nylon and particulate present on the IV surface, the external background $\gamma$s and the laser light diffused from teflon bowls, located on the IV external surface. All these methods, with the exception of the external background $\gamma$s, reconstruct the IV radius at about 4.60 m. The external $\gamma$s give a slightly larger number for the radius. Because a calibration with external sources has not been done yet, the Borexino Collaboration has decided to assume an IV with 4.60 m, with a total very conservative error of 25%.

The FV is defined by considering a volume containing the 35\% of the total events, corresponding to the ratio between the nominal FV and IV. In addition a cut on the vertical axis, less than 1.8 m, has been applied in this analysis of the first days, due to a temporary presence in the north hemisphere of Rn, consequence of refilling operations. Then, according with these criteria, the total fiducial volume for the analysis, we are referring here, is 87 tons.

The light yield was evaluated first fitting only the $^{14}$C spectra shape (featuring an electron with 156 keV end point [3]) and also by assuming it as free parameter in a global fit on the total energy spectrum and in particular by fitting the $^{14}$C distribution, the $^{210}$Po width and the $^7$Be neutrino Compton edge.

The light yield corresponds to about 500 photoelectrons per MeV. This value already takes into account the quenching factor. The high light yield favors a good spatial resolution (16 cm at 500 keV, with a $N_{p.e.}^{-1/2}$ scaling) and a good energy resolution (10\% at 200 keV, 8\% at 400 keV, 6\% at 1 MeV).
The background levels in the detector are in general better than what expected:

A) The $^{14}$C presence fits the design goal. The measured ratio $^{14}$C/$^{12}$C is $2.7 \pm 0.6 \times 10^{-18}$.

B) The background introduced by the Th family is measured via the sequence of the $^{212}$Bi-$^{212}$Po ($\tau=236 \mu s$), assuming a secular equilibrium. This method, already checked in CTF, has 93% efficiency. The measured contamination is $<6.6 \times 10^{-18}$ g/g, definitively better that our goal.

C) A very low background level was measured also for the $^{238}$U family contamination. In this case the $^{214}$Bi-$^{214}$Po coincidence ($\tau=236 \mu s$) has been used and a value of $^{238}$U equivalent $<2 \times 10^{-17}$ g/g was found. A check of our ability to identify the sequence $^{214}$Bi-$^{214}$Po has been made studying the same correlated decays when, during the filling, a very well detectable Rn and Rn daughters were present in the detector. The decay time of the $^{214}$Po has been measured to be $236 \pm 4 \mu s$, in perfect agreement with the nominal value.

D) An important presence of $^{210}$Po is observed ($\approx 90$ cpd/1 ton) without evidence of $^{210}$Bi. The measurement of its decay time shows a value in agreement with its nominal $\tau$ (200 d) and this supports the hypothesis that the contamination of $^{210}$Pb should be small. When the $^{210}$Po will be reduced, we will be able to understand better how negligible is the presence of $^{210}$Pb and consequently of its daughters (as $^{210}$Bi). For the moment the possible background due to $^{210}$Bi has been taken as free parameter in the fits.

E) Another important contaminant can be the $^{85}$Kr. Its presence in the scintillator can be studied directly via the well tagged decay $^{85}$Kr-$^{85m}$Rb-$^{85}$Rb, with the sequence $\beta$ (173 keV) and $\gamma$ (514 keV), 1.46 $\mu$ s apart [4]. The B.R. of this decay is very small (0.43%) and consequently a longer time of data taking is needed. Nevertheless we searched for this decay, finding two events which give an upper limit of 35 cpd/ton (90% c.l.). Until the statistics will be not improved the $^{85}$Kr is taken as free parameter in the total fit.

6. Data analysis and results

In figure 2 the photoelectron distribution of the raw data is shown. The lower plot is obtained after the subtraction of the muons and the $\mu$ correlated activities, the $^{222}$Rn daughters, the $\alpha$ particles (via the $\alpha/\beta$ discrimination). In addition the FV cut is applied. The shape of the distribution shows a remarkable agreement with what we can expect from the most important signal and unavoidable background: $^7$Be, $^{14}$C,$^{11}$C (figure 3).

