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# SOLAR NEUTRINO WITH BOREXINO: RESULTS AND PERSPECTIVES

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Borexino is a unique detector able to perform measurement of solar neutrino fluxes in the energy region around 1 MeV or below due to its low level of radioactive background. It was constructed at the LNGS underground laboratory with a goal of solar $^7$Be neutrino flux measurement with 5% precision. The goal has been successfully achieved marking the end of the first stage of the experiment. A number of other important measurements of solar neutrino fluxes have been performed during the first stage. Recently the collaboration conducted successful liquid scintillator repurification campaign aiming to reduce main contaminants in the sub-MeV energy range. With the new levels of radiopurity, Borexino can improve existing and challenge a number of new measurements including: improvement of the results on the solar and terrestrial neutrino fluxes measurements; measurement of *pp* and CNO solar neutrino fluxes; search for nonstandard interactions of neutrino; study of the neutrino oscillations on the short baseline with an artificial neutrino source (search for sterile neutrino) in context of SOX project.

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## 1. BOREXINO DETECTOR

Borexino is a unique detector able to perform measurement of solar neutrino fluxes in the energy region around 1 MeV or below because of its low level of radioactive background. After several years of efforts and tests with the prototype CTF detector, the design goals have been reached and for some of the radioactive isotopes (internal $^{238}$U and $^{232}$Th) largely exceeded. The low background is an essential condition to perform the measurement: in fact solar neutrino induced scintillations cannot be distinguished on an event-by-event analysis from the ones due to background. The energy shape of the solar neutrino is the main signature that has to be recognized in the experimental energy spectrum by a suitable fit procedure that includes the expected signal and the background. The basic signature for the monoenergetic 0.862 MeV $^7$Be neutrinos is the Compton-like edge of the recoil electrons at 665 keV.

The detector is located deep underground (approximately 3800 m of water equivalent, mwe) in the Hall C of the Laboratori Nazionali del Gran Sasso (Italy), where the muon flux is suppressed by a factor of $10^6$. The main goal of the experiment was the detection of the monochromatic neutrinos that are emitted in the electron capture of $^7$Be in the Sun with 5% precision.

The complete up to date technical description of the Borexino detector has been reported in [1] and [2]. The detector is schematically depicted in Fig. 1. The inner part is an unsegmented stainless steel sphere (SSS) that is both the container of the scintillator and the mechanical support of the photomultipliers. Within this sphere, two nylon vessels separate the scintillator volume in three shells of radii 4.25, 5.50, and 6.85 m, the latter being the radius of the SSS itself. The inner nylon vessel (IV) contains the liquid scintillator solution, namely PC (pseudocumene, 1,2,4-trimethylbenzene $C_6H_3(CH_3)_3$) as a solvent and the fluor PPO (2,5-diphenyloxazole, $C_{15}H_{11}NO$) as a solute at a concentration of 1.5 g/l (0.17% by weight). The second and the third shell contain PC with a small amount (5 g/l) of DMP (dimethylphthalate) that is added as a light quencher in order to further reduce the scintillation yield of pure PC. The PC/PPO solution

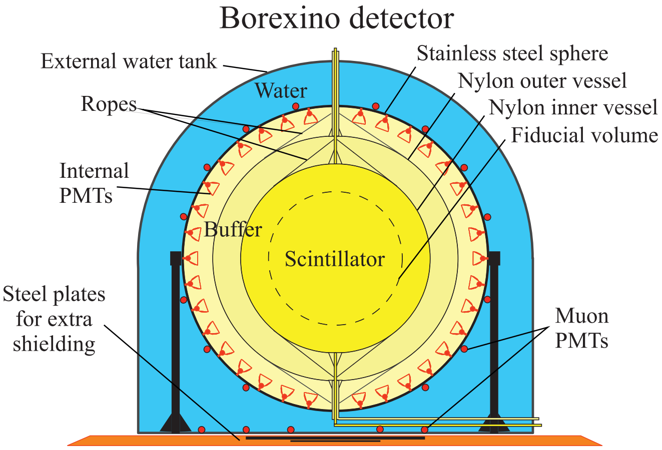

Fig. 1. Sketch of the Borexino detector. The base of the dome-like structure is 18 m in diameter

adopted as liquid scintillator satisfies specific requirements: high scintillation yield ($\sim 10^4$ photons/MeV), high light transparency (the mean free path is typically 8 m) and fast decay time ($\sim$ 3 ns), all essential for good energy resolution, precise spatial reconstruction, and good discrimination between $\beta$-like events and events due to $\alpha$ particles. Furthermore, several conventional petrochemical techniques are feasible to purify the hundred of tons of fluids needed by Borexino.

