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New results and strategy of Borexino

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Summary. — The Borexino detector was designed to perform the first real-time measurement of the monoenergetic neutrinos from the electron capture on the ^{7}Be in the core of the Sun. The measurement with a precision of 10% has already been reported. The goal of 5% can be obtained in the future thanks to the intense calibration campaign performed in order to tune the Borexino reconstruction code. The ^{8}B solar neutrino analysis with the lowest threshold achieved so far of 3 MeV has also been reported. The unprecedentedly low intrinsic radioactivity achieved in Borexino offers a unique tool for the sensitive anti-neutrino study in the MeV energy range and made possible the first observation at more than 3 σ CL of the geo-neutrino (geo-$\bar{\nu}_e$) signal.

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

1. – Introduction

The first real-time measurement of the solar neutrino fluxes in the sub-MeV energy range became possible with the Borexino multiton liquid scintillator (LS) detector [1] which has been constantly taking data since May 15th of 2007. The main goal of the Borexino experiment is the 5% precision measurement of the monochromatic solar neutrinos of the energy $E_\nu = 0.862\,\text{MeV}$ that are emitted in the electron capture decay of ^{7}Be in the core of the Sun. The solar neutrinos in Borexino are detected via the neutrino elastic scattering on the electrons of the LS target.

The expected in Borexino rate of the ^{7}Be solar neutrinos of about 50 counts per day (cpd) in 100 tons of LS imposes to achieve an extremely high level of purity of the target scintillator. The core of the Borexino detector should be 9-10 orders of magnitude less radioactive than anything on Earth. Years of dedicated studies brought to the development of the successful purification strategy which allowed to obtain the desirable purity level of the scintillator [2].

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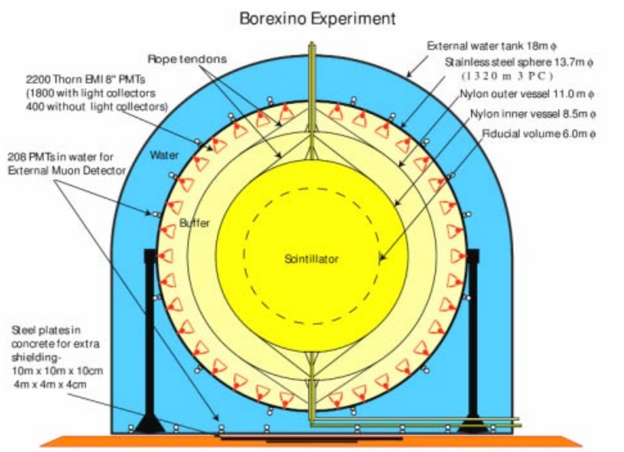

Fig. 1. – Schematic view of the Borexino detector.

2. – Detector design and experiment location

The Borexino detector is an unsegmented multiton liquid-scintillator detector, which can be subdivided into three concentric parts (see fig. 1).

The first, external, part is a Water Tank (WT) with a cylindrical base (18 m in the diameter) and a hemispherical top with a maximum height of 16.9 m. The Water Tank is filled with 2400 m^3 of high-purity water which provides a 2m shielding against the external background (γ-rays and neutrons from the rock). Equipped by 208 PMTs that collect the Cerenkov light emitted by the muons in water, the WT also serves as a muon veto.

Inside the WT the Stainless Steel Sphere (SSS), the scintillator container and the holding structure for the 2212 $8''$ PMTs mounted on its inner surface, is placed. The SSS is divided into two parts: the most inner part, the core of the detector, is filled by the LS target, the mixture of the solvent pseudocumene and the fluor PPO at a concentration of 1.5 g/l, enclosed in a thin 125 μm nylon Inner Vessel (IV). Outside the IV the SSS is filled with a not scintillating mixture of pseudocumene and DMP (buffer liquid) at a concentration of 5.0 g/l. This buffer liquid represents a second layer (1.5 m) of shielding mainly against the internal radiation from the PMTs and the construction materials. In order to prevent a Rn diffusion toward the central part of the detector a second nylon vessel (shroud) is placed in the SSS, close to the PMTs.

The Borexino experiment is located in the Hall C of the Gran Sasso National underground Laboratory (LNGS, Italy). The surrounding mountain provides 3800 m.w.e. of shielding against the cosmic radiation, the residual muon flux is $1.16 \pm 0.03\,\mathrm{m}^{-2}\,\mathrm{h}^{-1}$ with an average energy of $320 \pm 4(\mathrm{stat}) \pm 11(\mathrm{syst})$ GeV [3].