Figure 2. Energy spectrum of the raw data (see text).

Figure 3. Spectrum of the more important signal and irreducible background (see text).

In these first weeks of data taking and analysis, we have focused our efforts on the $^7$Be region. The 250-800 keV energy region is being fitted, once subtracted from the spectrum the identified $^{212}$Bi, $^{214}$Po and a number of $^{210}$Pb decays equivalent to the $^{214}$Bi-$^{214}$Po coincidences. We proceeded with two
different fits: one without $\alpha$ subtraction and a second one with the $\alpha$ statistical subtraction, via the $\alpha/\beta$ discrimination, based upon the Gatti Parameter [5].

The statistical errors are determined by the $\chi^2$ profile. The systematic errors are dominated by the uncertainty in the FV definition.

Because in the energy range of the fit the CNO and $^{210}$Bi spectra are overlapped, their contributions are fitted together.

In figures 4 and 5 the two fits are presented, without and with $\alpha$ subtraction, respectively.

**Figure 4.** Energy spectrum without alpha subtraction

**Figure 5.** Energy spectrum once subtracted alphas via $\alpha/\beta$ discrimination.

The first fit has been carried out in two steps. In a first step the energy region 250-800 keV is fitted leaving the following parameters free: Light Yield, $^{210}$Po, $\sigma_{210}$, $^8$Kr, CNO+$^{210}$Bi, $^7$Be. In a second one the fit has been restricted to the range 560-800 keV, with only $^7$Be and CNO+$^{210}$Bi as free parameters, while the other ones are kept fixed at the values obtained from the 1st fit. The results are summarized in table 1, in cpd/100 tons, together with the statistical errors.

|          | $^{7}$Be | $^{85}$Kr | CNO+$^{210}$Bi |
|----------|----------|-----------|----------------|
|          | 49±7     | 16±9      | 19±3           |

The statistical error quoted for $^7$Be includes, in addition to the contribution obtained from the $\chi^2$ profile, also the change in the $^7$Be rate best fit if the $^{85}$Kr contribution is fixed at its maximum value (rate + 3$\sigma$).

The second fit is carried out on the energy spectrum where the alphas have been subtracted using the Gatti parameter [5], as shown in figure 5. This method, already tested in CTF [6] is based on the different time response of the scintillator for $\beta$ and $\alpha$ particle. The reference curves have been obtained from the study of the $^{214}$Bi-$^{214}$Po decays, present in the scintillator during the filling period, as the $^{222}$Rn daughters (the number of photoelectrons for individual shapes within 2 ns is taken into account; the times of the PMT hits are compensated for the travel distances). Then the Gatti parameter distributions for each 20 keV bins in the full range 200-800 keV have been calculated and the alphas have been subtracted from them (CTF tests demonstrated that the pulse shapes do not depend on energy). The efficiency of the method is 98.5%.

The fit on this spectrum has been carried out in the 240-800 keV range, assuming as free parameters: $^7$Be,CNO+$^{210}$Bi, $^8$Kr and the residual $^{219}$Po. The results of this fit are summarized in Table 2.
Table 2. (cpd/100 tons)

|          | ⁷Be      | ⁸²Kr     | CNO+⁴⁰Bi  | ²¹⁰Po (resid.) |
|----------|----------|----------|-----------|----------------|
|          | 47±7     | 22±7     | 15±4      | 0.9±1.2        |

In both cases the fits show a good degree of confidence; in the first fit we obtain $\chi^2/NDF=22.2/21$; in the second $\chi^2/NDF=41.9/47$.

The results of the fits on the two spectra, with and without alpha subtraction, agree very well each to other. The quoted errors are statistical only; a total systematic error of 25% has to be added on both the results.