The scintillation light is collected by 2212 photomutipliers (PMTs) that are uniformly attached to the inner surface of the SSS. All but 384 photomultipliers are equipped with light concentrators that are designed to reject photons not coming from the active scintillator volume, thus reducing the background due to radioactive decays originating in the buffer liquid or $\gamma$'s from the PMTs. The tank has a cylindrical base with a diameter of 18 m and a hemispherical top with a maximum height of 16.9 m. The Water Tank (WT) is a powerful shielding against external background ($\gamma$ rays and neutrons from the rock) and is also used as a Cherenkov muon counter and muon tracker. The muon flux, although reduced by a factor of $10^6$ by the 3800 m.w.e. depth of the Gran Sasso Laboratory, is of the order of 1 $\mathrm{m}^{-2} \cdot \mathrm{h}^{-1}$, corresponding to about 4000 muons per day crossing the detector. This flux is well above Borexino requirements and a strong additional reduction factor (about $10^4$) is necessary. Therefore, the WT is equipped with 208 photomultipliers that collect the Cherenkov light emitted by muons in water. In order to maximize the light collection efficiency, the SSS and the interior of the WT surface are covered with a layer of Tyvek, a white paper-like material made of polyethylene fibers.

The Borexino has an excellent energy resolution for its size, this is the result of the high light yield of $\sim$ 500 p.e./MeV/2000 PMTs. The energy resolution ($1\sigma$) at the $^7$Be Compton edge energy (662 keV) is as low as 44 keV (or 6.6%).

## 2. SOLAR NEUTRINO MEASUREMENTS AT THE FIRST STAGE OF THE EXPERIMENT

Analysis of the Borexino data showed that the main goals concerning the natural radioactivity have been achieved. The contamination of the liquid scintillator with respect to the U/Th is at the level of $10^{-17}$ g/g; the contamination with $^{40}$K is at the level of $10^{-19}$ g/g ($10^{-15}$ in natural potassium); the $^{14}$C content is $(2.7 \pm 0.1) \cdot 10^{-18}$ g/g with respect to the $^{12}$C. Among the other contamination sources only $^{85}$Kr, $^{210}$Bi, and $^{210}$Po have been identified. The $^{85}$Kr counts $\sim$ 0.3 eV/day/t, it is $\beta$-emitter with 687 keV end-point. The $^{210}$Po is the most intense contamination (with initial activity of 60 counts/day/t), it decays emitting monoenergetic $\alpha$ with 5.3 MeV energy, the half-life time of the isotope is 134 days. The residual contaminations do not obscure the expected neutrino signal, the presence of the 862 keV monoenergetic $^7$Be solar neutrino is clearly seen in the experimental spectrum. In such a way, the collaboration succeeded to

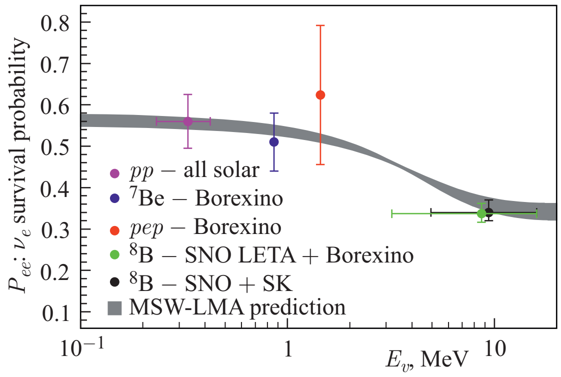

Fig. 2. Electron neutrino survival probability, three points in this plot are derived from the Borexino data. It should be noted that the precision of the $^7$Be neutrino flux itself is much better than the $P_{ee}$ error at the corresponding point, this is related to the solar model uncertainties

purify the liquid scintillator from residual natural radioactive isotopes down to the levels much lower than was initially envisaged for the $^7$Be neutrino measurement, which resulted in broadening of the initial scientific scope of the experiment.

