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Recent results and future perspectives of the Borexino experiment

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Summary. — We present the main results achieved by the Borexino experiment on solar neutrino physics. Borexino is a large mass/high radiopurity liquid scintillator detector located under the Gran Sasso mountain (Italy). It has collected high quality data since May 2007. The results presented here refer to the so-called Phase 1 of the experiment which ended in May 2010. Borexino Phase 2 started in October 2011 after an intensive campaign of purification which significantly improved the (already exceptional) quality of the scintillator. The physics potentialities and future perspectives of this second phase of Borexino will be shortly discussed.

PACS `95.55.Vj` – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
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1. – Introduction

The Earth is reached every second by a large number of neutrinos coming from the Sun (flux $\sim 10^{10} \nu\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$). These neutrinos are mainly produced in reactions of the so-called *pp-cycle* which provides most of the Sun energy. Solar neutrinos are extremely elusive which makes their detection an experimental challenge: large target masses and

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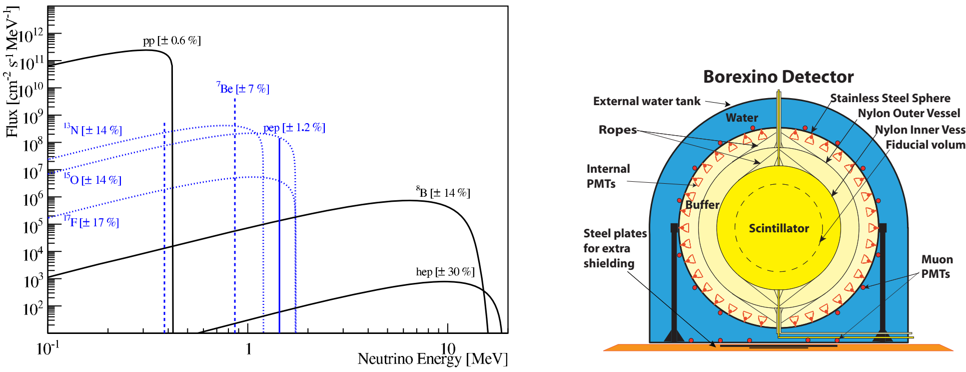

Fig. 1. – Left plot: solar neutrino spectrum from the Standard Solar Model. Right plot: a scheme of the Borexino detector.

efficient background suppression are key ingredients for the success of solar neutrino experiments. Studying solar neutrinos has proven to be extremely rewarding in many respects: on the particle physics side, it has brought to the evidence of neutrino oscillations (which in turn implies that neutrinos have mass); on the astrophysical side, it has provided beautiful confirmation of how our Sun shines. The wealth of data collected in the past 40 years by dedicated experiments has allowed us to definitely assess that solar electron neutrinos have a non-zero probability of changing their flavour during their trip from Sun to Earth and that oscillations are enhanced in the solar matter through the MSW resonant mechanism. The combined fit to solar and KamLAND experiments selects the so-called Large Mixing Angle solution in the oscillation parameter space, corresponding to values of $\Delta m^2 = 7.6 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\sin^2 2\theta_{12} = 0.87$ [1].

In spite of this great success, the study of solar neutrinos is far from being completed. Before Borexino only radiochemical experiments could observe solar neutrinos below 1 MeV, while real-time experiments were only sensible to a small fraction of the solar neutrino spectrum, namely the portion above ~ 5 MeV (see fig. 1, left). The exceptional radiopurity of Borexino makes it possible to work with a very low energy threshold (down to ~ 200 keV and possibly below), thus allowing the experiment to perform a complete spectroscopy of solar neutrinos, focusing in particular on the low energy portion of the solar neutrino spectrum.

In this paper we report the main results obtained by Borexino Phase 1 (2007–2010) for what concerns solar neutrinos, which include the measurement of the ^{7}Be flux with total error below 5% and its day/night asymmetry [2, 3], the measurement of the ^{8}B neutrino flux down to the unprecedented threshold of 3 MeV [4] and the first observation of neutrinos from the *pep* reaction [5]. We also review the current status and future perspectives of the Borexino Phase 2 (started in October 2011).