3. – Solar neutrinos

Since the first observation of the solar neutrinos in 1968 [4] a clear discrepancy between the experimental results and the theoretical predictions was noticed, named later as the solar neutrino problem. Among various explanations the most favourite appeared to be the solar neutrino flavour oscillations due to the MSW effect [5] that was experimentally confirmed by the SNO experiment in 2001 [6]. Further experimental investigation performed by SNO and KamLAND experiments allowed to constrain the MSW parameters to the so-called Large Mixing Angle (LMA) region in the $\theta_{12} : \Delta m^2$ plane [7].

The MSW-LMA scenario predicts the correlation of the neutrino oscillations (and therefore the survival probability) with the neutrino energy [8]. In the energy range above $\sim 3\,\mathrm{MeV}$ the oscillations are dominated by matter effects, while below $\sim 0.5\,\mathrm{MeV}$ a more important role is played by the vacuum effects. Before Borexino started to take data, in real time only the matter-dominated region was studied by observation of ^{8}B neutrinos starting from 5 MeV. The direct measurement of the survival probability (P_{ee}) in the region between $\sim 0.5\,\mathrm{MeV}$ and $\sim 3\,\mathrm{MeV}$, the so-called transition zone, and below represents an important test of the MSW-LMA solution.

3˙1. ^{7}Be *solar neutrinos.* – The detection of the ^{7}Be solar monoenergetic electron neutrinos with energy of 0.862 MeV produced in the process $^7\mathrm{Be}(\mathrm{e}^-, \nu_e)^7\mathrm{Li}$ allowed for the first time to test the MSW-LMA prediction in the transition zone.

The present Borexino result based on 192 days of statistics is $49 \pm 3(\mathrm{stat}) \pm 4(\mathrm{syst})$ cpd/100 tons of LS [9]. Considering the high-metallicity Standard Solar Model (BS07(GS98) SSM), found rate corresponds to a flux $\Phi(^7\mathrm{Be}) = 5.08 \pm 0.25 \times 10^9\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The expected signal in case of non-oscillating neutrinos is 74 ± 4 cpd/100 tons. The MSW-LMA scenario predicts the rate of 48 ± 4 cpd/100 tons that is in a good agreement with observation. The non-oscillation hypothesis ($P_{ee} = 1$) is rejected at 4σ CL.

Currently reached accuracy of 10% on the ^{7}Be flux does not allow to resolve the recently arisen problem of the chemical composition of the Sun, the so-called Solar metallicity problem [10].

The originally expected precision of 5% is feasible thanks to the recent improvements performed in the Borexino reconstruction code basing on the new calibration data from the 2008-2009 calibration campaign.

3˙2. ^{8}B *solar neutrinos.* – The electron neutrinos produced in the decay of ^{8}B in the core of the Sun were the most accessible for the experimentalists due to the high visible end point energy of 16.3 MeV. Boron solar neutrino spectroscopy, however, has been performed so far only by the water Cerenkov detectors KamiokaNDE, SuperKamiokaNDE and SNO.

The main detection process is the elastic ν-e scattering, SNO experiment used also the nuclear reaction channels on deuterium contained in the heavy water target. The high level of intrinsic contamination and low photon yield impose a high threshold in the water Cerenkov experiments of 5 MeV. The lowest threshold achieved so far is 3.5 MeV after the application of the new analysis technique performed by the SNO Collaboration [11].

The Borexino liquid-scintillator detector has better energy resolution and higher level of radiopurity with respect to the water Cerenkov detectors. This provides an advantage in search of the ^{8}B neutrinos. At present the Borexino experiment performed the measurement of boron electron neutrinos based on 488 live days of statistics with a threshold of 3 MeV. The current threshold is limited by the 2.6 MeV gamma of the ^{208}Tl decay from the ^{232}Th chain. The observed rate is $0.217 \pm 0.038(\mathrm{stat}) \pm 0.01(\mathrm{syst})$ cpd/100 tons of LS which corresponds to a flux of $\Phi(^8\mathrm{B}) = 2.4 \pm 0.04 \pm 0.01 \times 10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (considering high metallicity SSM) [12]. The obtained result is in a good agreement with previous measurements.

