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Borexino—The achievements and prospects

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Summary. — The Borexino detector, located in the Gran Sasso National Laboratory in Italy, has been designed for real-time spectroscopy of low-energy solar neutrinos. It is also capable to register geo-neutrinos and neutrinos from artificial sources. In Phase I of the experiment lasting for three years between May 2007 and May 2010, we performed the first independent measurements of ^{7}Be, ^{8}B and *pep* solar-neutrino fluxes, as well as the first measurement of antineutrinos from the Earth. After a dedicated purification campaign of the liquid scintillator in 2011 Borexino entered into Phase II, which allowed to investigate the seasonal modulation in the ^{7}Be signal, to study the cosmogenic backgrounds and to update the measurement of the geo-neutrinos. Within Borexino a new project SOX is also under development. It is devoted to search for sterile neutrinos via the use of a ^{51}Cr neutrino source and a ^{144}Ce-^{144}Pr antineutrino source placed in close proximity of the detector active volume.

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

1. – The Borexino detector

Borexino, located at the Gran Sasso Laboratory [1, 2], is a liquid-scintillator (LS) detector with active mass of 278 tons. The scintillator is a mixture of pseudocumene (PC, solvent) and diphenyloxazole (PPO, concentration of 1.5 g/l), the latter one serving as a wavelength shifter. The main goal of the experiment was the real-time registration of sub-MeV solar neutrinos (mainly ^{7}Be neutrinos) through their elastic scattering on the LS electrons. The lack of directionality of the light emitted by the scintillator makes it impossible to distinguish neutrino-scattered electrons from electrons due to natural radioactivity. This is leading to a crucial requirement of the Borexino technology, namely an extremely low radioactive contamination of the detection medium. This has been achieved after extensive R&D studies and presently the detector purity is at an unprecedented level, never achieved so far in any other project. In this sense the Borexino detector is very unique worldwide and allows to study extremely week processes.

The scintillator is confined within a thin spherical nylon vessel with a radius of 4.25 m. The detector core is shielded from external radiation by 890 tons of buffer liquid, a solution of PC and the light quencher (dimethylphthalate). The buffer is divided in two volumes by the second nylon vessel with a 5.75 m radius, preventing inward radon diffusion. All this is contained in a 13.7 m diameter stainless-steel sphere instrumented with 2212 8$''$ PMTs detecting the scintillation light. An external, domed water tank of 9 m radius and 16.9 m height, filled with ultrahigh-purity water, serves as a passive shield against neutrons and gamma rays as well as an active muon veto. The Cherenkov light radiated by muons passing through the water is registered by 208 8$''$ external PMTs, also mounted on the SSS. The detector is schematically shown in fig. 1.

The Borexino scintillator provides high light yield of about 10^4 photons/MeV, resulting in 500 detected photoelectrons/MeV. The fast time response ($\sim$ 3 ns) allows

