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Measurement of ^{7}Be and ^{8}B solar neutrinos with BOREXINO

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Summary. — Borexino is a real-time liquid-scintillator detector for low-energy neutrino spectroscopy located at the Gran Sasso National Laboratories (Italy). Thanks to the unprecedented radiopurity of the target mass it is providing the first direct and simultaneous measurement of the solar neutrino survival probability in both vacuum-dominated (^{7}Be ν) and matter-enhanced regions (^{8}B ν) by a single experiment. The measured interaction rates for both the ^{7}Be and ^{8}B solar neutrinos are in fair agreement with the SSM predictions in case of the LMA-MSW oscillation solution and a further confirmation of the LMA scenario is provided by the absence of a day-night asymmetry in the ^{7}Be signal. These experimental results allow to improve the upper limit on the neutrino effective magnetic moment. Calibration campaigns aiming to reduce the systematical errors on fiducial volume definition and detector energy response are presently in progress.

PACS `95.55.Vj` – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS `29.40.Mc` – Scintillation detectors.

1. – Introduction

The Sun is an intense source of electron neutrinos, produced in nuclear reactions of the p-p chain and of the CNO cycle. They provide a unique probe for studying both the nuclear fusion reactions that power the Sun and the fundamental properties of neutrinos. They have been studied for 30 years by means of radiochemical and water Cherenkov detectors and brought to the discovery of the ν flavour oscillations. The range of the parameters describing the oscillation phenomenon has been constrained using the data coming from solar and reactor neutrinos experiments to the so-called LMA (Large Mixing Angle) region of the plane θ_{12} Δm^2_{12} ($\tan^2(2\theta_{12}) = 0.47^{+0.06}_{-0.05}$ and $\Delta m^2_{12} = 7.59^{+0.21}_{-0.21} \cdot 10^{-5}\,\mathrm{eV}^2$ [1]). Matter effects in the Sun play a crucial role too (MSW effect). A central feature of the MSW-LMA solution is the prediction that neutrino oscillations are dominated by vacuum oscillations at low energies ($< 1\,\mathrm{MeV}$) and by resonant matter-enhanced oscillations, taking place in the Sun's core, at higher energies ($> 5\,\mathrm{MeV}$). A measure of the survival probability as a function of the ν energy is very important to confirm the MSW-LMA solution or to exploit possible traces of non-standard neutrino-matter interactions or non-standard neutrinos properties (mass varying ν) [2]. The relevance of the measurements of the various solar neutrinos components is then twofold: from one side they can increase the confidence in the oscillation scenario and from the other side, assuming the knowledge of the oscillation parameters, they could provide a measurement of the absolute solar neutrino fluxes, helping for example in the scientific debate between high- and low-metallicity solar models [3].

Among existing experiments on solar neutrinos SNO and Super-K measure the solar neutrinos fluxes with high threshold (5 MeV) because of the low Cherenkov light yield and the high intrinsic backgrounds so they are only sensitive to ^{8}B neutrinos. Radiochimical detectors did not measure the ν energy.

Borexino has opened a new chapter in the experimental history of solar ν making feasible the solar ν's spectroscopy in real time down to 200 keV. This was possible by employing a liquid-scintillator technique which has several advantages: the light yield is a factor 50 higher than the Cherenkov one and the very low solubility to ions and metal impurities makes it possible to reach unprecented levels of radiopurity. Solar neutrinos are detected in Borexino through their elastic scattering on electrons in the scintillator. Electron neutrinos (ν_e) interact through charged and neutral currents and in the energy range of interest they have a cross-section 5 times larger than ν_μ and ν_τ, which interact only via neutral current. The electrons scattered by neutrinos are detected by means of the scintillation light retaining the information on the energy while information on the direction of the scattered electron is lost. Electron-like events induced by solar neutrinos interaction cannot be distinguished, on an event-by-event basis, from electrons or gammas due to radioactive decays so a strong effort has been devoted to the containment and comprehension of the background. 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. All components were screened and selected for low radioactivity and the scintillator and buffer were purified on site at the time of filling. The purification strategy relies on filtration, multistage distillation and nitrogen sparging. The present work reports, after a brief detector description, the main goals reached in the so-called Borexino phase I data taking period (May 2007-Oct 2008), namely the measurement of ^{7}Be solar neutrinos fluxes and D/N asimmetry, the ^{8}B solar neutrinos fluxes and the best current limits on the ν magnetic moment. Calibrations campaigns and next goals are also described.

