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Abstract. The Borexino experiment is running at the Laboratori del Gran Sasso in Italy since 2007. Its technical distinctive feature is the unprecedented ultralow background of the inner scintillating core, which is the basis of the outstanding achievements accumulated by the experiment. In this talk, after recalling the main features of the detector, the impressive solar data gathered so far by the experiment will be summarized, with special emphasis to the most recent and prominent result concerning the detection of the fundamental pp solar neutrino flux, which is the direct probe of the engine mechanism powering our star. Such a milestone measurement puts Borexino in the unique situation of being the only experiment able to do solar neutrino spectroscopy over the entire solar spectrum; the counterpart of this peculiar status in the oscillation interpretation of the data is the capability of Borexino alone to perform the full validation across the solar energy range of the MSW-LMA paradigm. The talk will be concluded highlighting the perspectives for the final stage of the solar program of the experiment, centered on the goal to fully complete the solar spectroscopy with the missing piece of the CNO neutrinos. If successful, such a measurement would represent the final crowning of the long quest of Borexino to unravel all the properties of the neutrinos from the Sun.

1. Introduction

Borexino at Gran Sasso is the last player which entered the solar neutrino arena, where thanks to its unprecedented low background it provided breakthrough results in the low energy sub-MeV regime. Having already measured three components of the solar neutrino spectrum over the past years, i.e. ^{7}Be, ^{8}B and pep (providing jointly with this component also a stringent upper limit on the CNO contribution), Borexino has recently crowned its remarkable series of results with the detection of the fundamental pp neutrino flux, coming from the reaction which provides most of the Sun's energy. Therefore Borexino is the first experiment able to perform an almost complete spectroscopy of the whole solar neutrino flux, allowing a thorough data-model comparison [1]. The last step of this investigation will be the attempt to measure the tiny CNO flux, which Borexino will undertake over the next years.

Moreover, Borexino has also detected an unquestionable geoneutrino signal (i.e. anti-neutrinos from the radioactivity inside the Earth), contributing to pave the way to a complete new method to investigate the interior of our planet.

In the following the experimental characteristics which made possible these outstanding accomplishments will be briefly reviewed, together with the features of the results achieved so far.

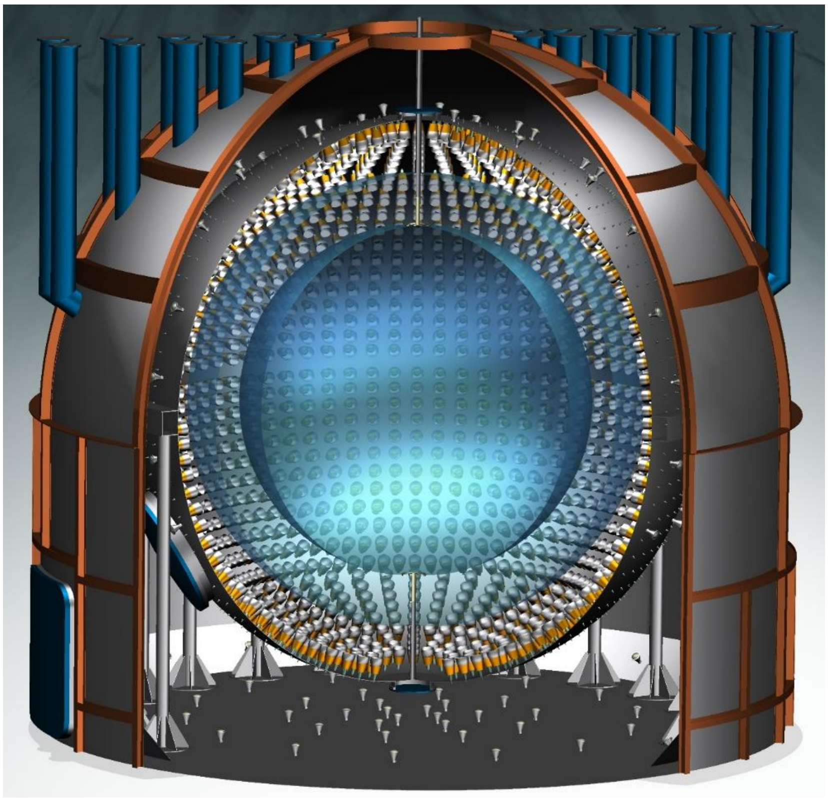

Figure 1. Sketch of the Borexino experiment, highlighting its major components arranged according to a graded shielding design.