2. – The Borexino detector

The core of Borexino is 300 tons of ultra-pure liquid scintillator (pseudocumene + 1.5 g/l of PPO) contained in a 4.25 m-radius, 120 μm-thick nylon vessel (see fig. 1, right). In order to shield the scintillator from external background, the vessel is immersed in

1000 tons of pure liquid (pseudocume + DMP, a light quencher) contained in a Stainless Steel Sphere (SSS) of 7 m radius. To further increase shielding, the SSS is surrounded by 2000 tons of ultra-pure water contained in a cylindrical dome. Furthermore, the detector is located under the Gran Sasso mountain to block cosmic rays. The water in the external part of the detector serves also as an active shield to suppress the residual background due to cosmic muons which are able of penetrating underground. In order to do so, 200 photomultiplier tubes are mounted on the external part of the SSS to detect the Cerenkov light emitted by muons which cross the water. The intrinsic radiopurity of the scintillator has been brought to exceptional levels thanks to the successfull purification strategy developed during 15 years of dedicated R&D studies [6].

Solar neutrinos are detected by Borexino as they scatter off electrons of the 300 tons of liquid scintillator. The recoil energy acquired by the electrons is deposited in the scintillator causing light emission. The emitted photons are collected by 2212 photomultiplier tubes mounted on the SSS and pointing towards the center. Approximately 500 photoelectrons are detected for 1 MeV of deposited energy which guarantees a good energy resolution. Unfortunately scintillator light is not directional, which makes the signal virtually indistinguishable from background. This is the reason for which radiopurity is an essential pre-requisite for the success of the Borexino experiment. Besides that, a number of selection cuts must be applied to discriminate between signal and residual background events. The selection cuts are based on different reconstructed observables of the event, like the energy, position and time distibution of the scintillation signal. A crucial point is the definition of a fiducial volume in which the signal-to-background ratio is maximized.

2˙1. *Calibrations.* – In order to extract the solar neutrino signal from data, a solid knowledge of the details of the detector response is mandatory. In this respect, the calibration program has been essential for the success of Borexino. Three dedicated campaigns of ~ 3 weeks each have been performed between 2008 and 2009 by inserting different types of radioactive sources in the liquid scintillator, in order to precisely assess the energy scale of the detector and to investigate possible systematics associated to the event position reconstruction.

The energy scale was studied by inserting 8 different gamma-emitting sources (^{57}Co, ^{139}Ce, ^{203}Hg, ^{85}Sr, ^{54}Mn, ^{65}Zn, ^{60}Co and ^{40}K) spanning the energy range of interest for the ^{7}Be, *pep* and CNO analysis (from ~ 100 keV to 1.4 MeV). An AmBe neutron source was also used, in order to have calibration points at higher energies, relevant for ^{8}B solar neutrinos and geo-neutrinos. Due to the quenching phenomenon, the energy scale of a scintillator is not linear and depends also on particle type. The calibration campaigns allowed to reduce the uncertainty on the energy scale between 0 and 2 MeV to less than 1.5%. The position reconstruction has been studied by performing a complete mapping of the scintillator volume by deploying a ^{222}Rn source in more than 200 positions. This was used also to study the uniformity of the detector response. The systematic errors associated to energy and position reconstruction have been significantly reduced thanks to the calibration effort. For more details concerning the Borexino detector and its calibration see [7, 8] and [9].

3. – Borexino Phase 1: results on solar neutrinos

Borexino Phase 1 started in May 2007 and ended in May 2010. In this section we present a summary of the results obtained on solar neutrinos during this period of data taking.

