PROCEEDINGS OF SCIENCE

Results and physics implications of the precision measurement of the ^{7}Be solar neutrino flux performed with the Borexino detector

Gioacchino Ranucci[1]
Istituto Nazionale di Fisica Nucleare
Via Celoroia 16, 20133 Milano, Italy
E-mail: `gioacchino.ranucci@mi.infn.it`

G. Bellini, J. Benziger, D. Bick, S. Bonetti, G. Bonfini, M. Buizza Avanzini, B. Caccianiga, L. Cadonati, F. Calaprice, C. Carraro, P. Cavalcante, A. Chavarria, D. D'Angelo, S. Davini, A. Derbin, A. Etenko, K. Fomenko, D. Franco, C. Galbiati, S. Gazzana, C. Ghiano, M. Giammarchi, M. Goeger-Neff, A. Goretti, L. Grandi, E. Guardincerri, S. Hardy, Aldo Ianni, Andrea Ianni, V. Kobychev, D. Korablev, G. Korga, Y. Koshio, D. Kryn, M. Laubenstein, T. Lewke, E. Litvinovich, B. Loer, F. Lombardi, P. Lombardi, L. Ludhova, I. Machulin, S. Manecki, W. Maneschg, G. Manuzio, Q. Meindl, E. Meroni, L. Miramonti, M. Misiaszek, D. Montanari, P. Mosteiro, V. Muratova, L. Oberauer, M. Obolensky, F. Ortica, M. Pallavicini, L. Papp, C. Peña-Garay, L. Perasso, S. Perasso, A. Pocar, R.S. Raghavan, G. Ranucci, A. Razeto, A. Re, A. Romani, A. Sabelnikov, R. Saldanha, C. Salvo, S. Schönert, H. Simgen, M. Skorokhvatov, O. Smirnov, A. Sotnikov, S. Sukhotin, Y. Suvorov, R. Tartaglia, G. Testera, D. Vignaud, R.B. Vogelaar, F. von Feilitzsch, J. Winter, M. Wojcik, A. Wright, M. Wurm, J. Xu, O. Zaimidoroga, S. Zavatarelli and G. Zuzel (Borexino Collaboration)

Borexino is 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, the accurate determination of the corresponding day/night asymmetry, and their physics implications are described in this work.

The 2011 Europhysics Conference on High Energy Physics, EPS-HEP2011
Grenoble, Rhône-Alpes, France
July 21-27 2011

[1] Speaker

PoS(EPS-HEP2011)082

1. Introduction

It is now well known, after several decades of theoretical and experimental investigations, that neutrinos are abundantly produced in the core of the Sun. They originate from the nuclear reactions that power our star, producing the energy required to sustain it over the billions of years of its life. Two different chain reactions occur at the temperatures characteristic of the core of the Sun, the so called pp chain and CNO cycle, respectively. Actually for the sun the vast majority of the energy (>98%) is coming from the pp chain, while the CNO contribution is estimated to less than 1.6 %.

The effort to develop a model able to reproduce fairly accurately the solar physical characteristics, as well as the spectra and fluxes of the several produced neutrino components, was led for more than forty years by the late John Bahcall [1]; this effort culminated in the synthesis of the so called Standard Solar Model (SSM), which represents a true triumph of the physics of XXth century, leading to extraordinary agreements between predictions and observables. Such a beautiful concordance, however, has been somehow recently spoiled as a consequence of the controversy risen regarding the surface metallic content of the Sun, stemming from a more accurate 3D modeling of the Sun photosphere. Therefore, there are now two versions of the SSM, according to the adoption of the old (high) or revised (low) metallicity of the surface [2].

From the experimental side, solar neutrino experiments also represent a successful 40 years long saga, commenced with the pioneering radiochemical experiments, i.e Homestake, Gallex/GNO and Sage, continued with the Cerenkov detectors Kamiokande/Super-Kamiokande in Japan and SNO in Canada, and with a last player which entered the scene more recently, Borexino at the Gran Sasso Laboratory, which introduced in this field the liquid scintillation detection approach.

