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Borexino: recent solar and terrestrial neutrino results and description of the SOX project

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Important neutrino results came recently from Borexino, a massive, calorimetric liquid scintillator detector installed at the underground Gran Sasso Laboratory. With its unprecedented radiopurity levels achieved in the core of the detection medium, it is the only experiment in operation able to study in real time solar neutrino interactions in the challenging sub-MeV energy region. The recently achieved precise measurement of the ^{7}Be solar neutrino flux and the results concerning the pep, ^{8}B and CNO fluxes, together with their physics implications, are described in this work. Moreover the detector has also provided a clean detection of terrestrial neutrinos, from which they emerge as a new probe of the interior of the Earth. In the near future the scope of the experiment will be broadened to the sterile neutrino issue, through the SOX project based on the deployment of a powerful neutrino source nearby the detector.

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PoS(EPS-HEP 2013)529

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, i.e. ^{7}Be, ^{8}B and pep (providing jointly with this component also a stringent upper limit on the CNO contribution), Borexino aims now to measure the major pp flux and to improve the understanding of the challenging CNO signal: in this way it will become the first experiment able to perform a complete spectroscopy of the whole solar neutrino flux, for a thorough data-model comparison [1].

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.

The experimental characteristics which made possible these accomplishments, essentially the extremely high radiopurity, 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, open now the possibility of a new investigation which will bring Borexino at the centre of the current hot debate about the existence of a beyond-standard-model sterile neutrino state. The core of the SOX (Short Oscillation with BoreXino) project is the deployment of an intense neutrino source close to the detector to test the effect of the putative oscillation $\nu_e \rightarrow \nu_s$, which should originate in the liquid scintillator target the distinctive signature of an oscillatory spatial pattern in the profile of the detected events.

2.Characteristics of the Borexino experiment

Borexino [2] is a scintillator detector which employs as active detection medium 300 tons of pseudocumene-based scintillator. The intrinsic high luminosity of the liquid scintillation technology is the key toward the goal of Borexino, the real time observation of sub-MeV solar neutrinos through νe elastic scattering, being the ^{7}Be component the main target at the time of the design. However, the lack of directionality of the method makes it impossible to distinguish neutrino scattered electrons from electrons due to natural radioactivity, thus leading to the other crucial requirement of the Borexino technology, e.g. an extremely low radioactive contamination of the detection medium, to a degree never reached before.

The active scintillating volume is observed by 2212 PMTs located on a 13.7 m diameter sphere and is shielded from the external radiation by more than 2500 tons of water and by 1000 tons of hydrocarbon equal to the main compound of the scintillator (pseudocumene), to ensure zero buoyancy on the thin Nylon Inner Vessel containing the scintillator itself. Of paramount importance for the success of the experiment are also the many purification and handling systems, which were designed and installed to ensure the proper manipulation of the fluids at the exceptional radiopurity demanded by Borexino.

When data taking started in May 2007, it appeared immediately that the daunting task of the ultralow radioactivity was successfully obtained, representing *per se* a major technological

PoS(EPS-HEP 2013)529

breakthrough, opening a new era in the field of ultrapure detectors for rare events search. The achieved ultra-low background 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.

3. Detector response

Several steps are required to extract from the raw data the quantitative information of interest regarding the solar neutrino fluxes: the raw signals must be converted into meaningful amplitude variables, of the total accumulated signals only those satisfying the scintillation event acceptance criteria are kept, the data spectrum is constructed by accepting only events which are reconstructed within a fiducial volume far from the wall of the containment vessel, and finally the spectrum is fitted to a global signal-plus-background model in which the flux amplitude to be evaluated is a fit parameter.

The challenging task to obtain a detailed understanding of the detector response has been accomplished through two coordinated efforts, i.e. an intensive, careful calibration campaign and the development of a complete MC able to reproduce accurately the detector features.

3.1 Calibration

The calibration of the detector has been accomplished both to characterize the energy and time response of Borexino. A plurality of sources have been deployed in several locations within the liquid scintillator: gamma sources producing monoenergetic lines spanning the energy range of interest from 0.122 to 1.4 MeV, a Radon source realized by filling with liquid scintillator taken from the Inner Vessel a small quartz vial which was successively loaded with Radon, and an Am-Be neutron source.

The gamma lines and the Radon source, positioned in several hundreds locations, gave an accurate probe of the energy response of the experiment as function of the event position; furthermore they also provided a way to careful calibrate the capability of the time signals from the array of photomultipliers to identify precisely the vertex of the events.

Jointly, the energy and spatial measurements obtained throughout the calibration campaign provided a complete map of the detector response, leading to the following estimates of the crucial features of the detector: energy resolution $5\%/\sqrt{E(\mathrm{MeV})}$, linearity of the energy scale of the order of 1%, fiducial volume uncertainty close to 1%, too.

3.2 MC tuning

The second ingredient at the basis of the precise measurements accomplished is the accurate Monte Carlo description of the detector. It required a while to develop a full MC code incorporating all the complex details of the light generation and transport in the liquid scintillator, of the behavior of the photomultipliers and of the electronics response. At the end of this complex development path we were able to produce a very complete simulation suited to be confronted with the many outputs stemming from the calibration campaign.

PoS(EPS-HEP 2013)529

Such a comparison has been extensively used to contrast the source data with the corresponding simulated events; in this way it has been possible on one hand to perform a fine tuning of the MC code, so to ensure the best match between the measured and simulated data, and on the other to quantify precisely the crucial, residual uncertainties on the energy scale and on the fiducial volume, already listed before. A thorough account of this effort has been recently published in [3].