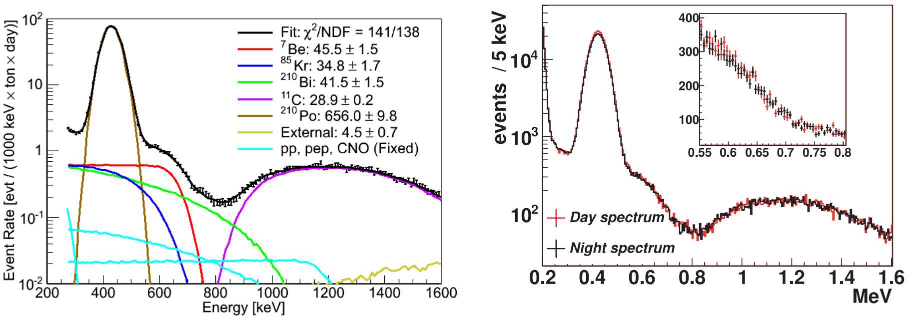

Fig. 2. – Left plot: an example of the spectral fit to extract the ^{7}Be flux from data. Right plot: day spectrum (red curve) and night spectrum (black curve) normalized to the same live time.

3·1. ^{7}Be *neutrino flux and its day/nigh asymmetry*. – After few months from the beginning of Phase 1, Borexino has published the first real-time observation of neutrinos from the ^{7}Be reaction [10], followed one year later by an improved measurement of their rate [11]. At the end of Phase 1 an even more precise measurement of the ^{7}Be neutrino rate (total error less than 5%) has been released [2]. The analysis to extract the ^{7}Be neutrino signal is based on a spectral fit, which includes the characteristic Compton-like shape of the signal and the spectral shape of the residual background components: ^{85}Kr, ^{210}Bi, ^{210}Po, ^{11}C. The fit has been performed following two different strategies: in the first one, the spectral shapes of signal and backgrounds have been derived by Monte Carlo simulations, in the second one they have been derived analytically. Figure 2 (left) shows an example of the Monte-Carlo–based fit. The results of this and all other fits performed varying the fit conditions and the data preparation are consistent: the difference has been included as systematic error of the fit and amounts to 2%. Our best estimate for the ^{7}Be flux is $46 \pm 1.5(\text{stat.})^{+1.5}_{-1.6}(\text{syst.})$ counts/day/100 tons. Besides the error due to the fit procedure, the systematic uncertainty includes also the error on the fiducial mass ($^{+0.5\%}_{-1.3\%}$) and on the energy response (2.7%), both significantly reduced with respect to previously published articles, thanks to the extensive calibrations of the detector.

The expected count rate in case of no oscillations (following the latest Standard Solar Model predictions (SSM) [12] and in the high-metallicity hypothesis [13]) would be 74 ± 4 counts/day/100 tons: the observed interaction rate is 5σ lower. Under the assumption of oscillations we can extract a precise measurement of the survival probability, P_{ee} in the vacuum dominated oscillation regime $P_{ee} = 0.51 \pm 0.07$ (see fig. 3, right) The precision measurement of ^{7}Be neutrinos with Borexino is also a direct probe of the SSM: under the MSW-LMA oscillation assumptions the relative ratio $f_{\text{Be}} = \Phi(^7\text{Be})/\Phi_{SSM}(^7\text{Be})$ is found to be 0.97 ± 0.05. Furthermore, the inclusion of our result in a global solar neutrino analysis performed with free fluxes (under the luminosity constraint) allows to determine $f_{pp} = \Phi(\text{pp})/\Phi_{SSM}(\text{pp}) = 1.013^{+0.003}_{-0.010}$ and $f_{\text{CNO}} = \Phi(\text{CNO})/\Phi_{SSM}(\text{CNO}) < 2.5$ (95% CL).

For oscillation parameter values typical of the so-called Large Mixing Angle solution there should be no measurable asymmetry ($< 0.1\%$) between the ^{7}Be neutrino rate during day and during night, while in other regions of the oscillation parameters space, such as the so-called LOW region, there would be a significant asymmetry (up to 80%) due to coherent regeneration of ν_e's as they cross the Earth.

