Results and perspectives of the solar neutrino experiment Borexino

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Borexino is a massive, calorimetric, liquid scintillator detector aimed at the detection of low energy sub-MeV solar neutrinos, installed at the Gran Sasso Laboratory. After several years of construction, data taking started in May 2007, providing immediately incontrovertible evidence of the unprecedented radiopurity of the target mass, at the level required to ensure the successful detection of 7Be solar neutrinos, which was then announced in the 2007 summer. In this talk first the main technical characteristics of the detector will be highlighted, with special emphasis on the exceptional purity challenges successfully faced by the Collaboration, and afterwards the physics outputs reached so far will be carefully reported and illustrated, together with the perspectives for the future measurements that will complete the broad program of the experiment.

1. INTRODUCTION

The Borexino Collaboration reported in early works [1], [2] the first real time measurement of the flux of the monoenergetic neutrinos from the 7Be electron capture in the core of the Sun, marking a fundamental scientific and technological breakthrough in the experimental field of solar neutrinos. This success represents the achievement of a 20 year long research, deeply rooted in the quest and development of purification techniques able to reach the new ground of the unprecedented radiopurity levels required for the successful 7Be neutrino detection. In particular, the impressive
background results obtained through the pilot prototype CTF [3], the first demonstration ever obtained of scintillator purities in the range required for low energy solar neutrino spectroscopy, were the key which opened the way towards the Borexino challenge.

The present work reports an account of the \(^7\)Be neutrinos flux measurement, based upon almost 200 days of data, after a short description of the main features of the detector and of the unprecedented low background levels achieved. Finally the future, further measurement perspectives of the experiment are described.

2. DETECTOR DESCRIPTION

The key features of the Borexino detector and of its components have been thoroughly described in [4][5], and thus only a succinct summary is reported here.

Borexino is a scintillator detector which employs as active detection medium a mixture of pseudocumene (PC, 1,2,4-trimethylbenzene) and PPO (2,5-diphenyloxazole, a fluorescent dye) at a concentration of 1.5 g/l. Because of its intrinsic high luminosity (50 times more than in the \(\bar{\nu}_e\) Cerenkov technique) the liquid scintillation technology is extremely suitable for massive calorimetric low energy spectroscopy. However, no directionality is possible and therefore, as a consequence, it is not possible to distinguish neutrino scattered electrons from electrons due to natural radioactivity. Thus the key requirement in the technology of Borexino is an extremely low radioactive contamination.

To reach ultra low operating background conditions in the detector, 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. The scintillator mass (278-ton) is contained in a 125 µm thick nylon Inner Vessel (IV) with a radius of 4.25 m. Within the IV a fiducial mass is software defined through the estimated events position, obtained from the PMTs timing data via a time-of-flight algorithm.

A second nylon outer vessel (OV) with radius 5.50 m surrounds the IV, acting as a barrier against radon and other background contaminations originating from outside. The region between the inner and outer vessels contains a passive shield composed of pseudocumene and 5.0 g/l DMP (dimethylphthalate), a material that quenches the residual scintillation of PC so that spectroscopic signals arise dominantly from the interior of the IV.

A 6.85 m radius stainless steel sphere (SSS) encloses the central part of the detector and serves also as a support structure for the 2212 8" PMTs (ETL 9351), each equipped with an aluminium light concentrator. The region between the OV and the SSS is filled with the same inert buffer fluid (PC plus DMP) which is contained between the inner and outer vessels. Finally, the entire detector is contained in a tank (radius 9 m, height 16.9 m) of ultra-pure water, in which the 200 PMT’s forming the muon veto detector are immersed.

It must be also mentioned that for the success of the experiment key elements are the many liquid purification and handling systems, which were designed and installed to ensure the proper manipulation of the fluids at the exceptional purity level demanded by Borexino.

3. GENERAL DETECTOR FEATURES

3.1. Expected signals and backgrounds

In Borexino the extraction of the neutrino flux relies upon the precise fit of the data to a signal plus background model obtained through the weighted sum of the theoretical spectra of all the expected contributions.
The expected signals are clearly the neutrino spectra which are computed according to the standard solar model and the MSW-LMA [6] oscillation framework. Since the analysis window is up to 2 MeV, the spectra of interest are those of the pp, pep and 7Be neutrinos from the pp chain, as well as the spectrum stemming from the CNO cycle.

The other spectra of interest are those of the dominant backgrounds. Experimentally we observed that the prominent contaminants are, at low energy, the 14C, at high energy the 11C of cosmogenic origin, and at the energy of the 7Be recoil spectrum the 85Kr and the 210Po. Their respective spectra have been thus carefully computed for the purpose of neutrino analysis.

3.2. Events reconstruction and detector performances

Borexino is a self-triggering multiplicity detector, and thus the main trigger fires when at least K PMTs detect one photoelectron within a time window of 60 ns. Typically, K was equal to 30 in the data runs considered in this work, corresponding approximately to an energy threshold of 60 keV.