2. Characteristics of the detector

Borexino [2] 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 Cerenkov technique) the liquid scintillation technology is extremely suitable for massive calorimetric low energy spectroscopy. However, the lack of directionality of the method makes it impossible to distinguish neutrino scattered electrons from electrons due to natural radioactivity, as is done in the Cerenkov detector exploiting the association of the neutrino signals to the Sun direction. Therefore the crucial requirement of the Borexino technology is an extremely low radioactive contamination of the detection medium, at fantastic unprecedented levels, definitely below the acceptable limits in the water of SNO and Super-Kamiokande.

To reach ultralow operating background conditions in the detector, the design of Borexino (see figure 1) is based on the principle of graded shielding, with the inner scintillating core at the centre 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 (later reduced to 3.0 g/l) of 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 PMTs. The region between the OV and the SSS is filled with the same inert buffer fluid (PC plus DMP) which is layered between the inner and outer vessels.

Finally, the entire detector is contained in a tank (radius 9 m, height 16.9 m) filled of ultra-pure water. The total liquid passive shielding of the central volume from external radiation (such as that originating from the rock) is thus 5.5 m of water equivalent (m.w.e). The scintillator material in the IV was less dense than the buffer fluid by about 0.1% with the original DMP concentration of 5 g/l; this resulted in a slight upward buoyancy force on the IV, implying the need of thin low-background ropes made of ultra-high density polyethylene to hold the nylon vessels in place.

This modest buoyancy was further reduced of more than a factor 10 by removing via distillation a fraction of the total DMP content in the buffer: the process ended with a final DMP concentration of 3 g/l, still perfectly adequate to suppress the buffer scintillation, while at the same time appropriate to substantially prevent the outward scintillator flow from a small leaking point which developed on the vessel surface about 10 months after the start-up of the data taking.

The scintillation light is viewed by 2212 8” PMTs (ETL 9351) uniformly distributed on the inner surface of the SSS. All but 371 photomultipliers are equipped with aluminium light concentrators designed to increase the collection efficiency of the light from the scintillator, and concurrently minimizing the detection of photons not coming from the active scintillating volume. Residual background scintillation and Cerenkov light that escape quenching in the buffer are thus reduced. The PMTs without concentrators can be used to study this background, as well as help identify muons that cross the buffer and not the inner vessel.

All the materials of the internal components of the detector (stainless steel, phototubes, cables, light concentrators, nylon) were specially selected for extremely low radioactivity. Furthermore, only qualified ultraclean processes were employed for their realization, followed by careful surface cleaning methods.

The final assembly of the elements in the SSS was carried out in clean room conditions: the entire interior of the sphere was converted into a clean room of class 1000, while in front of the main entrance of the sphere itself an on purpose clean room of class 100-1000 was used for all the final cleaning procedures of the equipment. Phototubes and ancillary mounting parts, light concentrators, calibration optical fibres, inner and outer vessels together with the anchoring systems, all passed and were treated through the access clean room, as well as the elaborated scaffolding system which was designed specifically to make it possible to the operators the safe and clean access to the whole sphere surface.

Clearly, for the success of the experiment key elements were also the many liquid purification and handling systems, which were designed and installed to ensure the proper manipulation of the fluids at the exceptional level demanded by Borexino. Without entering in the details of the complex layout and functionality of these plants, some salient points deserve to be mentioned.

The PC specially produced for Borexino, according to a stringent quality control plan developed jointly with the company, was shipped to the Gran Sasso location through special transport tanks cleaned, treated and prepared by us; the first operation there was the transfer of the PC via a dedicated unloading station to four big reservoir tanks, forming the so called Storage Area, were the PC was stored prior to be inserted in the detector. Taken from the Storage Area, the PC was first purified via distillation, then either mixed with PPO for insertion in the Inner Vessel, or mixed with DMP for the insertion in the buffer region. Involved in this set of operations were the main Borexino plants: the Distillation Skids, the Filling Stations, the elaborate Interconnection system which allowed flexible transfers of the liquid throughout the various plants. Furthermore, the PPO was pre-mixed with a limited quantity of PC in a dedicated PPO System, originating a concentrated PPO solution which was then mixed in line with the PC at the level of the Filling Stations.