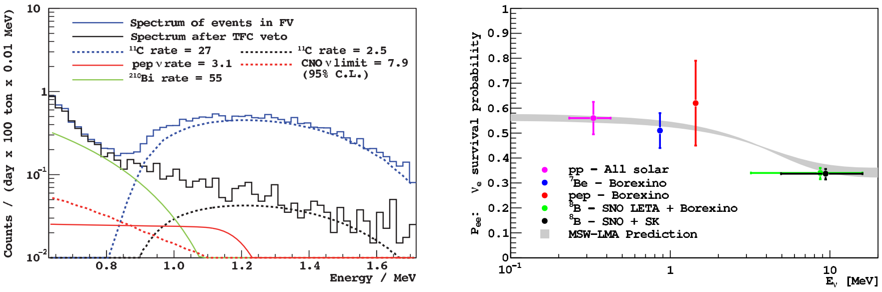

Fig. 3. – Left: energy spectra of the events in the FV (blue line) before and after the TFC veto is applied (black line). Right: survival ν_e probability P_{ee} as a function of energy for the current best-fit oscillation parameters [1] allowed to vary within 1σ band (grey band). The blu, red and green points represent the Borexino results on ^{7}Be, pep and ^{8}B neutrino rate, respectively, assuming the solar fluxes from the high-metallicity hypothesis [13]. The purple point is the result obtained for pp neutrinos combining Borexino and all other solar neutrino experiments.

Figure 2 (right) shows the energy spectrum obtained during days (red curve) superimposed to the one obtained during nights (black curve) normalized to the same experimental live-time. In order to extract the day-night asymmetry we subtract the day spectrum from the night one and fit the difference as the sum of a constant + ^{7}Be, assuming that backgrounds are constant between day and night. The fit shows no excess of ^{7}Be signal during night which yields to a day-night asymmetry consistent with zero within errors, $A_{dn} = 0.001 \pm 0.0012(\text{stat}) \pm 0.007(\text{sys})$. This tight contraint confirms the LMA solution-based on solar data only and allows to reject at more than 8.5 σ the LOW region of oscillation parameter space.

3˙2. *The* ^{8}B *neutrino flux.* – In spite of its relatively small dimensions, Borexino has been able of measuring also the rate of ^{8}B neutrinos which have a small flux [4]. The excellent radiopurity of the detector has allowed to reduce the energy threshold for the scattered electron energy down to the unprecedented level of 3 MeV. In Borexino, the main backgrounds affecting the ^{8}B analysis are the cosmogenic isotopes induced by muons and the external background from photomultipliers. The short lived cosmogenics ($\tau < 2$ s) are removed by vetoing the detector for 5 s after each muon crossing it, while ^{10}C is removed by the triple coincidence with the parent muon and the neutron capture on proton. The external background (mainly thallium from photomultiplier tubes) is rejected by a Fiducial Volume cut of $R < 3$ m. The contribution due to the small thallium internal contamination (0.008 counts/day/100 tons) is statistically subtracted from the final spectrum. The resulting ^{8}B neutrino rate above 3 MeV is found to be $0.22 \pm 0.04(\text{stat}) \pm 0.01(\text{sys})$ counts/day/ 100 tons. The corresponding total ^{8}B neutrino flux is $(2.7 \pm 0.4 \pm 0.1) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$, in very good agreement with previous more precise measurements performed by Cherenkov detectors.

3˙3. *First observation of pep neutrinos.* – The main result published by Borexino in 2012 concerns the first observation of neutrinos from the *pep* reaction [5]. These neutrinos belong to the pp-cycle and are monocromatic ($E = 1.44$ MeV). They have never been observed directly before, given their tiny flux and low energy. Borexino has been able to observe for the first time this class of neutrinos, thanks to its exceptional radiopurity and to its capability to exploit new analysis techniques to reject the main residual background: the cosmogenic ^{11}C. The Three-Fold-Coincidence (TFC) technique exploits the fact that in at least 95% of the cases the cosmic muon which produces ^{11}C by spallation in the scintillator also produces a neutron. This makes it possible to correlate in space and time the muon signal, the neutron capture gamma signal and the positron emitted as ^{11}C decays (with a half-life of 20 minutes). The TFC technique is very effective in removing ^{11}C as can be seen in fig. 3 (left). The second technique exploits the difference in the emitted photon time distribution in case of an electron (from the scattering of neutrinos, *i.e.*, the signal) and a positron (from the decay of ^{11}C, *i.e.*, the background). By combining the discriminating power of these two techniques and also other information, like the spectral shape and the radial distribution of events into a multivariate analysis fit, it is possible to extract a measurement of the pep rate: $3.1 \pm 0.6(\text{stat.}) \pm 0.3(\text{sys.})$ counts/day/100 tons. From this analysis it is also possible to obtain the strongest constraint to date on the CNO flux: rate(CNO) < 7.9 counts/day/100 tons (95% CL).