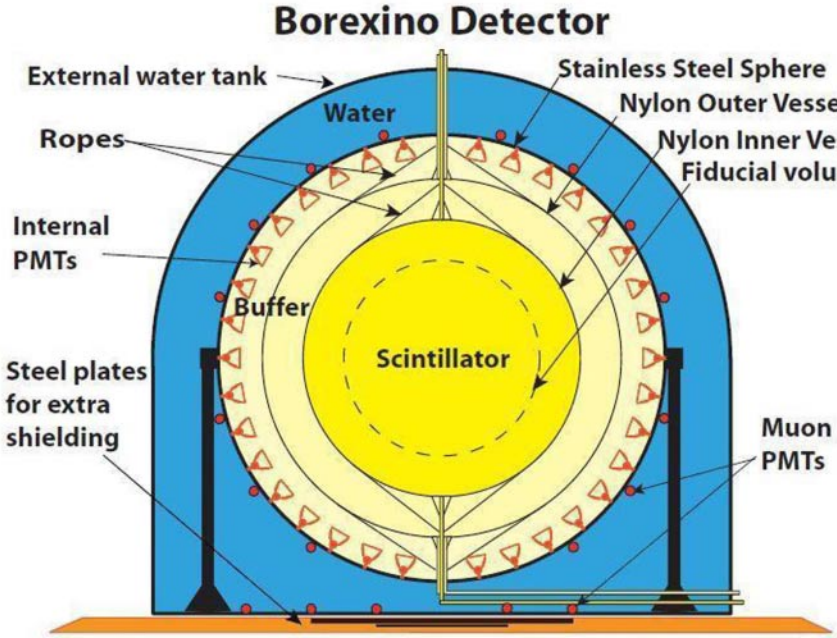

Fig. 1. – The Borexino detector, displaying its characteristic onion-like structure with fluid volumes of increasing radio-purity towards the center. While solar-neutrino measurements are made using events with reconstructed positions falling inside the innermost volume of scintillator (Fiducial Volume). It is surrounded by large mass, which is necessary for shielding and measurements of environmental radioactivity. Shielding against cosmic rays is provided by a rock overburden corresponding to a depth of 3800 m w.e.

reconstruction of the events position with ~ 14 cm precision. Depending on the analysis, the Fiducial Volume is defined between 75 tons and 150 tons. The signature of ^{7}Be neutrinos is a Compton-like shoulder at 665 keV in the electron recoil spectrum. The energy resolution at ^{7}Be energy is as low as 44 keV ($\sim 6.6\%$). The analysis threshold is 165 keV and the Pulse Shape Analysis (PSA) is performed to identify various classes of events: electronic noise, pile-up events, muons, α and β particles.

The timeline of the experiment is schematically shown in fig. 2 with the respective lists of achievements in Phase I and goals for Phase II. The residual contaminations of the Borexino scintillator are summarised in table I. As it can be noticed the ^{238}U and ^{232}Th concentrations are extremely low, exceeding the original requirements by about two orders of magnitude. Most other contaminants are at acceptable levels or have been reduced below required limits after a purification campaign performed between May 2010 and Aug. 2011. Not accounted for but present in the detector ^{210}Bi and ^{210}Po are not in equilibrium (^{210}Po is decaying away according to its half-life). ^{210}Po is of concern since its quenched α decays are registered at about 400 keV, just below the expected ^{7}Be edge. They can be however very efficiently tagged and removed by PSA. ^{210}Bi has been rising during the data taking due to unclear motivations, possibly related to the movement of the scintillator. This variation was modelled and taken into account in the ^{7}Be flux modulation analysis. The ^{210}Bi content was noticeably reduced by the purification campaign to a level which might allow the measurement of the CNO neutrino flux.

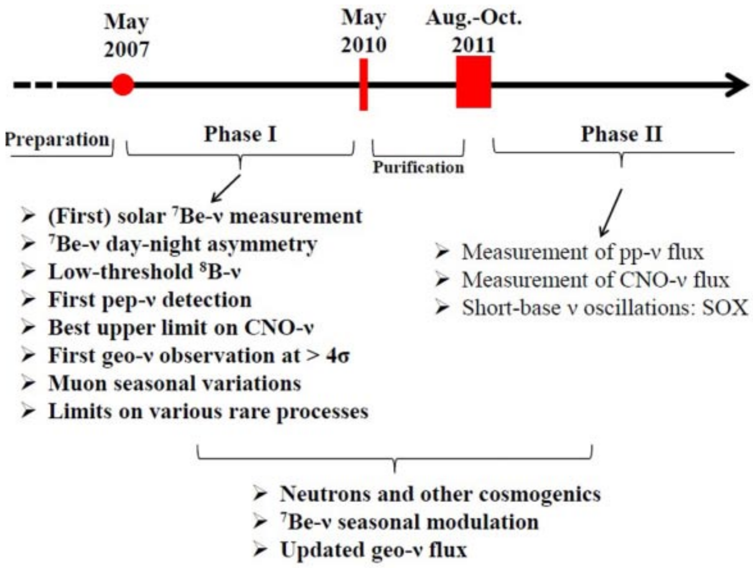

Fig. 2. – The timeline of the Borexino experiment. Phase I covers the period from May 2007 to May 2010. After the purification of the scintillator through the loop water extraction, in November 2011, Phase II started and is expected to last at least until the end of 2014. Measurements performed in Phase I and expected to be completed in Phase II are also listed. Some results were already obtained by combining data from both Phases.