Upon triggering, time and charge of each firing PMT are acquired and stored. The time is measured by a Time to Digital Converter (TDC) with a resolution of about 0.5 ns, while the charge (after integration and shaping of the PMT anode pulses) is measured through an 8 bit Analog to Digital Converter (ADC).

The readout sequence can also be activated by the outer muon detector through a suitable triggering system, which fires when at least six PMTs detect light in a time window of 150 ns. Regardless of the trigger type, both data from the inner and outer detectors are always acquired. The typical triggering rate during the runs analyzed in this paper was 15 Hz, including all trigger types. This rate is largely dominated by very low energy 14C events.

Event positions are estimated by analysis of the times of the triggered PMTs via a time-of-flight based likelihood methodology. The energy resolution scales as 5%/$\sqrt{E(\text{MeV})}$, while the position resolution is about 40 cm @ 150 keV.

The estimated light output is about 500 pe/MeV.

3.3. Measured background levels

As somehow expected from the successful CTF experience, U and Th proved immediately after the data taking start-up to be at an extremely low concentration level, i.e. (1.6±0.1) ·10^{-17} g/g for U and (6.8±1.3)·10^{-18} g/g for Th. For natural K the remarkable upper limit of <3·10^{-14} g/g has been obtained, as well.

Other important backgrounds in sizable, though tolerable, amount are 85Kr, evaluated to be 29±14 counts/(day·100 ton) via a special delayed coincidence tag, and 210Po (initial contamination of about 80 counts/day/ton, decaying afterwards following the intrinsic 200 days lifetime). By far, however, the major contaminant is 14C, whose isotopic ratio is evaluated from the detected counting rate equal to $^{14}\text{C}/^{12}\text{C}=(2.7±0.6) \cdot 10^{-18}$, perfectly suited for the planned analysis threshold of 200 keV. To be noted, finally, also the presence of the cosmogenic 11C signals, observed at an average rate of 25 c/d/100t, which is the range of the predictions stemming from the previous studies reported in [7] and [8], though slightly higher.

With the exception of the first couple of months after the end of the fill, the detected Rn contamination is very limited, at the level of few counts per week, the emanation from the vessel being its major source throughout most of the data taking period.

3.4. Event selections
The results presented here concern 192 live days between May 2007 and February 2008. Event selection is performed according to the following criteria:

(i) Only single cluster events are accepted, so to exclude pile-up and fast coincident events.

(ii) Muon events are rejected by means of the muon flag, i.e. of the signal registered in the outer water tank detector.

(iii) After each muon crossing the scintillator, all events (afterpulses and spurious events) within a time window of 2 ms are rejected.

(iv) The Radon induced $^{214}$Bi-$^{214}$Po sequences are identified and removed, as well as their precursor $^{214}$Pb signals.

(v) In order to remove the overwhelming external background, for neutrino analysis only signals reconstructed within a spherical 100 t fiducial volume are accepted.

Fig. 1 displays the spectra resulting from the selection cuts starting from the total raw spectrum. The solid black curve is the initial spectrum with only cuts (i-iii) applied. Two prominent components, $^{14}$C below 80 pe (i.e. photoelectrons) and $^{210}$Po at about 190 pe, are immediately visible.

4. EXTRACTION OF THE $^7$BE SOLAR NEUTRINO FLUX

The final spectrum after all the cuts is fitted to a global signal-plus-background model to extract quantitatively the value of the $^7$Be flux. Two independent analyses, providing consistent results, have been carried out.

The fit is performed roughly from 160 keV, thus including the extreme tail of the $^{14}$C, to 2 MeV, encompassing the entire $^{11}$C region. Free parameters are, besides the light yield, the amplitude multiplicative factors of the $^7$Be, CNO, $^{85}$Kr, $^{14}$C and $^{11}$C spectra. The pp and pep spectra are included in the fit, but at their nominal model value.
Figure 2. Global spectral fit in the energy region 160–2000 keV.

The fit output for the 192 days data sample considered here is reported in Fig. 2; the results are conventionally expressed in counts/day/100 tons of scintillator: the $^7$Be count rate is estimated to be $49 \pm 3$, Kr is $25 \pm 3$, consistent with the estimate stemming from the coincidence analysis, cumulatively CNO and $^{210}$Bi, that at this stage cannot be disentangled, are $23 \pm 2$, and $^{11}$C is $25 \pm 1$. The errors quoted so far are only the statistical errors, on top of which also the systematic errors should be considered. The uncertainties in the fiducial volume and energy scale determinations are the major sources of systematic errors, originating in the end the final $^7$Be evaluation of $49 \pm 3_{\text{stat}} \pm 4_{\text{sys}}$ counts/day/100 tons, which translates into a $^7$Be flux of $(5.08 \pm 0.25) \cdot 10^9$ cm$^{-2}$s$^{-1}$, very well in agreement with the prediction of the BS07(GS98) Standard Solar Model [9]. For comparison, the detected count rate in case of absence of oscillations would have been $74 \pm 4$ counts/day/100 tons. The resulting electrons survival probability at the $^7$Be energy is $P_{ee}=0.56 \pm 0.10$.