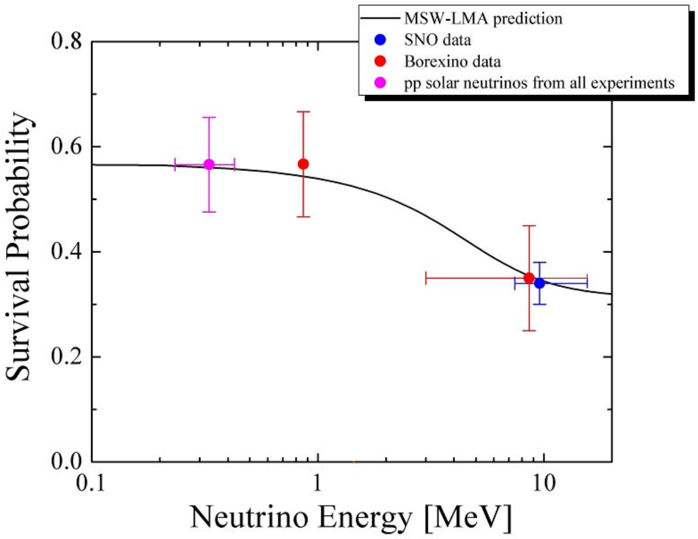

Fig. 2. – (Colour on-line) The mean electron neutrino survival probability (P_{ee}) as a function of neutrino energy. In red dots the $P_{ee}(^7\mathrm{Be})$ and $P_{ee}(^8\mathrm{B})$ measured by Borexino are shown.

The mean electron neutrino survival probability for the ^{8}B neutrinos at the effective energy of 8.6 MeV assuming BS07(GS98) SSM is found to be 0.35 ± 0.10. For the ^{7}Be this value is 0.56 ± 0.01 (see fig. 2). Removing the common sources of uncertainty, the ratio between ^{7}Be and ^{8}B neutrinos survival probabilities becomes 1.60 ± 0.33 which is 1.8 σ away from unity. This is the first measurement of the survival probability in both the transition zone and in the matter-dominated oscillation region obtained by the same detector.

4. – Calibrations

During a period of 2008-2009 three intense calibration campaigns were performed in Borexino in order to study in detail the detector response function. Three types of the radioactive sources (α, β and γ) were used for the precise definition of the energy scale in the wide range starting from 0.12 MeV up to 10 MeV.

The main source of uncertainty, as was reported in [9], is caused by the uncertainty on the fiducial volume definition (6%). Performed calibration allowed us to reduce this number down to 3.8%.

5. – First observation of the geo-neutrino signal

The geo-neutrinos, the electron anti-neutrinos ($\bar{\nu}_e$) generated in β decays of the long-lived radioactive isotopes mainly ^{40}K, ^{238}U and ^{232}Th which are naturally present in the Earth interior, were introduced in 1960s by Marx [13], Markov [14] and Eders [15] and the subject was reviewed in 2004 by Mantovani *et al.* [16].

The first experimental investigation of geologically produced $\bar{\nu}_e$'s was done by the KamLAND experiment in 2005 [17].

Extreme cleanliness of the scintillator achieved in Borexino together with high photon yield and the large number of free target protons ($\sim 1.7 \times 10^{31}$) offer a unique tool for the anti-neutrino ($\bar{\nu}_e$) study in the MeV energy range.

Borexino detects $\bar{\nu}_e$ by means of the well-established reaction of the inverse β decay $\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$ with a threshold of 1.806 MeV. This process offers a strong signature given by two signals correlated in space and time. The positron in the LS comes promptly to rest and annihilates emitting two 0.511 MeV γ-rays, giving a prompt signal, with a visible energy of $E_{\mathrm{prompt}} = E_{\bar{\nu}_e} - 0.782\,\mathrm{MeV}$. The emitted neutron, after the thermalization ($\tau \sim 256\,\mu\mathrm{s}$), is typically captured on proton with a resulting emission of a 2.22 MeV γ which provide a coincident delayed signal. Only $\bar{\nu}_e$ from the ^{238}U and ^{232}Th series satisfy the threshold (${E^{\bar{\nu}_e}}_{\mathrm{max}}(^{238}\mathrm{U}) = 3.26\,\mathrm{MeV}$, ${E^{\bar{\nu}_e}}_{\mathrm{max}}(^{232}\mathrm{Th}) = 2.25\,\mathrm{MeV}$), while the ^{40}K $\bar{\nu}_e$ are below the threshold (${E^{\bar{\nu}_e}}_{\mathrm{max}}(^{40}\mathrm{K}) = 1.3\,\mathrm{MeV}$) and therefore remain undetected.

The present $\bar{\nu}_e$ analysis is based on the 537.2 days of live-time collected between December 2007 and December 2009 that correspond, after all cuts, to an exposure of 252.6 ton y [18].