2. – Selected Phase-I results

The main aim of Borexino was the detection of the mono-energetic ^{7}Be neutrinos (862 keV) with 5% precision. This goal has been achieved during the realization of Phase I of the experiment [3,4]. The ^{7}Be neutrino signal was extracted from a spectral fit along

Table I. – *Residual contamination of the Borexino liquid scintillator before and after the purification performed in* 2010-2011*. For* ^{210}Po *and* ^{210}Bi *we give additionally (in brackets) the count rate right after the start of the experiment (in May* 2007*).*

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	$\leq 0.8 \times 10^{-19}$ g/g
^{232}Th	$\leq 10^{-16}$ g/g	$(3.8 \pm 0.8) \times 10^{-18}$ g/g	$\leq 1.0 \times 10^{-18}$ 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	≤ 1 cpd/100 t	(30 ± 5) cpd/100 t	≤ 5 cpd/100 t
^{39}Ar	≤ 1 cpd/100 t	$\ll$ ^{85}Kr	$\ll$ ^{85}Kr
^{210}Po	not specified	$\sim$ (70) 1 cpd/100 t	unchanged
^{210}Bi	not specified	$\sim$ (20) 70 cpd/100 t	(20 ± 5) cpd/100 t

with other neutrino signals and background components. The fit is performed both using analytical spectral shapes and Monte Carlo generated curves, with and without the statistical subtraction of the α events identified by PSA. The results were always consistent within the uncertainties. The latest reported rate after 741 days of live-time (Phase I) is $R_{\mathrm{Be}} = 46 \pm 1.5_{\mathrm{stat}} \pm 1.6_{\mathrm{syst}}\ \nu/\mathrm{d}/100\,\mathrm{t}$. It is worth underlining that the achieved experimental uncertainty (4.8%) is lower than the theoretical one (7%). The measured rate can be translated into the ^{7}Be neutrino flux of $\Phi_{\mathrm{Be}} = (3.10 \pm 0.15) \times 10^9\ \nu/\mathrm{cm}^2/\mathrm{s}$. Thus the survival probability is $P_{ee} = 0.51 \pm 0.07$ (at 862 keV).

The stability of the detector allowed also to study the day-night effect of the ^{7}Be solar-neutrino signal. Our data is consistent with no asymmetry between the day and the night rates: $A_{\mathrm{DN}} = 0.001 \pm 0.012_{\mathrm{stat}} \pm 0.007_{\mathrm{syst}}$. This result allows to exclude (at 8.5 σ) the LOW solution of the neutrino oscillation basing on solar data alone [5].

The very good energy resolution achieved in the Borexino detector allows to look at the solar ^{8}B neutrinos starting practically from the energies of the so-called thallium limit of 2.8 MeV (the lowest threshold achieved up to date in the ^{8}B neutrino real-time measurements). The analysis reported in [7] has been performed using one year statistics (246 days of live-time). It is particulary interesting since it allows to inspect the vacuum-matter transition region of the LMA solution. The transition is expected to be smooth but there are models predicting different behaviour (Non Standard Neutrino Interactions models). The measured rate is $R_{\mathrm{B}} = 0.22 \pm 0.04_{\mathrm{stat}} \pm 0.01_{\mathrm{syst}}\ \nu/\mathrm{d}/100\,\mathrm{t}$ and corresponds to the flux of $\Phi_{\mathrm{B}} = (2.4 \pm 0.4_{\mathrm{stat}} \pm 0.1_{\mathrm{syst}}) \times 10^6\ \nu/\mathrm{cm}^2/\mathrm{s}$. Calculating the corresponding mean electron neutrino survival probability one gets thus is 0.29 ± 0.10 for the effective energy of 8.6 MeV.

Another very good candidates to investigate the vacuum-matter transition region of the MSW solution are the mono-energetic *pep* neutrinos ($E_\nu = 1.44\,\mathrm{MeV}$). Borexino reported the first direct detection of these neutrinos in [7]. It was possible thanks to the careful rejection of ^{11}C events (with a threefold coincidence tagging and orthopositronium pulse-shape discrimination techniques). The measured rate based on 590 live-days is $R_{pep} = (3.1 \pm 0.6_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}})\ \nu/\mathrm{d}/100\,\mathrm{t}$. Thus the absence of *pep* neutrinos is rejected at 98% C.L. The established rate corresponds to a flux of $\Phi_{pep} = (1.6 \pm 0.3) \times 10^8\ \nu/\mathrm{cm}^2/\mathrm{s}$ and a survival probability of $P_{ee} = 0.62 \pm 0.17$ at 1.44 MeV. *pep* neutrinos are also very important for another reason: they are closely related to the fundamental *pp* neutrinos and have their flux theoretically well constrained by this relation (the flux of *pep* neutrinos is predicted with 1.2% accuracy). Measurement of the *pep* neutrinos allows therefore also to test the core of the Standard Solar Model (SSM).