The main goal of the experiment was the detection of the monochromatic neutrinos that are emitted in the electron capture of $^7$Be in the Sun with 5% precision. This goal has been achieved during the first stage of the experiment [3–5]. The Borexino reported the first measurement of $^8$B neutrinos with liquid scintillator detector with a 3 MeV threshold on electrons recoil [6]. The stability of the detector allowed one also to study the day-night effect of the $^7$Be solar neutrino signal, thereby allowing to completely exclude the LOW solution of the neutrino oscillation based on solar data alone [7]. Finally, the low background of the detector, the refined analysis on threefold coincidences [8], and the positronium discrimination method based on the positronium formation study made it possible to explore the 1–2 MeV region with unprecedented sensitivity. This led to the first observation of solar neutrinos from the basic *pep* reaction [9]. In addition, the best limit for the CNO production in a star has been established. In this way, Borexino has completed direct detection of $^7$Be, *pep* and $^8$B solar neutrino components thereby providing complete evidence of the transition from MSW and vacuum oscillation of the LMA solution of the Solar Neutrino Problem (Fig. 2).

## 3. SOLAR NEUTRINO PROGRAM OF THE BOREXINO PHASE II

One of the goals of the Borexino experiment is the measurement of all the solar neutrino fluxes, with the exception of the hep flux, too faint for detection in Borexino. The $^7$Be, *pep* and $^8$B (this last with the lowest threshold to date) have been already measured, but the experimental uncertainties can be reduced. In addition, Borexino will try to measure the *pp* and CNO fluxes.

In the Table the solar fluxes measured by Borexino so far are compared with the SSM prediction, for low and high metallicity. The experimental results agree, within the errors, with the SSM predictions, but cannot distinguish between the two metallicities, due to the uncertainties of the model and the experimental errors. It would be useful, at this moment, to recall what the metallicity puzzle is. The solar surface heavy element abundance has been calculated about ten years ago with a 1D model, which uses data from spectroscopic observations of the elements present in the photosphere (GS98 [10]). This model agrees with the helioseismology observations, namely, the measurement of the speed of the mechanical waves in the Sun. More recently, a 3D hydrodynamical model (AGSS09 [11]) of the near-surface solar convection, with improved energy transfer, has changed the $Z/X$ ratio with respect to the previous 1D treatment: 0.0178 (low metallicity) to be compared with the previous 0.0229 (high metallicity). The 3D model results perfectly reproduce the observed solar atmospheric line (atomic and molecular) profiles and asymmetries, but are in clear disagreement with the helioseismology data. At present there is no satisfactory solution to this controversy [12]. The 1D and the 3D models predict different neutrino fluxes from the various nuclear reactions, as shown in the Table, where they are compared with the experimental results obtained until now. As stated above, it is not possible, at present, to discriminate the solutions due to model uncertainties and experimental errors. A measurement of the CNO flux, with reasonable errors, could distinguish between the two models which predict substantially different fluxes. The *pp* solar neutrino flux has been never measured directly. Gallex and Sage have measured the integrated solar flux from 233 keV, which, together with the Borexino $^7$Be neutrino flux measurement and the experimental data on the $^8$B neutrino flux, can be used to infer the *pp* neutrino flux with a relatively small uncertainty, once the luminosity constraint is applied (Fig. 2). Nevertheless, a direct experimental observation, which can be compared with the solar luminosity and the SSM prediction, would

**SSM predictions and current experimental results**

| $\nu$ flux | GS98 | AGS09 | $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ | Experimental result |
|---|---|---|---|---|
| *pep* | $1.44 \pm 0.012$ | $1.47 \pm 0.012$ | $10^8$ | 1.6±0.3 Borexino |
| $^7$Be | $5.00 \pm 0.07$ | $4.56 \pm 0.07$ | $10^9$ | $4.87 \pm 0.24$ Borexino |
| $^8$B | $5.58 \pm 0.14$ | $4.59 \pm 0.14$ | $10^6$ | $5.2 \pm 0.3$ SNO + SK,+ Borexino,+ KamLAND<br>$5.25 \pm 0.16^{+0.011}_{-0.013}$ SNO-LETA |
| $^{13}$N | $2.96 \pm 0.14$ | $2.17 \pm 0.14$ | $10^8$ | $< 7.4$ Borexino (total CNO) |
| $^{15}$O | $2.23 \pm 0.15$ | $1.56 \pm 0.15$ | $10^8$ | |
| $^{17}$F | $5.52 \pm 0.17$ | $3.40 \pm 0.16$ | $10^8$ | |

be an important achievement. The *pp* flux measurement is a part of the Borexino phase II program.