Two main sources of $\bar{\nu}_e$'s were considered in the analysis: the reactor $\bar{\nu}_e$'s whose energy spectrum extends up to $\sim 8\,\mathrm{MeV}$, and $\bar{\nu}_e$'s from the Earth ($1.8\,\mathrm{MeV} < E_{\bar{\nu}_e} < 3.26\,\mathrm{MeV}$). The predicted geo-neutrino signal in Borexino with the visible energy up to $\sim 2.6\,\mathrm{MeV}$ considering the Bulk Silicate Earth (BSE) model [16] is $2.5\ ^{+0.3}_{-0.5}$ events in 100 ton y.

The advantageous location of Borexino detector, far from nuclear plants, guarantees the low contribution from the reactor-$\bar{\nu}_e$'s in the geo-neutrino energy window ($\sim$ 1–2.6 MeV). Among all nuclear plants considered in the analysis 97.5% of the overall signal is given by the 194 reactors in Europe while other 245 reactors around the world contribute to only 2.5%. Based on data about all European nuclear plants (nominal thermal power and monthly load factor) from IAEA and EDF the calculated expected reactor-$\bar{\nu}_e$ signal in whole energy range (up to 8 MeV) in case of 100% detection efficiency is 5.7 ± 0.3 events in 100 ton y (with neutrino oscillations) and 9.9 ± 0.5 events in 100 ton y (without neutrino oscillations). Moreover, only $\sim 35\%$ of the total reactor-$\bar{\nu}_e$ signal will contaminate the geo-neutrinos energy window, while remaining 65% will be in the reactor-$\bar{\nu}_e$ window (2.6–8 MeV).

The intense and detailed study of all possible sources of background, mainly the sources of events capable to mimic the $\bar{\nu}_e$ signature, such as radioactive spallation isotopes (^{8}He, ^{9}Li), fast neutrons and fake $\bar{\nu}_e$ from the (α-n) reaction including the study of accidentals, bring to the overall background rate of 0.14 ± 0.02 events in 100 ton y. See [18] for more details.

A total of twenty-one (21) $\bar{\nu}_e$ candidates were selected after application of all cuts (see fig. 3). The expected background in the whole data set is 0.40 ± 0.05 events. Therefore, the resulting signal-to-background ratio is an unprecedented $\sim 50:1$. The best estimates of the geo-$\bar{\nu}_e$ and the rector-$\bar{\nu}_e$ rates obtained from the unbinned maximum likelihood analysis are: $N_{\mathrm{geo}} = 9.9^{+4.1}_{-3.4}\ (^{+14.6}_{-8.2})$ and $N_{\mathrm{react}} = 10.7^{+4.3}_{-3.4}\ (^{+15.8}_{-8.0})$ at 68.3% CL (99.73% CL).

6. – Future plans

The recent efforts of the Borexino Collaboration are focused on the achievement of the 5% precision measurement of the ^{7}Be solar neutrino flux and on the study of the pep, CNO and possibly pp solar neutrinos. In order to extend the Borexino solar neutrino program, further purification of the detector will be done in the near future in order to reduce the contamination which prevents this analysis, mainly ^{85}Kr and ^{210}Bi.

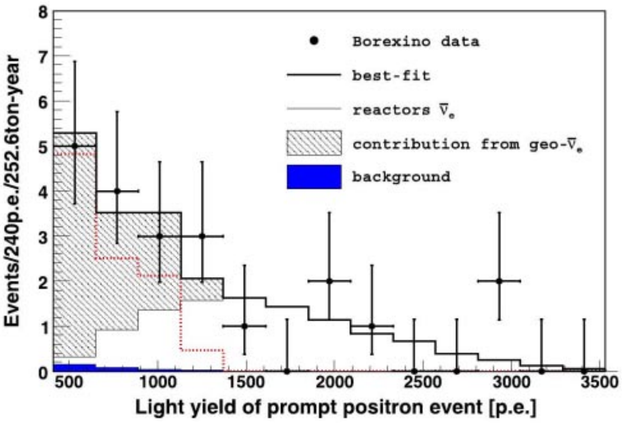

Fig. 3. – The light yield spectrum for the positron signals of 21 selected $\bar{\nu}_e$ candidates and the best fit. See [18] for details.

For what concerns the geo-$\bar{\nu}_e$ study a greater statistics is needed (accumulation of 1000 ton-y exposure is planned) in order to try to perform the spectral measurement of ^{238}U and ^{232}Th components of the geo-$\bar{\nu}_e$ signal.

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