The Borexino results on solar neutrinos have been important to probe the ν_e survival probability P_{ee} at different energies as can be seen in fig. 3 (right). In particular Borexino is the only experiment which has been able of probing solar neutrino oscillations both in the vacuum dominated region (low energies) and in the matter-dominated region (high energies).

4. – Borexino Phase 2: status and perspectives

After the end of Borexino Phase 1, several cycles of purification with water-extraction were performed on the scintillator to further increase its radiopurity. The main goal of the purification was to reduce ^{85}Kr and ^{210}Bi, which were present in the first phase of Borexino at an average level of ~ 30 counts/day/100 tons and ~ 40 counts/day/100 tons, respectively. These backgrounds affect significantly the ^{7}Be and *pep* neutrino analysis. Furthermore ^{210}Bi is the main limiting factor for the CNO neutrino analysis and ^{85}Kr affects the lowest energy portion of the spectrum, thus having an impact on the search for *pp* neutrinos. The purification has been very successfull: it reduced ^{85}Kr to values compatible with zero and ^{210}Bi to less than half of its previous rate. These achievements have important implications on the Borexino Phase 2 program. The most important goal for the Borexino Phase 2 is the direct observation of neutrinos from the CNO cycle: this group of reactions is believed to contribute with a small fraction to our Sun luminosity (less than 1%), but is believed to be the main source of energy for more massive stars. Given their small flux and low energy, CNO neutrinos have never been observed directly: therefore their detection with Borexino would be of exceptional astrophysical interest. The fact that ^{210}Bi has been significantly reduced by the latest purification cycles is of great importance for the success of the CNO neutrino search. However, simulation studies show that it would be even more important to independently measure the ^{210}Bi content, in order to be able of fixing its contribution in the spectral fit. Since ^{210}Bi decays into ^{210}Po, we are evaluating the possibility to estimate the ^{210}Bi rate by studying the evolution in time of the ^{210}Po rate.

A second important goal for Borexino Phase 2 will be the first direct detection of neutrinos coming from the *pp* reaction. These neutrinos provide more than 90% of the total solar neutrino flux, but have never been observed directly given their low energy ($E < 0.42$ MeV). The fact that purification has removed ^{85}Kr is an important step towards the *pp* neutrino detection. However, the main source of background for this

