Neutrino physics with the Borexino experiment

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Summary. — Borexino is a large mass, high radiopurity detector located under the Gran Sasso mountain (Italy) and designed to measure in real-time the flux of low energy solar neutrinos. Borexino has been taking data continuously since May 2007. This talk is focused on the main goal of Borexino, the measurement of solar neutrinos produced in the ^{7}Be reaction: I will present the result on the ^{7}Be flux obtained in 2008 after 192 days of data-taking together with a preliminary evaluation of the day-night asymmetry of the signal. I will also discuss the impact on the analysis of the two extensive calibration campaigns performed in 2009. Thanks to these campaigns a new measurement of the ^{7}Be flux will be shortly published with significantly reduced error. Borexino is also able of measuring the ^{8}B neutrino flux with an unprecedented low threshold of 3 MeV (scattered electron kinetic energy): it is the only experiment able of probing the survival probability in the vacuum dominated oscillation regime (with ^{7}Be neutrinos) and in the matter enhanced oscillation regime (with ^{8}B). Finally, I will also present an other important result of Borexino, namely the first clear observation of geo-neutrinos.

PACS `95.55.Vj` – 29.40.Mc.

1. – Introduction

Solar neutrinos have been studied for 30 years by means of radiochemical and water-Cerenkov detectors. These studies have yielded to the discovery of neutrino oscillations in the Sun and to the determination of the oscillation parameters $\Delta m^2 = 7.6 \cdot 10^{-5} eV^2$ and $\sin^2 2\theta_{12} = 0.87$ (K. Nakamura et al.2010)[10]. However, the investigation of the solar neutrino spectrum is far from being complete, having been limited on one hand by the fact that radiochemical experiments cannot measure neutrino energies, and on the other by the fact that water-Cerenkov detectors must work with a high experimental threshold (E> 4.5 MeV) because of radioactive background. The Borexino experiment has opened a new chapter in the experimental history of solar neutrinos, by proving the feasibility of the solar neutrino spectroscopy in real-time down to the uprecedented energy threshold of 250 keV [4, 5]. This was made possible by employing a liquid scintillator technique which has several advantages over both radiochemical and water-Cerenkov ones: on one hand, it allows detection in real-time (unlike the radiochemical technique), on the other, it makes it possible to lower the energy threshold down to few hundresd keVs. This last feature stems from two main characteristics of an organic liquid scintillator: the large light yield (with respect to the Cerenkov one) and the fact that it provides very low solubility to ions and metal impurities which makes it possible to bring it to unprecedented level of radiopurity.

In this talk we report the main results obtained so far by the Borexino experiment, which include the measurement of the ^{7}Be flux after 192 days of data-taking, the measurement of the ^{8}B neutrino flux down to the unprecedented threshold of 3 MeV. We will also discuss preliminary results on the day-night asymmetry of the ^{7}Be neutrinos. We will finally show the results concerning the first clear detection of geo-neutrinos. More details can be found in reference (Arpesella et al., 2008) [4], [5] and in [8].

2. – The Borexino detector

The Borexino detector is located under the Gran Sasso mountain in the Laboratori Nazionali del Gran Sasso, Italy. It detects solar neutrinos via their elastic scattering on the electrons of 300 tons of liquid scintillator. The scintillator (pseudocumene as a solvent + 1.5 g/l of PPO as a solute) is contained in a large spherical nylon vessel (R=4.25m). The scintillation light is viewed by 2214 photomultiplier tubes mounted on a Stainless Steel Sphere (SSS) concentric with the vessel at a radius of 6.85 m (see Fig. 1). In order to reduce external background (γ's from the PMTs and γ's + neutrons from the rock), 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.

The innermost shield is provided by 1000 tons of pure pseudocumene contained in the SSS. The outermost one consists in 2000 tons of ultrapure water contained in the cylindrical dome (diameter=18 m, height=16.9 m) which encloses the entire detector. The external water serves also as a Cerenkov radiator to detect residual cosmic muons crossing the detector. Besides keeping external backgrounds at a low level, the key requirement for measuring low energy neutrinos with Borexino is the extreem radiopurity of the scintillator itself: the neutrino signal, in fact, is indistinguishable from the beta-like events due to natural radioactivity. Therefore, the rate of events due to radioactive background must be lower or comparable to the expected interaction rate for the ^{7}Be signal, namely 50 counts/(day·100tons). During 15 years of dedicated R&D studies, the Borexino collaboration developed a successful purification strategy which proved to be effective in removing the most dangerous contaminants from the scintillator. In particular, the contamination due to ^{238}U and ^{232}Th was brought to the unprecedented levels of (1.6 ± 0.1) 10^{-17}g/g and (6.8 ± 1.5) 10^{-18}g/g, respectively, one order of magnitude better than the designed goal of 10^{-16}g/g. For more details concerning the Borexino detector see [2],[3].