Other important ancillary plants, fundamental for the success of the operations, are the nitrogen systems, which delivered regular nitrogen, or on site purified nitrogen, or specially produced nitrogen with exceptionally low content of ^{39}Ar and ^{85}Kr, to be used for the crucial manipulations of the liquid in the inner vessel.

Finally, an ultrapure water system was used to produce the water for the cleaning operations, for the fill of the External Tank, and for the preliminary water fill of the Inner Detector.

Obviously, besides the design for the proper operating conditions, the cleanliness of the manufacturing processes used for the assembly of all these plants was of paramount importance for the success of Borexino, as well as the thorough and accurate cleaning procedures that they underwent upon their installation on site.

The stability of the detector and the perfect understanding of its response gained with a detailed MC contrasted with the results from a thorough calibration campaign have been the last ingredients of its success.

When data taking started in May 2007, it appeared immediately that the daunting task of the ultralow radioactivity was successfully achieved, representing *per se* a major technological breakthrough, opening a new era in the field of ultrapure detectors for rare events search.

The exceptional purity obtained implies that, once selected by software analysis the design fiducial volume of 100 tons and upon removal of the muon and muon-induced signals, the recorded experimental spectrum is so clean to show spectacularly the striking feature of the ^{7}Be scattering edge, i.e. the unambiguous signature of the occurrence of solar neutrino detection.

In the next paragraphs the major results of Borexino are succinctly recapitulated.

3. Solar results and physics implications

3.1. The ^{7}Be flux

The latest ^{7}Be result has been published in [3]. Taking into accounts the systematic errors, stemming essentially from the uncertainty in the energy scale and in the fiducial volume selection, the ^{7}Be evaluation is 46 ± 1.5stat(+1.5-1.6)sys counts/day/100 tons: hence, summing quadratically the two errors, a remarkable 5% global precision has been achieved in this critical measurement.

By assuming the MSW-LMA solar neutrino oscillations, the Borexino result can be used to infer the ^{7}Be solar neutrino flux. Using the oscillation parameters from [4], the detected ^{7}Be count rate corresponds to a total flux of $(4.84 \pm 0.24) \times 10^9$ cm^{-2}s^{-1}, very well in agreement with the prediction of the Standard Solar Model [1]. For comparison, the measured count rate in case of absence of oscillations would have been 74 ± 5.2 counts/day/100 tons.

Finally, the resulting electrons survival probability at the ^{7}Be energy is Pee=0.51± 0.07.

3.2. ^{8}B

The distinctive feature of the ^{8}B neutrino flux measurement performed by Borexino [5] is the very low 3 MeV threshold attained, decisively lower than the previous measurements from the Cerenkov experiments.

The measurement is very difficult, since the total background, both of radioactive and cosmogenic origin, in the raw data is overwhelming if compared to the expected signal. The specific background suppression strategy adopted in this case is based on two ingredients: on one hand a careful MC evaluation of the main radioactive contaminants of relevance for this measure, i.e. ^{214}Bi from Radon and the external ^{208}Tl from the nylon wall of the Inner Vessel, and on the other the “in-situ” identification and suppression of the muon and associated cosmogenic signals.

The observed ^{8}B rate in the detector is 0.217±0.038(stat)±0.008(sys) cpd/100ton, corresponding to an equivalent flux Φ(8B)=(2.4±0.4±0.1)×10^6 cm^{-2}s^{-1} ; if as for the ^{7}Be case, we take into account the oscillation probability, then the ratio with the flux foreseen by the SSM is 0.88±0.19.

3.3. Pep and CNO

By far the most important background in studying pep and CNO solar neutrino fluxes is the 11C decay, a radionuclide continuously produced in the scintillator by the cosmic muons surviving through the rock overburden and interacting in the liquid scintillator. The beta plus decay of 11C originates a continuous spectrum which sits exactly in the middle of the energy region between 1 and 2 MeV, which is just the window for the pep and CNO investigation.

Actually, to a less extent also the external background induced by the gammas from the photomultipliers is an obstacle, especially above 1.7 MeV.

In [6] a threefold coincidence strategy encompassing the parent muon, the neutron(s) emitted in the spallation of the muon on a ^{12}C nucleus, and the final ^{11}C signal has been devised and described in detail. Such a strategy applied to the Borexino data led to a pep rate of 3.13±0.23 (stat.)±0.23 (syst.) counts per day/100ton [7], from which the corresponding flux can be calculated, assuming the current MSW-LMA parameters, as Φ(pep)= (1.6±0.3) 10^8 cm^{-2} s^{-1}, in agreement with the SSM: indeed the ratio of this result to the SSM predicted value is f_{pep}=1.1±0.2. The resulting electrons survival probability at the pep energy is Pee=0.51± 0.07; finally, it should be underlined that the significance of the pep detection is at the 97% C.L..