2. – The detector

The Borexino detector is located at the Gran Sasso National Laboratories (LNGS) in central Italy, at a depth of 3800 m.w.e. The active mass consists of 278 tons of pseudocumene (PC) doped with 1.5 g/l of PPO. The scintillator is contained in a thin (125 μm) nylon vessel and is surrounded by two concentric PC buffers doped with DMP, a scintillation light quencher. The scintillator and buffers are contained in a Stainless Steel Sphere (SSS) with a diameter of 13.7 m. The SSS is enclosed in a water tank (WT), containing 2100 tons of ultrapure water as an additional shield. The scintillation light is detected via 2212 8$''$ photomultiplier tubes uniformely distributed on the inner surface of the SSS. Additional 208 8$''$ PMTs instrument the WT and detect the Cherenkov light radiated by muons in the water shield, serving as a muon veto. A detailed description of the detector can be found in [4]. Key features of the scintillator are the high light yield (500 p.e./MeV) and the fast time response that allows to reconstruct the events position by means of a time flight technique. An event is recorded when at least 25 PMT pulses occur within a time window of 99 ns (the corresponding energy threshold is about 40 keV). When a trigger occurs, a 16 μs gate is opened and time and charge of each PMT is collected. The offline software identifies the shape and the length of each scintillation pulse and reconstructs the position and energy of the each deposit. Pulse shape analysis is performed to identify various classes of events, among which eletronic noise, pile up events, muons, α and β particles.

3. – Radiopurity and background levels

Besides reducing external background, the key requirement for measuring low-energy ν with Borexino is an extreme radiopurity of the scintillator itself. During 15 years of dedicated R&D studies, the Borexino Collaboration developed a purification strategy which proved to be effective in removing the most dangerous contaminants. In particular ^{40}K contamination was found to be below $3 \cdot 10^{-18}$ g/g (90% CL) while the contamination

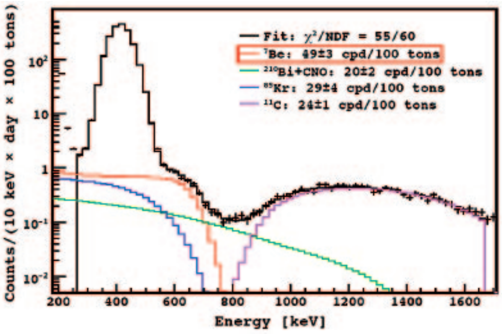

Fig. 1. – The Borexino energy spectrum obtained after applying the described analysis cuts (see text). Results of fitting procedure are also shown.

due to ^{238}U and ^{232}Th was reduced to the unprecented levels of $(1.6 \pm 0.1) \cdot 10^{-17}$ g/g and $(5 \pm 1) \cdot 10^{-18}$ g/g. By far the most important source of background is ^{14}C, a β emitter with 156 keV endpoint, which is naturally present in an organic liquid scintillator. Its isotopic ratio is evaluated to be $^{14}\mathrm{C}/^{12}\mathrm{C} = (2.7 \pm 0.6) \cdot 10^{-18}$, perfectly suited to the planned analysis threshold of 200 keV. Other important background is the 5.3 MeV α emitter ^{210}Po. The ionization quenching of the scintillator reduced the visible energy by a factor 13 and moves the α peak in the energy range of the ^{7}Be signal. Its contamination at the beginning of data taking was about 80 counts/day/ton, decreasing afterwards with time with the expected mean life of 200 days. This background could be statistically subtracted by use of a pulse-shape discrimination made possible by the PC-based scintillator. The most annoying background for the ^{7}Be ν analysis is ^{85}Kr, an air-borne contaminant, emitting electrons with 687 keV endpoint and a rate of the same order of the ^{7}Be signal. The ^{85}Kr content in the scintillator was probed through the rare decay sequence $^{85}\mathrm{Kr} \rightarrow {}^{85m}\mathrm{Rb} + e^{+} + \nu_e$, $^{85m}\mathrm{Rb} \rightarrow {}^{85}\mathrm{Rb} + \gamma$ $(\tau = 1.5\,\mu\mathrm{s}, BR = 0.43\%)$ that offers a delayed coincidence tag and it is evaluated to be (28 ± 7) counts/day/ton. The large error is due to low statistics. At energies above 800 keV the dominant background is cosmogenically produced ^{11}C (β^{+} decay, $Q = 1.98$ MeV). It is observed at an average rate of 25 counts/(day 100 tons), which is the range of prediction of the previous studies though slightly higher [5, 6].