4. Solar results and physics implications

4.1 The ^{7}Be flux

The updated ^{7}Be result has been published in [4]. 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 $46 \pm 1.5_{stat}(+1.5\text{-}1.6)_{sys}$ 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 [5], the detected ^{7}Be count rate corresponds to a total flux of $(4.84 \pm 0.24) \cdot 10^{9}$ $cm^{-2}s^{-1}$, 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 P_{ee}=0.51± 0.07.

4.2 ^{8}B

The distinctive feature of the ^{8}B neutrino flux measurement performed by Borexino [6] 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 $\Phi(^{8}B)=(2.4\pm0.4\pm0.1)\times10^{6}$ $cm^{-2}s^{-1}$; 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.

4.3 Pep and CNO

By far the most important background in studying pep and CNO solar neutrino fluxes is the ^{11}C 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 ^{11}C 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 [7] 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 [8], 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 P_{ee}=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.

4.4 MSW-LMA global picture

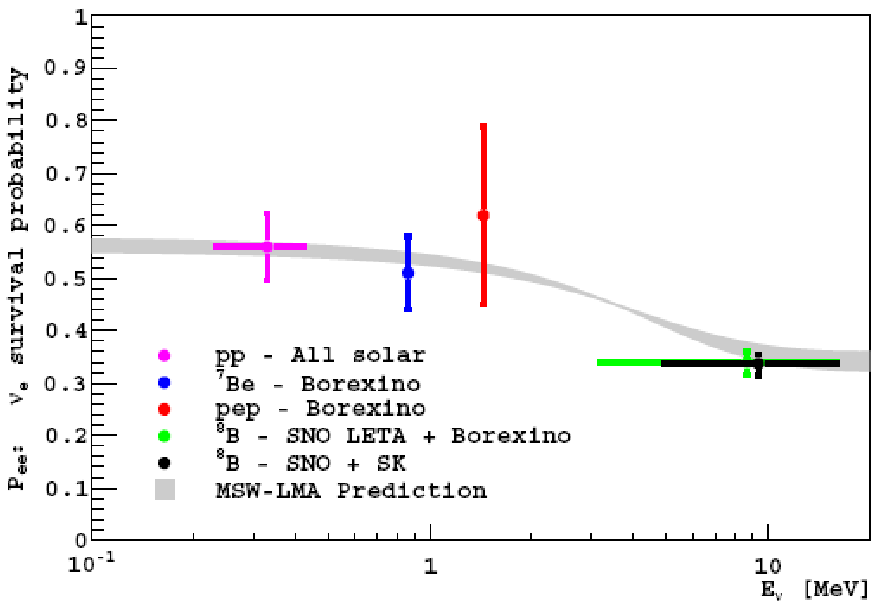

Fig. 1 – Low energy validation of the MSW-LMA solution provided by Borexino

In Fig. 1 the MSW predicted P_{ee} (electron neutrino survival probability) is shown, together with several experimental points, i.e. black the ^8B from all solar data, green ^8B from Borexino and SNO [9], blue the ^7Be Borexino point, magenta the pp datum as drawn by the comparison of Borexino with the Gallium experiments, and red the pep Borexino point: altogether from this figure we can conclude that 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 sub-MeV Vacuum MSW regime.

This striking confirmation is also complemented by the measure of the day-night asymmetry of the ^{7}Be flux [10], which is found equal to A_{dn} = 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.

5. 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 [11], for a data taking period of 1353 days. With a fiducial exposure of (3.69 ± 0.16) $\times 10^{31}$ 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.

6. The SOX project

SOX (acronyms which stands for Short Oscillations with BoreXino) is a project aimed to test a large fraction of the parameter space for short distance neutrino flavor oscillations into sterile component(s), probing in this way the several so called neutrino anomalies [12], a set of circumstantial evidences of electron neutrino disappearance at short distance from the source observed by several experiments. In [13] its characteristics are described at length.

The experiment will be done by placing a well-designed artificial neutrino (or antineutrino) source, ^{51}Cr in a first instance and possibly ^{144}Ce in the future, close (or even inside) the detector. The exceptional Borexino sensitivity, due to its very low radioactive background and witnessed by the impressive measurements described above, will be the key ingredient of the experiment. The expected discovery potential, calculated with high precision Monte Carlo simulations which implement our deep knowledge of the detector response, shows that the test holds the capability to shed substantial light on the hypothesis of sterile neutrino(s) as an explanation of the long standing neutrino anomalies.

A distinctive feature of the project is the clear signature of the oscillation-into-sterile effect, which would be unraveled by the peculiar spatial pattern (spatial waves) featured by the detected events in the detector: therefore this test is much more than a pure conventional disappearence or appearance experiment, being automatically equipped with a “smoking gun” indication that would make absolutely credible and unambiguous any possible discovery claim.

With most of the funding already secured, the test with the ^{51}Cr will be completed by the end of 2015.

7. Conclusions

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 and pep 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 low energy regime, strengthened also by the determination of the absence of day-night asymmetry in the ^{7}Be flux.

Furthermore, 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.

Finally, the SOX project, for the exploration of the hotly debated issue of the experimental anomalies pointing to possible sterile neutrino states, will exploit the exceptional features of Borexino coupled to a powerful neutrino source to provide illuminating data on this long standing puzzle.

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