The same analysis, keeping the pep flux fixed at the SSM value, originates a tight upper limit on the CNO flux, i.e. Φ(CNO) $\leq$ 7.4 10^8 cm^{-2} s^{-1} , corresponding to a ratio with the SSM prediction less than 1.4.

3.4. Pp neutrinos

The measure of the pp flux has been released by the Collaboration in [8], a fundamental additional milestone toward the full solar neutrino spectroscopy by a single solar neutrino experiment. The data used for this measurement were accumulated after an extensive purification campaign that was performed in 2010 and 2011 and reduced, in particular, the content of two isotopes: ^{85}Kr, now close to 0, and ^{210}Bi, which are important backgrounds in the low-energy region.

The pp neutrino rate has been extracted by fitting the measured energy spectrum of the selected events in the 165–590 keV energy window to the expected spectra of the signal and background components. Given the low energy of the pp induced signals in the liquid scintillator, the most important background for this analysis is the ^{14}C content intrinsic to the liquid scintillator itself. Even if the isotopic abundance of ^{14}C in the scintillator is in absolute value very low, at the level of 10^{-18}, this species originates a large count rate of low energy events, which therefore can also produce a pile effect. The associated pile-up spectrum had to be determined with great accuracy, since it extends over the same energy region of the expected pp signals. A data driven methodology was developed to extract with high precision from the data themselves both the ^{14}C and the pile-up spectra.

The main components of the fit used to infer the pp rate are the solar neutrino signal, i.e. the pp component and the low-energy parts of the ^{7}Be, pep and CNO components); the mentioned dominant ^{14}C background and the associated pile-up; and other identified radioactive backgrounds: ^{85}Kr, ^{210}Bi, ^{210}Po and ^{214}Pb. The free fit parameters are the rates of the pp solar neutrinos and of the ^{85}Kr, ^{210}Bi and ^{210}Po backgrounds. The ^{7}Be neutrino rate is constrained at the measured value, within the error, and pep and CNO neutrino contributions are fixed at the levels of the SSM, taking into account the values of the neutrino oscillation parameters.

The solar pp neutrino interaction rate measured by Borexino is 144±13 (stat.) ±10 (syst.) counts per day/100ton. The stability and robustness of the measured pp neutrino interaction rate was verified by performing fits with a wide range of different initial conditions. Once statistical and systematic errors are added in quadrature and the latest values of the neutrino oscillation parameters are taken into account, the corresponding solar pp neutrino flux is $(6.6\pm0.7)\times10^{10}$cm^{-2} s^{-1}, and the associated survival probability is 0.64±0.12.