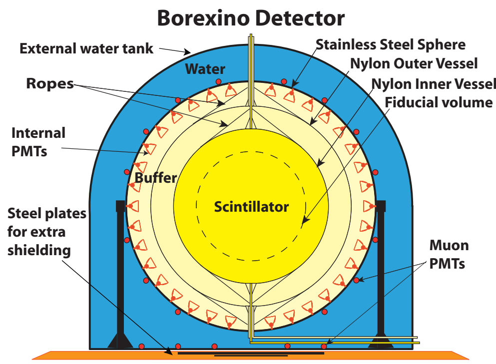

Fig. 1. – A scheme of the Borexino detector: the core of the experiment is represented by 300 tons of liquid scintillator contained in a spherical vessel (in yellow) of 4.25 m radius. The light emitted by the scintillator is viewed by 2200 photomultiplier tubes mounted on a sphere of 7 m radius.

3. – ^{7}Be neutrino flux

An event in Borexino is recorded when at least 25 PMT pulses occur within a time window of 99 ns (which corresponds to an energy threshold of approximately 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 lenght of the scintillator pulse and reconstructs the position of the energy deposit in the scintillator by means of a time of flight technique. Energy is determined by summing the photoelectrons collected for each event. The calibration of the energy scale has been obtained by means of internal contaminants, in particular ^{14}C. The scintillator Light Yield is found to be of the order of 500 photoelectrons/MeV of deposited energy.

The analysis described here refers to 192 live days of data taken in the period from May 16, 2007 to April 12, 2008. The selection cuts are needed to reject muons and residual external and internal backgrounds. For what concerns muons, they are rejected by using the combined information of the outer Cerenkov detector and the internal detector.

Events must be reconstructed within a spherical fiducial volume of 3 meters . The selection of the innermost region of the scintillator is essential to reduce external background to acceptable levels. Additionally, the z-coordinate of the event must be $|z| < 1.7\ m$ in order to remove background near the poles of the nylon vessel.

The resulting spectrum after applying all cuts is shown in Fig. 2 on the left. The prominent peak at approximately 450 keV is due to the 5.3 MeV α's from ^{210}Po , whose visible energy is reduced by light quenching as expected in an organic liquid scintillator. The high ^{210}Po contamination has unknown origins. However, ^{210}Po is not in equilibrium

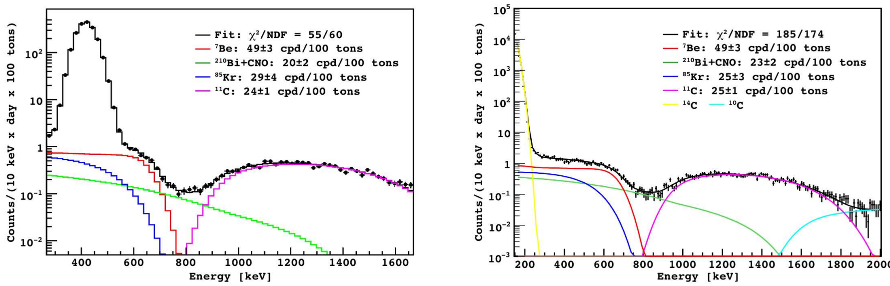

Fig. 2. – Borexino spectra obtained after applying the analysis cuts, before (left) and after (right) statistically subtracting the α's from ^{210}Po decay. The ^{7}Be rate is determined by a fit to the spectra which accounts also for the residual backgrounds ^{11}C, ^{85}Kr, ^{210}Bi and for neutrinos from the CNO reactions.

with the other elements of the ^{238}U chain to which it belongs and is decaying away with the expected lifetime ($\tau = 200.2$ days). It is possible to apply a pulse-shape discrimination technique to statistically subtract from the spectrum the contribution due to ^{210}Po α's. The resulting spectrum is shown in Fig. 2 on the right. A fit is performed on both spectra including the contribution of the ^{7}Be neutrino signal (with its characteristic Compton-like shape), plus the spectral shapes of the expected residual internal backgrounds, namely, ^{11}C, ^{85}Kr and ^{210}Bi. Since the shapes of ^{210}Bi and CNO neutrino spectra are almost indistinguishable, they are fitted together, using a single weight. The weights of all spectral components are left as free parameters of the fit, together with the light yield. The results obtained with and without alpha subtraction are consistent with each other. The main contributions to the systematic error come from the uncertainty on the fiducial mass and on the detector response function. The total systematic uncertainty is $\pm$ 8.5 %. This error will be substantially reduced thanks to the information coming from two calibration campaigns performed in 2009 (see dedicated paragrah).