**3.1. Improvement of the $^7$Be Solar Neutrino Flux Measurement.** The improving of the $^7$Be flux measurement is one of the goals for Borexino phase II. The physics goals of this study can be summarized in three main points.

1. Reduction of the total error (statistical+systematic) down to hopefully $\sim 3\%$. Even with such a precision, this measurement cannot solve unambiguously the metallicity puzzle, because of the uncertainties of the SSM. The $^7$Be flux measured in phase I falls in-between the two predicted flux values, for high and low metallicities, and a smaller uncertainty would not help if this will be the case also for phase II. A very precise experimental determination of the $^7$Be flux remains nonetheless an important tool for testing the Solar Model as well as a remarkable technical achievement.

2. In the context of the neutrino physics, the nonstandard neutrino interactions are currently debated. One way to study them is to analyze the shape of the oscillation vacuum–matter transition region. While $^7$Be cannot have a conclusive role in this matter, it can nevertheless help in restricting the range of the NSI flavor diagonal terms.

3. It is possible to constrain the NSI parameters studying the $\nu$–$e$ elastic scattering. Bounds are imposed by various other experiments on solar, atmospheric, and reactor (anti)neutrinos. But $^7$Be neutrinos have the strong advantage of being monoenergetic ($^8$B neutrino detected by the other solar experiments in real time has a continuous energy spectrum). In Borexino, the limitation to this analysis comes from the residual background, especially $^{85}$Kr, and, to lesser extend, $^{210}$Bi, which can mimic nonzero values of the NSI parameters $\epsilon_{\alpha L}$ and $\epsilon_{\alpha R}$. An increase of statistics does not help much if not accompanied by a reduction of such a background.

**3.2.** *pp* **Solar Neutrino Measurement.** This is the most important target of opportunity for phase II. The very low $^{85}$Kr and reasonably low $^{210}$Bi achieved, make a direct *pp* measurement a reality. A careful understanding of the spectrum response in the $^{14}$C end-point region is crucial, its study is possible through a dedicated effort. The main problem in the *pp*-neutrino study is the disentanglement of the very tail of the $^{14}$C spectrum (with possible pile-up) from the *pp*-neutrino spectrum. The feasibility of the measurement is under study. A direct detection of *pp* neutrinos would be a spectacular result and would justify the phase II alone.

The analysis group performed a study of sensitivity to *pp* solar neutrinos with the current background levels achieved, the expected statistical precision of the *pp*-neutrino flux measurement is below 10%, the systematics error will be mainly connected with uncertainty of the $^{14}$C pile-up spectrum and intensity determination.

**3.3.** *pep* **Solar Neutrino Measurement.** The first indication for *pep* solar neutrinos has been reported by the collaboration [9]. The value for the

$pep$ interaction rate obtained in phase I (590 live-days) was $(3.1 \pm 0.6(\text{stat.}) \pm 0.3(\text{syst.}))$ cpd/day/100 t, the absence of a $pep$ signal was rejected at 98% C.L. The current measurement, in conjunction with the SSM (the uncertainty in the $pep$ flux is as low as 1.2%), yields a survival probability of $P_{ee} = 0.62 \pm 0.17$ though the uncertainties are far from Gaussian. The precision is dominated by the statistical uncertainty (about 20%), though with more (background-free) data, systematic uncertainties (10%) will start to become important.

This is an extremely important result, but shy of the first measurement of $pep$ solar neutrinos. The addition of a modest batch of data with $^{210}$Bi reduced at or below 30 counts/(100 t · day) will result in the first measurement ($3\sigma$) of $pep$ solar neutrinos. A much prolonged data taking could also result in a $5\sigma$ precision measurement. The measurement will allow one to gauge the survival probability in the immediate proximity of the transition between two different oscillation regimes.

**3.4. Solar $^8$B Neutrino Flux Measurements.** The Borexino detector is the first large volume liquid scintillator detector sensitive to the low-energy solar neutrinos. It possesses a very good energy resolution in comparison to the water Cherenkov detectors, what allows one to search for the solar $^8$B neutrinos starting practically from the energies of the so-called thallium limit (maximum energy of $\gamma$ rays from the chains of radioactive decay of $^{232}$Th and $^{238}$U; gamma quantum with maximum energy $E = 2.6$ MeV is emitted in the decay of $^{208}$Tl). The measurements of the $^8$B above 2.8 MeV has been performed using one year statistics (246 days of live-time) of the Borexino data [6]. The threshold of 2.8 MeV is the lowest achieved so far in the $^8$B neutrino real-time measurements. The interest in the neutrino flux measurement with low threshold comes from the peculiar properties of the survival probability in this energy region. The electron neutrino oscillations at $E < 2$ MeV are expected to be driven by the so-called vacuum oscillation, and at energies $E > 5$ MeV — by resonant matter-enhanced mechanism. The energy region in-between has never been investigated in spectrometric regime, and is of particular interest because of the expected smooth transition between the two types of oscillations.