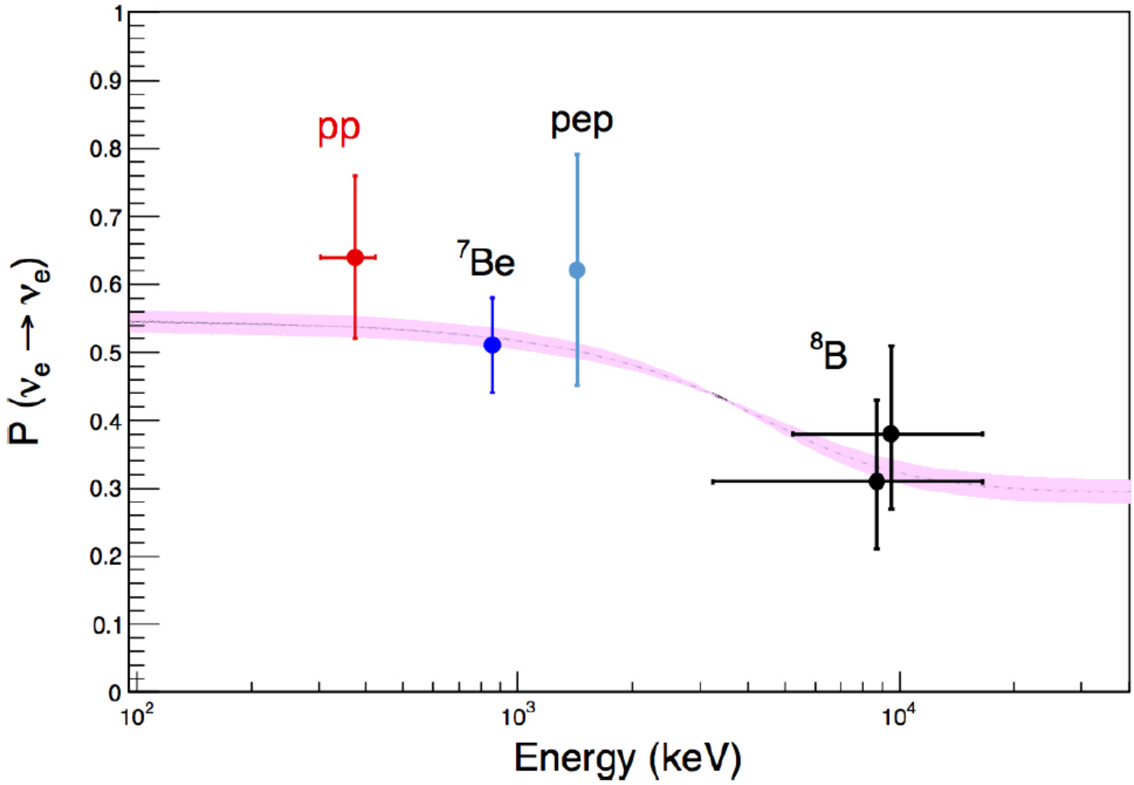

Figure 2. Validation over the full solar neutrino energy range of the MSW-LMA solution provided by Borexino with only its own data.

3.5. MSW-LMA global picture

In figure 2 the MSW predicted Pee (electron neutrino survival probability) is shown (the violet band corresponds to the $\pm1\sigma$ prediction of the MSW-LMA solution), together with several experimental points, all coming from Borexino: i.e. black the ^{8}B from the analyses with two different thresholds, light blue the pep, blue the ^{7}Be, red the very recent pp datum. This figure demonstrates the unique achievement of Borexino, which through an almost complete solar spectroscopy has been in condition, alone, to confirms spectacularly the MSW-LMA solar neutrino oscillation scenario, while providing the first direct measurements of the survival probability in the low energy sub-MeV Vacuum MSW regime.

This striking confirmation is also complemented by the measure of the day-night asymmetry of the ^{7}Be flux [9], which is found equal to Adn = 0.001 ± 0.012 (stat) ± 0.007 (syst), fully consistent with zero and hence with the model prediction. It is worth to mention that, by including this measure in the global fit of all solar neutrino experiments, the otherwise surviving LOW region is completely wiped out, even without including the KamLAND data.

4. Terrestrial neutrinos

As an ultra-pure liquid scintillator, Borexino is a perfect tool to detect anti-neutrinos (geoneutrinos) coming from Earth. The updated geoneutrino signal from Borexino has been reported in [10], for a data taking period of 1353 days. With a fiducial exposure of $(3.69 \pm 0.16)\times10^{31}$ proton × year, after all selection cuts and background subtraction, (14.3 ± 4.4) geo-neutrino events were detected, assuming a fixed chondritic Th/U ratio of 3.9. This result corresponds to a geoneutrino signal of (38.8 ± 12.0)

TNU (Terrestrial Neutrino Unit: = 1 event / year/ 10^{32} protons), disfavouring also the no-geoneutrino hypothesis with a p-value of 6×10^{-6}.

The only sizable background for this measure is represented by the anti-neutrinos from reactors, which we evaluated equal to 31.2(+7-6.1), well in agreement with the expectation (33.3±2.4), thus further confirming the validity of our entire measurement procedure.

5. Conclusion

The most recent solar and terrestrial neutrino results stemmed from Borexino have further reinforced the ultra-low background achievements of this experiment, an exceptional breakthrough in the field of techniques for rare processes search. The ^{7}Be, ^{8}B, pep and the very recently measured pp components have all been detected (together with a tight upper limit on CNO), leading to the validation of the MSW-LMA oscillation paradigm in the entire energy regime of the solar neutrinos, strengthened also by the determination of the absence of day-night asymmetry in the ^{7}Be flux. Very remarkably, Borexino performed this validation with its own data, without the need to resort to the results of other solar neutrino experiments.

Finally, the highly significant measurement of the terrestrial neutrinos not only complements the physics potentiality of the detector, but points towards a future new direction of research in the studies of the interior of the Earth.

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