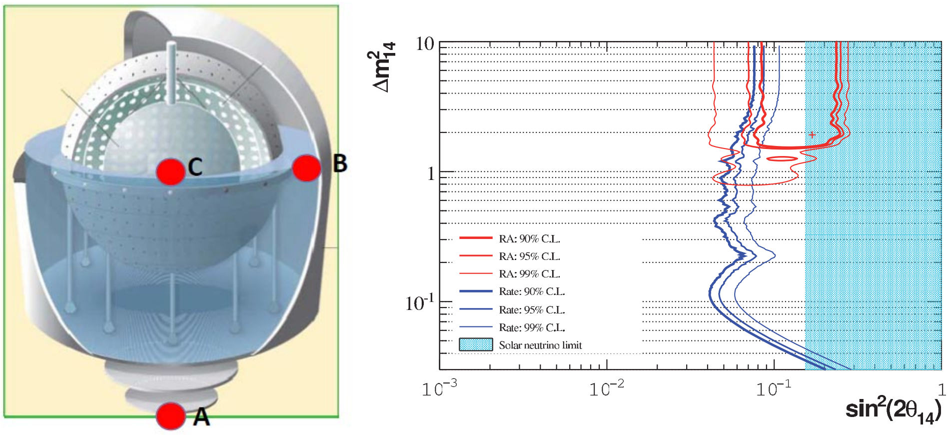

Fig. 4. – Left plot: locations of the radioactive source for the three phases of the SOX experiment. Right plot: sensitivity curves for SOX-A (blue lines). The curves are calculated assuming a 10 MCi ^{51}Cr (activity known at the $\sim 1\%$ level). The red curves are the regions allowed by the combined reactor and gallium anomalies and the turquoise area is the region already excluded by solar experiments plus θ_{13} results.

analysis is ^{14}C which is a non-eliminable intrinsic component of an organic liquid. ^{14}C decays β with an end-point of 156 keV, right in the middle of the detection window for *pp* neutrinos. Therefore, in order to be able of extracting the *pp* signal it will be crucial to know precisely both the rate and the spectral shape of ^{14}C and ^{14}C pile-up events.

4·1. *Short-distance neutrino oscillations with BoreXino: the SOX project.* – Oscillations between the three neutrino flavours are well-estabilished and have received many experimental confirmations. On the other hand, there are several experimental anomalies which cannot be accomodated in a simple three flavour scenario, but require the existence of one or more non-active neutrinos. Among these, we recall the so-called "reactor anomaly" [14] and "gallium anomaly" [15] which consist in a deficit of anti-ν_e and ν_e observed by short baseline reactor and source experiments, and the LSND and MiniBoone results [16]. These hints which point towards new physics deserve to be investigated thoroughly in order to either confirm or definitely disprove them. Borexino is in an excellent position to do so, by performing a short baseline experiment using an high activity neutrino source placed either outside or inside the detector (see fig. 4, left).

The least invasive option is that of placing a source just underneath the detector at 8.25 m from the center (position A in fig. 4). In this case a high activity source is needed (of the order of $\sim$ 10 MCi) and the only viable solution is a ^{51}Cr neutrino source. We are evaluating the possibility to re-activate (by neutron irradiation) the ^{50}Cr already used to calibrate the GALLEX experiment. This first phase of the SOX project (SOX-A) will be able of exploring a large portion of the oscillation parameters (Δm^2_{14}, $\sin^2 2\theta_{14}$) allowed by the reactor and gallium anomalies, since the characteristic L/E will be of the order of 1 eV^2. The experiment will work in a standard disappearance mode by observing (or not) a deficit of neutrinos and at the same time will exploit Borexino's capability of measuring the event position to possibly observe an oscillation pattern within the active volume. The sensitivity curves for SOX-A are shown in fig. 4 (right). SOX-A is planned to start by the beginning of 2015 and last for approximately 3 months, given the rather short lifetime of ^{51}Cr ($\tau \sim 40\,\mathrm{days}$). After the end of the solar phase of Borexino Phase 2 and depending on the outcome of the SOX-A experiment, a more invasive plan could be undertaken: SOX-B and SOX-C foresee to place a ^{144}Ce-^{144}Pr anti-ν source either in the buffer liquid (position B) or in the center of the detector (position C). In this last case the needed source activity would be relatively small ($\sim 50\,\mathrm{kCi}$), but the Borexino apparatus would require major modifications and refurbishing. However, the expected sensitity would be significantly higher with respect to SOX-A. More details on SOX can be found in [17].

5. – Conclusions and perspectives

Borexino is performing a complete real-time spectroscopy of solar neutrinos. Besides ^{7}Be neutrinos, which were the main original target of the experiment, Borexino Phase 1 has led to the first observation of *pep* neutrinos and to the measurement of ^{8}B neutrino rate with an unprecedented low energy threshold. Borexino Phase 2 aims at two even more challenging targets: CNO and *pp* neutrinos. These difficult objectives are within our reach thanks to the increased radiopurity of the scintillator after the latest purification campaign. In parallel to the rich solar neutrino program, the Borexino detector will be also part of the SOX project, a short baseline experiment, aiming at investigating the sterile neutrino hypothesis.

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