In the same energy region as the *pep* neutrinos are neutrinos originating from the solar CNO cycle. Their flux could however not be extracted due to the spectral shape degeneracy with the ^{210}Bi background. Only an upper limit on the rate could be derived and it is still the strongest up to date: $R_{\mathrm{CNO}} < 7.1\,\nu/\mathrm{d}/100\,\mathrm{t}$ at 95% C.L., corresponding to $\Phi_{\mathrm{CNO}} < 7.7 \times 10^8\ \nu/\mathrm{cm}^2/\mathrm{s}$.

Figure 3 shows the survival probability of the solar electron neutrinos after travelling to the Earth along with experimental values, out of which three were established by Borexino. The very interesting transition region between 1 MeV and 3 MeV is still not fully covered and there is room for alternative models with respect to smooth transition. There are essentially two ways to test these hypotheses or confirm the LMA solution: reducing the uncertainty on *pep* flux and/or lowering the threshold on ^{8}B neutrinos to observe (or not) the possible upturn of the spectrum. In Phase II Borexino is following both approaches.

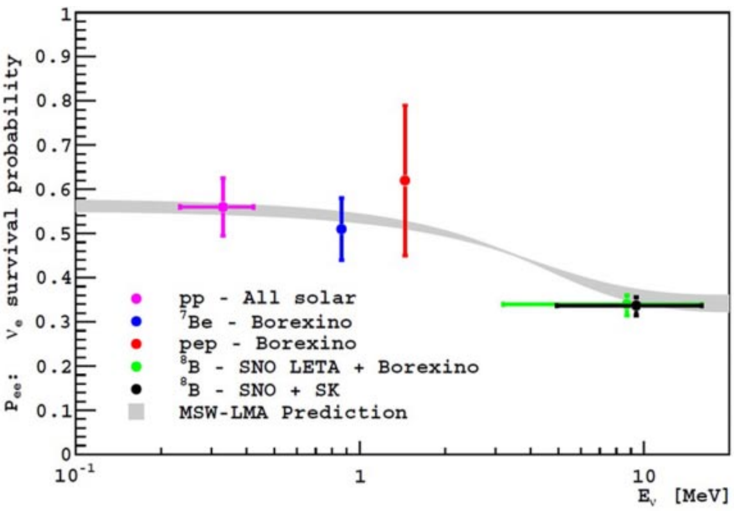

Fig. 3. – Electron neutrino survival probability: three points in the plot have been found by the Borexino experiment.

3. – Combined Phase-I and Phase II-results

Using the data from Phase I and Phase II we have improved the results of the geo-neutrino flux measurement [8], performed a thorough study of cosmogenic backgrounds in the detector [9], and studied the annual modulation of the flux of the ^{7}Be neutrinos [10]. The last topic is briefly discussed below.

The precise (4.8% accuracy) measurement of the solar ^{7}Be neutrino flux allowed to investigate its annual modulation. It is expected that the solar neutrino flux registered on Earth must undergo a yearly modulation due to the eccentricity of the Earth's orbit. The flux is minimal at the beginning of July and maximal at the beginning of January. The expected amplitude is only $\pm 3.4\%$ thus very difficult to observe (even with precise Borexino measurement). A very refined analysis based on dynamic and enlarged Fiducial Volume (141 tons *vs.* the "standard" 75 tons) have been performed thanks to precise determination of the Inner Vessel shape. The found oscillation period is $T = (1.01 \pm 0.07)$ y and the phase, measured from Jan 1st 2008, is $\phi = (11.0 \pm 4.0)$ d. The average ^{7}Be rate and the eccentricity ϵ are consistent within 2 σ with the spectral fit result and with the expected orbit eccentricity, respectively. The hypothesis of no modulation is thus rejected at $> 3\,\sigma$. The observation of this modulation in the ^{7}Be flux is the ultimate proof that Borexino is registering neutrinos coming from the Sun.