4. – The ^{7}Be signal: fluxes and day/night asymmetry

The basic signature for the monoenergetic 0.862 MeV ^{7}Be ν is the Compton like edge of the recoil electrons at 665 keV as shown in fig. 1. Events have been selected by means of the following cuts:

- Only 1 cluster events are accepted: the event must have a unique reconstructed cluster in the gate time window (16 μs) in order to reject pile-up and fast coincident events ($\epsilon \approx 100\%$).
- Muon and muon daughters are rejected: events associated with Cherenkov light in the water tank detector are identified as cosmic muon and rejected. A 2 ms veto is applied after each muon crossing the detector to remove afterpulses and muon-induced neutrons ($\tau \approx 250\,\mu$s); the measured muon rate in Borexino is $(0.055 \pm 0.002)\,\mathrm{s}^{-1}$ and the dead time introduced by this cut is negligible.

- Space and time correlated events are rejected: events occurring withing 2 ms at the same place ($\Delta R < 1.5$ m) are removed; the Rn daughters occurring before the ^{214}Bi-^{214}Po delayed coincidences are eliminated by vetoing events up to three hours before a coincidence. The total loss of fiducial exposure due to this cuts is 0.7%.

- Fiducial volume cut: to remove external backgrounds only events reconstructed in the innermost 100 tons are accepted. Another volumetric cut $|z| < 1.8$ m was applied in order to cut out the regions close to the poles with very different detectors response resulting in a nominal fiducial mass of 78.5 t.

In fig. 1 the measured spectrum in 192 days is a shown as obtained by applying the previous cuts. The most noticeable peak, around 400 keV, is the one due to the ^{210}Po α decay, while at energies above 800 keV the beta spectrum of ^{11}C is clearly visible.

The ^{7}Be signal rate in Borexino is obtained fitting the energy spectrum by a superposition of the spectra due to solar neutrinos and to the not taggable backgrounds. Two procedures were adopted: one of them includes the ^{210}Po α peak while in the second one a further pulse shape discrimination is applied to data and the α-like events are statistically subtracted. The two results are perfectly compatible [7] and they give the value of the ^{7}Be neutrinos interaction rate of $(49 \pm 3 \pm 4)$ ev/(day 100t) after 192 days of live time. According to the Standard Solar Model with high metallicity [8, 3] the expected signal for non-oscillated solar ^{7}Be ν is (74 ± 4), which is reduced to (48 ± 4) ev/(day 100t) according to the MSW-LMA oscillation parameters. The ν_e survival probability at the ^{7}Be ν energy corresponding to our results is $P_{ee} = (0.56 \pm 0.10)$ and the non-oscillation hypothesis ($P_{ee} = 1$) can be rejected at 4 σ CL. Therefore Borexino on the one hand confirms the MSW-LMA ν oscillation scenario and, on the other hand, provides the first direct P_{ee} measurement in the low-energy vacuum regime.

A preliminary analysis of the day and night spectra provides a further confirmation of the prediction of the MSW-LMA model through the absence of a significant day-night asymmetry in the ^{7}Be flux. Data corresponding to a total live time of 422.12 days with 212.87 days and 209.25 nights have been analysed. The day-night asymmetry A_{dn} is defined as $A_{dn} = (C_n - C_d)/(C_n + C_d)$ where C_n and C_d are the counts during day and night time and it includes the contributions both of the signal and of the background. Considering the statistical precision of the ^{7}Be flux determination in the day and night periods we get for the contribution of the signal alone in the ^{7}Be energy window $A^{\nu}{}_{dn} = (0.02 \pm 0.04)_{\text{stat}}$ [9], compatible with zero.