For more than 30 years the persisting discrepancy between the experimental results and the theoretical predictions of the Solar Model formed the basis of the so called Solar Neutrino Problem, which in the end culminated with a crystal clear proof of the occurrence of the neutrino oscillation phenomenon, via the MSW effect. In particular, the joint analysis of the results from the solar experiments and from the KamLAND antineutrino reactor experiment pin points with high accuracy the values of the oscillations parameter within the LMA (large mixing angle) region of the MSW solution [3].

In this rich and successful framework, the latest results from Borexino not only bring additional, strong evidence to the oscillation scenario, but represent also its first validation in the previous un-accessible sub-MeV Vacuum regime, through the direct measurement of the 0.862 MeV ^{7}Be solar neutrino line, made possible by the fantastic unprecedented background level reached by the experiment.

2. Characteristics of the Borexino experiment

Borexino at the Gran Sasso Laboratory [4] 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. 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 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 achieved, representing *per se* a major technological 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.

The previous data release of June 2008 [5] led to an evaluation of the ^{7}Be flux characterized by a 10% precision. Recently at the beginning of 2011 such a determination has been updated to a 5% precision, and has been complemented with the measurement of the associated day-night asymmetry.

3. Detector response

Several steps are required to extract from the raw data the quantitative information of interest regarding the ^{7}Be flux: 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 quantity to be evaluated, the ^{7}Be flux, is a fit parameter.

The challenging task to obtain a 5% precise measurement required a huge effort in term of detailed understanding of the detector response. This 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. To accomplish the latter task it was needed to know a-priori and independently the spatial coordinates of the source. For this purpose the movable arm used to deploy and locate the source within the Vessel was equipped with a red LED; the LED was flashed once reached each desired position: the red light detected by seven CCD cameras made it possible, via a geometrical triangulation algorithm, to determine the source coordinates within an accuracy of ± 2 cm.

Jointly, the energy and spatial measurements obtained throughout the calibration campaign provided an accurate map of the detector response, thus helping to reduce, together with the MC studies (see next subparagraph), the major uncertainties of the previous 10% ^{7}Be flux measurement, whose limiting factors where indeed the errors in the determination of the fiducial volume and of the energy scale.

The source data were paramount also to determine experimentally the detector energy resolution, which has been found to be energy dependent as 5%/√ E(MeV).

3.2 MC tuning

The second ingredient at the basis of the precise ^{7}Be measurement 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.

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 precise the crucial, residual uncertainties on the energy scale and the fiducial volume.

4. Results and physics implications

The fit output for the latest 740.7 days data sample released by the Collaboration [6] is reported in Fig. 1a (the results in the legenda are conventionally expressed in counts/day/100 tons of scintillator; they do not coincide exactly with the final result, which is obtained instead from the average of many fits like that in the figure, differing each other in some of the underlying assumptions). Taking into accounts the systematic errors, computed from the above mentioned uncertainties affecting the energy scale and the fiducial volume selection, the ^{7}Be evaluation is $46 \pm 1.5_{stat}(+1.5-1.6)_{sys}$ 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 [7], the detected ^{7}Be count rate corresponds to a total flux of (4.84 ± 0.24) $\cdot 10^{9}$ cm^{-2}s^{-1}, very well in agreement with the prediction of the Standard Solar Model [2]. For comparison, the measured count rate in case of absence of oscillations would have been 74 ± 5.2 counts/day/100 tons. The resulting electrons survival probability at the ^{7}Be energy is P_{ee}=0.51± 0.07.