The final result for the ^{7}Be rate in Borexino including both statistical and systematic error is $(49\pm3_{stat}\pm4_{sys})$ counts/(day·100tons). The expected signal from the Solar Standard Model ([1]) [6], in case of no-oscillation is 74±4 counts/day ·100 tons: the no-oscillation hypothesis is rejected by the Borexino data at the 4σ level. On the other hand, the rate expected in Borexino in case of oscillations for the current best-fit MSW-LMA parameters [10] is 48±4 counts/(day·100tons), in perfect agreement with what found experimentally. From our measurement, under the constraint from the high metallicity SSM and of the MSW-LMA scenario, our best estimate for the flux of ^{7}Be neutrinos is $\Phi(^{7}\mathrm{Be})=(5.18\pm0.51)\times10^{9}$ cm^{-2}s^{-1}.

The Borexino measured rate can be combined with the other solar neutrino measurements to constrain the flux normalization constants for the other solar neutrino sources. In particular, using the luminosity constraint, one obtains $f_{pp} = 1.005\pm^{+0.13}_{-0.19}$ and $f_{CNO} < 3.80$(90%C.L.), where f_{pp} and f_{CNO} are the ratios between the measured

([1]) Depending on the assumptions made on the solar abundances of high-Z elements, the ^{7}Be flux predicted by the Standard Solar Model changes by approximately 10%. We arbitrarily choose as a reference the latest SSM based on abundances reported in reference [9].

and the expected fluxes of pp and CNO sources under the assumptions of the SSM and MSW-LMA.

4. – ^{7}Be neutrino day-night asymmetry

A preliminary analysis of the day-night asymmetry of the ^{7}Be signal has been performed. This measurement can give an independent confirmation of the LMA region: the day-night asymmetry predicted in the LMA region hypothesis is in fact very small (<0.1%) while can be as large as 80% in other regions of the oscillation parameter space (like in the so-called LOW solution region). For this analysis we use events in a Fiducial Volume defined by the R<3m cut only and we perform the fit described in the previous paragraph to extract the signal on the day and night spectra separately. The day-night asymmetry is defined as $A_{dn} = 2\,\frac{R_N - R_D}{R_N + R_D}$ where R_N and R_D are the ^{7}Be rate for night and day respectively. A preliminary analysis based on 387.46 days during the day time and 401.57 days during the night time leads to A_{dn}=0.007 ±0.073, consistent with zero in agreement with the LMA hypothesis. A more accurate measurement of the day-night asymmetry will be published in the near future.

5. – The ^{8}B neutrino flux

Borexino is the first experiment capable to probe the oscillation hypothesis both in the vacuum dominated regime at low energies (with the ^{7}Be neutrinos) and in the matter enhanced regime at higher energies by also measuring the ^{8}B neutrino flux [7]. With respect to the large Cerenkov detectors designed on purpose to measure ^{8}B neutrinos, Borexino has the disadvantage of a relatively small mass and is not capable to correlate the signal to the sun, since scintillation signal lacks directionality. In spite of that, the excellent radiopurity reached by the detector has made it possible not only to measure the ^{8}B flux, but also to reduce the energy threshold for the scattered electron energy down to the unprecedented level of 3 MeV. In Borexino, the main backgrounds affecting the ^{8}B analysis are the cosmogenic isotopes induced by muons and the external background from photomultipliers. The short lived cosmogenics (τ <2s) are removed by vetoing the detector for 5 s after each muon crossing it, while ^{10}C is removed by the triple coincidence with the parent muon and the neutron capture on proton. The external background (mainly Thallium from photomultiplier tubes) is rejected by a Fiducial Volume cut of R<3 m. The contribution due to the small Thallium internal contamination (0.008 counts/(day·100tons)) is statistically subtracted from the final spectrum. Figure 3 (left) shows the spectrum after data selection (red dots), with superimposed the expected contributions from residual backgrounds. The resulting ^{8}B neutrino rate above 3 MeV is found to be $(0.22 \pm 0.04_{stat} \pm 0.01_{sys})$ counts/(day·100tons). This result is obtained analyzing a total of 488 live days of data-taking, corresponding to an exposure of 345.3 days after all cuts. The corresponding total ^{8}B neutrino flux is $(2.7 \pm 0.4 \pm 0.1) \times 10^6$ cm^{-2} s^{-1}, in very good agreement with previous more precise measurements performed by Cherenkov detectors. Figure 3 (right) shows the electron neutrino survival probability P_{ee} for the ^{7}Be and ^{8}B energies as obtained from the Borexino data (assuming the Standard Solar Model predictions for the fluxes in [6] and [9]). Eliminating common sources of systematic errors the ratio between the two probabilities is 1.6 ± 0.33 confirming the expectations of the LMA-MSW oscillation scenario at 93% C.L.