A huge experimental and analysis effort is now in progress to reduce the errors associated to the measurement of the ^{7}Be signal rate. Among the not taggable backgrounds, the most important source of uncertainty in the ^{7}Be flux determination is the ^{85}Kr content. This contamination can be measured through a very rare branch which gives a β/γ fast coincidence. At the time of our last published results [7] only 8 β/γ coincidences were selected in 192 days of live time and the contamination value was taken as a free parameter in the fitting procedure because of the too large statistical uncertainty. Now after one year of live time, the uncertainty has been reduced by 50% and the amount of contamination is contrained to (28 ± 7) counts/(days 100t) so it can be fixed in the fitting procedure. Presently the possibility to reduce the ^{85}Kr contamination throught a scintillator purification is under study. In particular, ^{85}Kr is a noble gas and the experience gained with CTF, the 4 tons prototype of Borexino [10], showed than nitrogen sparging is particularly effective to remove this background. A ^{7}Be rate measurement with a few percent accuracy requires also a strong reduction of systematical errors: the

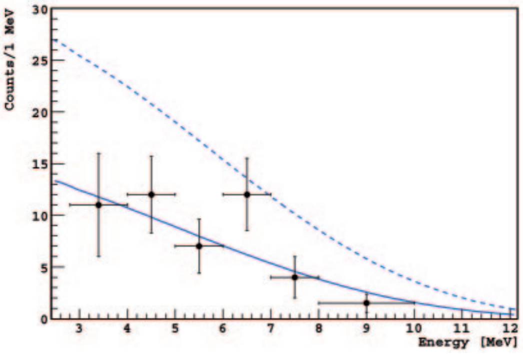

Fig. 2. – Energy spectrum of the events surviving all cuts applied in the ^{8}B ν analysis. The expected electron recoil spectrum due to oscillated (not oscillated) ^{8}B ν interaction and determined from solar model [8] with high metallicity is represented by the solid (dashed) line.

main contributions are coming from the imperfect knowledge of the fiducial volume and of the detector energy response (each of them is giving a contribution to the systematical error of 6%). We are presently reducing these uncertainties through the detector calibration: two calibration campaigns have been already completed, others are scheduled for the next months and the results are under analysis.

5. – The ^{8}B neutrinos fluxes and the survival probability in the vacuum-matter oscillation transition

The extreme radiopurity of Borexino, combined with the efficient software rejection of cosmogenic background allows to investigate the recoiled electron spectrum induced by ^{8}B solar ν, down to the energy threshold of 2.8 MeV. This value is mainly due to the presence at lower energies of a large background coming from penetrating γ-rays emitted by ^{208}Tl decay in the PMT's material. So far Borexino is the first experiment providing the real-time measurement of ^{8}B ν below 5 MeV. The major background sources at the energy above 2.8 MeV are muons, gammas from the neutron capture, radon emanation from the nylon vessel, short-lived ($t < 2$ s) and long-lived ($t > 2$ s, ^{10}C) cosmogenic isotopes and bulk ^{208}Tl contamination. In addition to the already discussed cuts, a stronger cosmogenic cut is applied by vetoing the overall detector for 5 s after a crossing muon; ^{10}C candidates are removed by the triple coincidence with the parent muon and the neutron capture on protons and the ^{208}Tl contamination due to the internal radioactivity is evaluated by measuring the delayed coincidence of its branching competitor ^{212}Bi-^{212}Po in the ^{232}Th chain and statistically subtracted. Energy spectrum of events surviving all cuts is shown in fig. 2 after statistical ^{208}Tl subtraction. The number of selected events is (48 ± 8) in 245.9 days of live time and they correspond to a rate of ^{8}B solar ν interactions (above 2.8 MeV) of $(0.26 \pm 0.04_{\mathrm{stat}} \pm 0.02_{\mathrm{sys}})$ counts/(day 100 tons) [11]. The equivalent ν_e flux survival probability, assuming the Standard Solar Model [8], is (0.35 ± 0.10) at the effective energy of 8.6 MeV. So the non-oscillation model is excluded at 4.2σ CL. Borexino is the first experiment able to simultaneously measure solar ν fluxes both in vacuum-dominated (^{7}Be ν) and matter-enhanced regions (^{8}B ν). The obtained results for P_{ee} are shown in fig. 3 and compared with expectation due to MSW-LMA theory [7]. The agreement is fair. In the case ^{8}B neutrinos fluxes an improvement in the precision