4. – Phase-II programm

The main goals for Borexino Phase II are the following:

– measurement of the *pp* neutrino flux,

– reduction of the uncertainty of the *pep* neutrino flux down to $\sim 10\%$,

– measurement of the CNO neutrino flux,

– reduction of the uncertainty of the ^{7}Be neutrino flux down to $\sim 3\%$,

– search for the sterile neutrinos within the SOX project.

The direct real-time measurement of the neutrinos from the fundamental pp reaction in the core of the Sun would be one of the major achievements of Borexino. It seems possible mainly due to the very low ^{85}Kr and ^{210}Bi concentrations achieved with the purification campaigns. A dedicated effort has also been made to understand the ^{14}C spectrum and to disentangling it from the expected spectrum caused by the *pp* neutrinos. The release of the results is expected still within 2014.

A precision measurement of the *pep* neutrino flux, possibly with 10% precision, and an attempt to determine the CNO flux also have very high priorities. This is due to their fundamental astrophysical importance, in particular as the they can help resolve the solar metallicity problem [11]. Since for this analysis contamination with ^{210}Bi is crucial, an additional purification campaign is considered to reduce it to an acceptable level.

Another goal is to reduce the overall error on the ^{7}Be flux down to 3%. This will not help to solve the metallicity problem due to theoretical uncertainties but it would make it possible to observe the seasonal variation effect over many cycles, which should be much more pronounced.

One of the Borexino Phase II aims is also to search for fourth neutrino family (sterile neutrinos, whose existence was postulated by some experiments) with masses expected to be in the eV regime and the oscillation length of the order of 1 m. The Borexino large size (8.5 m diameter of the active volume) and a good position reconstruction (precision of ~ 14 cm at 1 MeV) make it therefore 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 [12]. The location for a source is the pit present under the detector, which was excavated for this purpose before the detector's construction thus no work on the detector is needed (no contamination risks). It is foreseen to use a ^{51}Cr and a ^{144}Ce-^{144}Pr source in 2015 and in 2016. ^{51}Cr is a dichromatic neutrino emitter with energies of 430 keV (10%) and 750 keV (90%) and a relatively short decay time (~ 40 d). The activity required is of the order of 10 MCi and we plan to achieve this by re-activating the Chromium material used in Gallex and GNO experiments. The ^{144}Ce-^{144}Pr source instead is a β-emitter of antineutrinos with energies up to 3 MeV and a decay time of 411 d. Thanks to the neutron tagging, which makes antineutrino detection essentially background free such that one can perform the measurement with a source activity of about 100–120 kCi. According to the Monte Carlo simulations SOX will be able to unambiguously prove or reject the hypothesis about the existence of the sterile neutrino. In case of the existence, with parameters indicated by the reactor anomaly, SOX will surely discover the effect and measure the parameters of oscillation.

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REFERENCES

[1] Alimonti G. *et al.*, *Nucl. Instrum. Methods A*, **600** (2009) 586.
[2] Bellini G. *et al.*, *JINST*, **6** (2011) 5005.
[3] Arpesella A. *et al.*, *Phys. Rev. Lett.*, **101** (2008) 091302.
[4] Bellini G. *et al.*, *Phys. Rev. Lett.*, **107** (2011) 141302.
[5] Bellini G. *et al.*, *Phys. Rev. B*, **707** (2012) 22.
[6] Bellini G. *et al.*, *Phys. Rev. D*, **82** (2010) 033006.
[7] Bellini G. *et al.*, *Phys. Rev. Lett.*, **108** (2012) 051302.
[8] Bellini G. *et al.*, *Phys. Lett. B*, **722** (2013) 295.
[9] Bellini G. *et al.*, *JCAP*, **08** (2013) 49.
[10] Bellini G. *et al.*, *Phys. Rev. D*, **89** (2014) 112007.
[11] Haxton W. C. *et al.*, *Annu. Rev. Astron. Astrophys.*, **51** (2013) 21.
[12] Bellini G. *et al.*, *JHEP*, **08** (2013) 038.