Therefore, Borexino on one hand spectacularly confirms the MSW-LMA solar neutrino oscillation scenario, and on the other provides the first direct measurement of the survival probability in the low energy vacuum MSW regime [10].

5. FUTURE PERSPECTIVES

Given the exceptional, unprecedented purity results achieved in Borexino, further measurements beyond the original goal of the $^7$Be detection are prospectively possible in the next years of running of the detector.

First of all a broad and accurate investigation of the solar neutrino spectrum is well within our experimental reach: not only the $^7$Be can be pinpointed to an accuracy of 5% (with respect to the 10% uncertainty of the measurement reported here), but also the other important medium and high energy components of the solar neutrino spectrum are suitable to be searched for. This is specifically true for the $^8$B neutrinos [11], as well as for the extremely challenging pep and CNO fluxes. For the latter two, in particular, it will be needed to cope with the background represented by the $^{11}$C signals, adhering to the strategy already devised by the Collaboration in [8].

The extremely low $^{14}$C level, coupled to the good achieved energy resolution, opens also a possible exploration window between 200 and 240 keV in which the observation of the fundamental pp flux can be attempted.

Other important fields of investigation for Borexino will be the neutrino magnetic moment (a limit of $< 5.4 \cdot 10^{-11} \, \mu_B$ (90% C.L.) being reported in [2]), the geoneutrinos [12] and the supernovae search.
6. CONCLUSIONS

After a long quest for the ultimate radiopurity, Borexino entered with great success the solar neutrino experimental arena providing the first real time detection of $^7$Be solar neutrinos, marking a fundamental milestone in the field of ultra low background techniques, as well as in the solar neutrino physics.

Such a success opens the way to further investigations of other solar $\nu$ sources ($^8$B, pep, CNO, pp), being the rich Borexino program suitable to be extended to neutrino magnetic moment, antineutrinos and supernovae studies.

References

[1] C. Arpesella et al. (Borexino Collaboration), “Direct Measurement of the $^7$Be Solar Neutrino Flux with 192 Days of Borexino Data”, Physical Review Letters, vol. 101, Issue 9, id. 091302, August 2008.

[2] C. Arpesella et al. (Borexino Collaboration), “First real time detection of $^7$Be solar neutrinos by Borexino”, Physics Letters B, Volume 658, Issue 4, p. 101-108, January 2008.

[3] G. Alimonti et al. (Borexino Collaboration), “Ultra-low background measurements in a large volume underground detector”, Astroparticle Physics, Volume 8, Issue 3, p. 141-157, February 1998.

[4] G. Alimonti et al. (Borexino Collaboration), “Science and technology of Borexino: a real-time detector for low energy solar neutrinos”, Astroparticle Physics, Volume 16, Issue 3, p. 205-234, January 2002.

[5] G. Alimonti et al. (Borexino Collaboration), “The Borexino detector at the Laboratori Nazionali del Gran Sasso”, arXiv:0806.2400.

[6] B. Aharmim et al. (SNO Collaboration), “Independent Measurement of the Total Active $^8$B Solar Neutrino Flux Using an Array of $^3$He Proportional Counters at the Sudbury Neutrino ObservatoryUltimo”, Physical Review Letters, vol. 101, Issue 11, id. 111301, September 2008.

[7] T. Hagner et al., “Muon-induced production of radioactive isotopes in scintillation detectors”, Astroparticle Physics, Volume 14, Issue 1, p. 33-47, August 2000.

[8] H. Back et al. (Borexino Collaboration), “CNO and pep neutrino spectroscopy in Borexino: Measurement of the deep-underground production of cosmogenic C11 in an organic liquid scintillator”, Physical Review C, vol. 74, Issue 4, id. 045805, October 2006.

[9] C. Peña-Garay, talk at the conference “Neutrino Telescopes 2007”, March 6-9, 2007, Venice, available online at neutrino.pd.infn.it/conference2007/Garay talk.

[10] J. N. Bahcall and C. Peña-Garay, “A road map to solar neutrino fluxes, neutrino oscillation parameters, and tests for new physics”, Journal of High Energy Physics, Issue 11, pp. 004, November 2003.

[11] G. Bellini et al. (Borexino Collaboration), “Measurement of the solar $^8$B neutrino flux with 246 live days of Borexino and observation of the MSW vacuum-matter transition”, arXiv:0808.2868.

[12] M.G. Giammarchi and L. Miramonti, “Geoneutrinos in Borexino”, Earth, Moon, and Planets, Volume 99, Issue 1-4, pp. 207-220, December 2006.