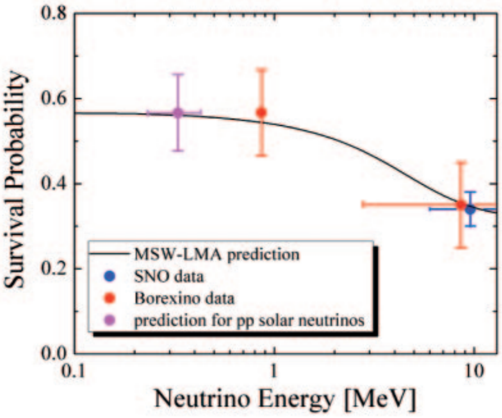

Fig. 3. – ^{7}Be and ^{8}B electron neutrino survival probability as measured by Borexino compared to previous measurements and MSW-LMA predictions.

of the measurement requires an increase of the time of measure and of the fiducial mass, besides a better definition of the fiducial volume mass and of the energy response of the detector.

6. – Neutrino effective magnetic moment

In a case of a non-null ν magnetic moment, the ν scattering cross-section off electrons is modified by the addition of an electromagnetic term, $\mathrm{d}\sigma/\mathrm{d}T_{\mathrm{em}} = \mu_\nu^2 \pi \alpha_{\mathrm{em}}^2 / m_e^2 [1/T - 1/E_\nu]$ where E_ν is the ν energy and T is the electron kinetic energy. The shape of the solar ν spectrum is sensitive to the possible presence of a non-null magnetic moment, and the sensitivity is enhanced at low energy since $\mathrm{d}\sigma/\mathrm{d}T_{\mathrm{em}}$ is proportional to $1/T$. By analysing the α subtracted energy spectrum we obtain an upper limit of $5.4 \cdot 10^{-11} \mu_B$ (90% CL) [7] which is currently the best experimental limit.

7. – Detector calibrations

Two calibration campaigns have been already completed, others are scheduled for the next months. The goal is to reduce the systematical uncertainties in the ^{7}Be and ^{8}B signal at a level of few percent. Radioactive sources have been inserted in the inner vessel center and along the vertical axis (first calibration campaign) and in more than 100 positions on and off vertical axis (second calibration campaign). An Am-Be source and several gamma sources have been used for the energy calibration while a source made by a quartz sphere filled by scintillator loaded with radon and ^{14}C was used to study the position reconstruction as a function of the event energy and of the event type (α, β and γ) and to map the relative changes of the reconstructed energy at various positions. The true position can be determined within 1 cm accuracy through the use of a red light laser (mounted on the source support) monitored by a system of CCD cameras. The position is then compared with the one reconstructed by means of time-of-flight technique from the scintillation light induced by radioactive dacays and detected by the PMT's. Particular care has been devoted to the design of the source insertion system, to the choice of its material and to the definition of the insertion procedure in order to minimize the risk of introduction of any radioactive contaminants in the detector that would spoil the unprecented performances of Borexino. The calibration results are under analysis.

8. – Future perspectives

Borexino has provided the first real time measurements of the ^{7}Be and the lowest threshold ^{8}B neutrinos fluxes. A preliminary result about the ^{7}Be signal day/night asymmetry has also been provided. Calibrations campaigns are presently in progress and together with eventual purifications open the way to very precise ^{7}Be ν signal rate measurements (at the level of few percent) and to an improvement in the precision of the ^{8}B signal. Given the exceptional, unprecented purity levels achieved in Borexino, a broad investigation of the solar ν spectrum is prospectively possible in the future. A feasibility of pep, CNO and possibly pp solar neutrinos measurement is extensively studied. The study of geoneutrinos is also promising due to the fact that Borexino is located far away from any of the European reactors. A set of candidates has been already collected but requires statistics in order to get evidence for a signal at the 3σ level. Finally Borexino has joined the SNEWS community since February 2009 and it is now ready to detect supernova events.

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