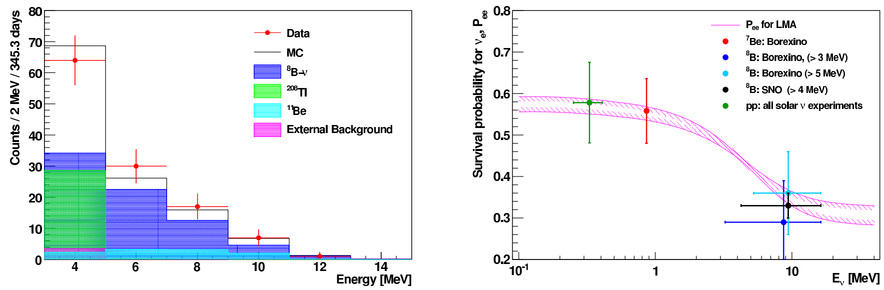

Fig. 3. – Left plot: residual spectrum after all selection cuts (red dots). The expected electron recoil spectrum (from ^{8}B neutrinos including oscillations) is shown in filled blue histogram, together with the expected residual backgrounds. Right plot: the electron neutrino survival probability of the LMA-MSW model and the experimental results discussed in this talk. The curve is computed for PBS09(GS98) and oscillation parameters $\mathrm{tg}^2\theta_{12}$ =0.45 and $\Delta\mathrm{m}^2_{12}$ = 7.69×10^{-5} eV^2.

6. – Geoneutrinos

Geo-neutrinos (geo-$\bar{\nu}_e$) are electron anti-neutrinos produced in β-decays of isotopes naturally present in the Earth like ^{40}K and several nuclides in the ^{238}U and ^{232}Th chains. They can be used as a unique direct probe of the Earth interior, in particular they can give information on the content and distribution of the long-lived radioactive elements in the Earth. Radiogenic heat is generally considered as the main contribution to the total heat budget of Earth. The geochemical Bulk Silicate Earth (BSE) model predicts about 19 TW of radiogenic heat from which 9TW is produced in the crust (mainly continental) and 10 TW in the mantle. Other models predict a much larger contribution from radiogentic heat, while more exotic ones predict possible additional heat sources such as the presence of a nuclear geo-reactor in the core. These models can be discriminated by geo-$\bar{\nu}_e$ measurements, which, especially when performed at different sites, can give information about the spatial distribution of radiogenic elements, about their concentration in the mantle, and about the compatibility of the terrestrial Th/U ratio with the chondritic value of 3.9.

Borexino detects $\bar{\nu}_e$ via the inverse β-decay reaction $\bar{\nu}_e$ + p $\rightarrow$ n + e$^+$. The positron comes to rest and annihilates emitting two 511 keV γ-rays, yielding a prompt event, with a visible energy of $\mathrm{E}_p = E_{\bar{\nu}_e}$ -0.782 MeV. The emitted neutron is typically captured on protons with a mean time of $\tau \simeq 256$ μs resulting in the emission of a 2.22 MeV de-excitation γ-ray, which provides a coincident delayed event. The characteristic time and spatial coincidence of prompt and delayed events offers a clean signature of $\bar{\nu}_e$ detection. Borexino identifies 21 $\bar{\nu}_e$ candidates during 540 livedays with a total exposure after all selection cuts of 252.6 ton-yr. Besides geoneutrinos, the known $\bar{\nu}_e$ sources are reactor $\bar{\nu}_e$, while supernova relic $\bar{\nu}_e$'s give a negligble contribution. The expected reactor signal with (without) neutrino oscillation and 100% detection efficiency is 5.7 $\pm$ 0.3 events/100ton·yr (9.9 $\pm$ 0.5 events/100ton·yr). The energy spectrum for the prompt signal of the 21 candidates surviving the analysis cuts is shown in Fig. 4. An unbinned maximum likelihood analysis is used to extract the contribution from geo-neutrino and from reactor anti-neutrinos: our best estimate for the number od detected geo-neutrinos is $N_{geo}=9.9^{+4.1}_{-3.4}(^{+14.6}_{-8.2})$ and of reactor antineutrinos is $N_{rea}=10.7^{+4.3}_{-3.4}(^{+15.8}_{-8.0})$ at 68.4%C.L. (99.73%C.L.). By studying the profile of the log-likelihood with respect to N_{geo} we have calculated that the null hypothesis for geo-$\bar{\nu}_e$ (i.e., N_{geo}=0) can be rejected at 99.997%. This results hint at a higher rate for geo-$\bar{\nu}_e$ than current BSE predictions, but the present uncertainty prevents firm conclusions. We plan to accumulate at least an exposure of 1000 ton-yr, which should reduce the error by a factor two.