In figure 6 the survival probability for $\nu_e$ from the Borexino (⁷Be) and SNO (⁸B) are compared with the curve expected from the best fit LMA oscillation values ($\Delta m^2_{12}=7.92\times10^{-5}\text{eV}^2, \sin^2\theta_{12}=0.314$) [7] and from the Solar Standard Model values quoted in BPS07 [8] (based upon the metallicity as in GS98). In the same plot the determination of the pp flux before and after Borexino data are also shown.

Figure 7. Survival probability for $\nu_e$ compared with the model curve (see text).

7. What next

The very good radio-purity achieved in Borexino, definitively higher than expected, opens possibilities beyond the experiment goals. Then in addition to the ⁷Be flux, we are confident to be able to measure also the pep and CNO fluxes: the main problem for the study of these two fluxes is the production, $\mu$ induced, of ¹¹C nuclides within the scintillator. Its production triggers a sequence of events, which provides a very good tagging: $\mu + ^{12}\text{C} \rightarrow ^{11}\text{C} + n + \mu$, $^{11}\text{C} \rightarrow ^{11}\text{Be} + e^- + \nu_e$, neutron capture after $\sim$300 $\mu$m with the emission of a 2.2 $\gamma$. With this threefold coincidence we can disentangle the ¹¹C, while missing only 14% of $\nu_e$ events; this method has been already checked in CTF [9].

In addition, due to the very good resolution, the pp flux could be studied because the ¹⁴C spectrum ends well below 200 keV.

A direct check of the $\nu$ origin can be obtained by studying the seasonal variations of the flux, due to the Earth orbit eccentricity. Taking into account the radio-purity achieved in Borexino, we can reproduce this effect with a C.L. of 2.5 $\sigma$ in one year and of 3.6 $\sigma$ in two years.

Another subject for our analysis program concerns the search for $\overline{\nu}$ from the Sun, Earth (geo-neutrinos) and nuclear reactors. We expect 7-17 events per year for geo-neutrinos, depending on the Earth models, to be selected using the Reines-Cowan detection reaction [10]. The background due to the reactor $\overline{\nu}$ is particularly favourable at Gran Sasso, due to the absence of reactors in Italy; a S/N $\approx 1$ is expected in the energy range of the geo-neutrinos. The total flux of $\overline{\nu}$ from reactors is $\approx 20$
events/years with a baseline of 1000 km, on the average. In both cases the whole detector of 300 tons is considered, due to the very good tagging of the $\bar{\nu}$ interactions: prompt positron followed by a $n$ capture after $\sim 300 \mu s$.

Borexino is also a good observatory for a Supernova explosion in our Galaxy. In Table 3 the channels with higher rate are quoted for a Supernova Standard @ 10kpc together with their total fluxes.

Table 3. The higher rates channels in Borexino for a Supenova explosion @ 10 kpc.

| Channel                                                | Rate |
|--------------------------------------------------------|------|
| Inverse beta decay $\rightarrow 79$ (E$_{\nu} > 1.8$ MeV) |      |
| $\nu$-p elastic scattering $\rightarrow 55$ (E$_{\nu} > 0.25$ MeV) |      |
| $^{12}$C($\nu$,p)$^{12}$C* $\rightarrow 17$ (E$_{\gamma} = 15.1$ MeV) |      |

For the first and the third channels other experiments can collect more statistics. For the second channel Borexino is almost unique because, due to the quenching, the p is pushed toward the low energies and, to detect it, a very low threshold is needed. In addition only the higher energy $\nu$ from Supernova are effective, and then this channel is triggered only by $\nu_\mu$ and $\nu_\tau$.

Finally we plan to push the limit of the $\nu$ magnetic moment to $\sim 5 \times 10^{-11}$ Bohr Magneton, by means a 2.5 MCi $^{51}$Cr source, to be installed in a access pipe designed on purpose below the Borexino at $\sim 8.25$ m from the detector's centre.

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