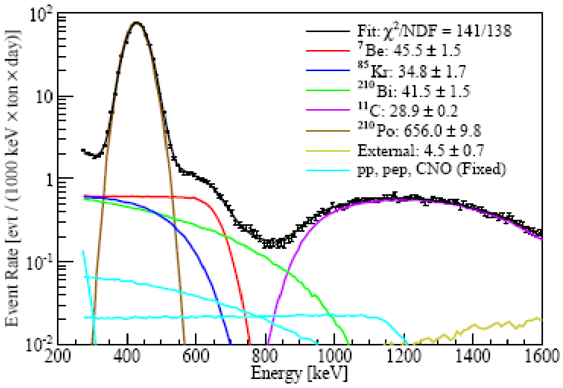

Fig. 1a – Fit of the experimental Borexino spectrum

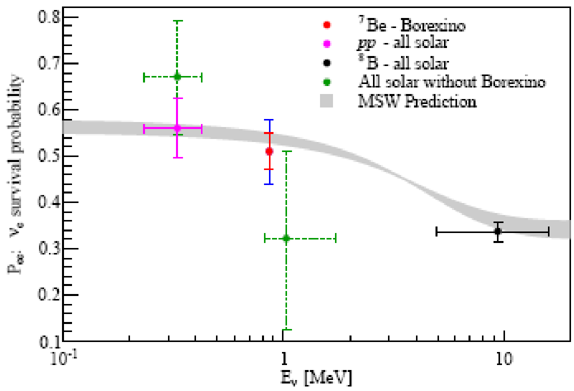

Fig. 1b – Low energy validation of the MSW-LMA solution provided by Borexino

In Fig. 1b the MSW predicted P_{ee} is shown, together with several experimental points, i.e. black the ^{8}B from all solar data, red the ^{7}Be Borexino point from this work, magenta the pp datum as drawn by the comparison of Borexino with the Gallium experiments (the green points on the other hand witness the “unclear” situation before the Borexino results): 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 Vacuum MSW regime.

This striking confirmation is also complemented by the measure of the day-night asymmetry of the ^{7}Be flux [8], 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. Conclusions

The ultra-low background achievement of Borexino, an exceptional breakthrough in the field of techniques for rare processes search, have opened a very sensitive exploration window for sub-MeV solar neutrinos, whose far reaching implications represent in particular a validation of the MSW-LMA oscillation paradigm in the low energy regime, through the precise detection of the ^{7}Be neutrino flux. This important outcome is further strengthened by the determination of the absence of day-night asymmetry in the same flux.

Within the future evolutions of the project, the exceptional background conditions featured by the liquid scintillator can potentially lead to a full solar neutrino spectroscopy, partially already achieved through the determination of the ^{8}B and pep neutrino fluxes.

Finally it should be mentioned that in the framework of the current experimental hints for short baseline oscillations involving a putative sterile neutrino, Borexino thanks to its outstanding technical features and excellent radiopurity is well positioned to host a sensitive neutrino source test able to shed light on this intriguing possibility.

References

[1] http://www.sns.ias.edu/~jnb/ John Bahcall's home page

[2] A.M. Serenelli, W.C. Haxton and C. Pe~na-Garay, *Solar models with accretion. I. Application to the solar abundance problem here and back again,* arXiv:1104.1639 (2011).

[3] B. Aharmim et al. (SNO Collaboration), *Combined Analysis of all Three Phases of Solar Neutrino Data from the Sudbury Neutrino Observatory*, arXiv:1109.0763 (2011).

[4] G. Alimonti et al. (Borexino Collaboratio), *The Borexino detector at the Laboratori Nazionali del Gran Sasso*, Nucl. Instr. and Meth and Meth. A 600, 568 (2009)

[5] C. Arpesella et al. (Borexino Collaboratio), *Direct Measurement of the ^{7}Be Solar Neutrino Flux with 192 Days of Borexino Data,* Phys. Rev. Lett. 101, 091302 (2008)

[6] G. Bellini et al. (Borexino Collaboratio), *Precision measurement of the ^{7}Be solar neutrino interaction rate in Borexino,* Phys. Rev. Lett. 107, 141302 (2011)

[7] Review of Particle Physics, K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010)

[8] G. Bellini et al. (Borexino Collaboratio), *Absence of day-night asymmetry of 862 keV Be-7 solar neutrino rate in Borexino and MSW oscillation parameters,* arXiv:1104.2150 (2011).