The observed prompt positron spectrum above 2.6 MeV is compatible with the one expected from nuclear reactors (mean baseline of approximately 1000 Km). Our measurement of reactor anti-neutrinos excludes the non-oscillation hypothesis at 99.60% C.L. Furthermore, this measurement rejects the hypothesis of an active geo-reactor in the Earth's core with a power above 3 TW at 95% C.L.

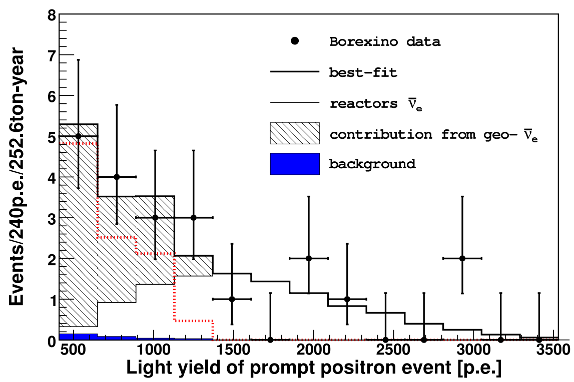

Fig. 4. – Spectrum (number of photoelectrons) for the positron prompt events of the 21 $\bar{\nu}_e$ candidates and the best-fit curve (black solid)

7. – Calibrations

Two calibration campaigns were performed in 2009 to study possible systematics associated to the position reconstruction of the events, and to determine the energy scale and the detector response function with high precision. Before calibrations, reconstruction of position and energy was tested and tuned on internal contaminants (like ^{14}C, ^{222}Rn and so on) in a non optimal way and this is reflected in the high systematic error associated to the ^{7}Be measurement described in this talk. During the two calibration campaigns several radioactive sources were inserted in many positions throghouth the active volume of the detector. In order to calibrate the detector without introducing unwanted contaminations, the source containers have been carefully designed. We have used a quartz sphere (one inch diameter) either filled by ^{222}Rn loaded scintillator identical to the Borexino or filled with γ emitters in aqueous solution. The quartz sphere was attached to a set of stainless steel bars that allowed to locate the source in almost any position within the IV. The Rn source, deployed in more than 200 positions, was mainly used to study the position reconstruction and the position dependence of the detector response. The nominal source position was determined independently by a system of 7 CCD cameras located on the Stainless Steel Sphere (where also the 2200 phototubes are

Isotope	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K
Energy(keV)	122	165	279	514	834	1115	1173-1332	1460

TABLE I. – Calibrations sources used to determine the energy scale. The isotopes are γ-emitters and span the energy region of interest for the ^{7}Be analysis.

mounted). The calibration campaign allowed to reduce the overall systematic uncertainty on the Fiducial Volume selection from 6% down to ≈1%.

The energy scale was studied by inserting 8 different gamma-emitting sources (see table I) spanning the energy range of interest for the ^{7}Be analysis (from ≈100 keV to 1.4 MeV). An AmBe neutron source was also used, in order to have calibration points at higher energies, relevant for ^{8}B solar neutrinos and geo-neutrinos. Due to the quenching phenomenon, the energy scale of a scintillator is not linear and depends also on particle type. The calibration campaigns allowed to reduce the uncertainty on the energy scale between 0 and 2 MeV to less than 1.5%.

8. – Conclusions and perspectives

Borexino has performed the first direct measurement of the ^{7}Be solar neutrino flux in real-time. The results confirm the neutrino oscillation hypothesis and are in agreement with what expected in the LMA-MSW scenario. We have also measured the flux of ^{8}B neutrinos thus probing oscillations both in the vacuum and in the matter enhanced regimes. Borexino has also performed the first clear detection of geoneutrinos.

The calibration campaigns performed in 2009 will have a crucial role in reducing the systematic errors and a new, more precise measurement of the ^{7}Be flux will be published soon. The exceptional levels of radiopurity of the experiment have opened the possibility to explore in a near future other solar neutrino sources, like the so-called pep, CNO and possibly pp. In particular, we are currently purifying the scintillator to try and reduce even further the content of ^{210}Bi and ^{85}Kr, which are the main sources of background for these analyses.

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