The rate of $^8$B solar neutrino interaction as measured through their scattering on the target electrons is $(0.22 \pm 0.04(\text{stat.}) \pm 0.01(\text{syst.}))$ cpd/100 t. This corresponds to an equivalent electron neutrino flux of $\Phi^{\text{ES}}_{^8\text{B}} = (2.4 \pm 0.4 \pm 0.1) \cdot 10^6\ \text{cm}^{-2} \cdot \text{s}^{-1}$, as derived from the elastic scattering only, in good agreement with existing measurements and predictions. The corresponding mean electron neutrino survival probability, assuming the BS07(GS98) Standard Solar Model (High Z model), is $0.29 \pm 0.10$ at the effective energy of 8.6 MeV. The ratio between the measured survival probabilities for $^7$Be and $^8$B is $1.9\sigma$ apart from unity (see Fig. 2). For the first time the presence of a transition between the low-energy vacuum-driven and the high-energy matter-enhanced solar neutrino oscillations is confirmed using the data from a single detector, the result is in agreement with the prediction of the MSW-LMA solution for solar neutrinos.

Acquiring more statistics (of up to 5 years of the calendar time) the Borexino will provide the competitive measurement of the $^{8}$B neutrino flux.

**3.5. SOX Campaign.** The Borexino large size and possibility to reconstruct an interaction point (with a precision of 14 cm at 1 MeV energy deposit) makes it an appropriate tools for searching of sterile neutrinos. If the oscillation baseline is about 1 m (which corresponds to $\Delta m^2 \sim 1$ eV$^2$), exposure of the detector to a compact powerful neutrino source should give rise to a typical oscillation picture with dips and rises in the spatial distribution of events density with respect to the source. Right beneath the Borexino detector, there is a cubical pit (side 105 cm) accessible through a small squared tunnel (side 95 cm) that was built at the time of construction with the purpose of housing neutrino sources for calibration purposes. Using this tunnel, the experiment with neutrino source can be done with no changes to the Borexino layout. The center of the pit is at 8.25 m from the detector center, requiring a relatively high activity of the neutrino source in order to provide detectable effect.

The experiment SOX (for Short distance neutrino Oscillations with BoreXino) [13] will be carried in three stages with gradually increasing sensitivity:

**Phase A**: a $^{51}$Cr neutrino source of 200–400 PBq activity deployed at 8.25 m from the detector center (external with respect to the detector);

**Phase B**: deploying a $^{144}$Ce–$^{144}$Pr antineutrino source with 2–4 PBq activity at 7.15 m from the detector center (placed in the detector's water buffer);

**Phase C**: a similar $^{144}$Ce–$^{144}$Pr source placed right in the center of the detector.

Figure 3 shows a schematic layout of the Borexino detector and the approximate location of the neutrino and antineutrino sources in the three phases. Two types of neutrino sources are considered: the $^{51}$Cr source and the $^{144}$Pr based source. $^{51}$Cr decays via electron capture into $^{51}$V, emitting two neutrino lines of 750 keV (90%) and 430 keV (10%), while $^{144}$Pr decays $\beta$ into $^{144}$Nd with an end-point of 3 MeV (parent $^{144}$Ce decays too, but end-point of its $\beta$-decay is below the IBD threshold). The portion of the $^{144}$Pr spectrum above the 1.8 MeV detection threshold is the only of importance for the experiment. Elastic scattering of $\bar{\nu}_e$ on electrons induce negligible background.

The source activity of 200–400 PBq is challenging, but only a factor 2–4 higher than what already done by Gallex and SAGE in the 1990s. The $^{144}$Ce–$^{144}$Pr experiment in the Phases B and C does not require high source activity. The phase C is the most sensitive but it can be done only after the shutdown of the solar neutrino program, because it needs modification of the detector. The Phases A and B will not disturb the solar neutrino program of the experiment, which is supposed to continue until the end of 2015, and do not require any change to Borexino hardware. The challenge for the Phase C is constituted by the large background induced by the source in direct contact with the scintillator,

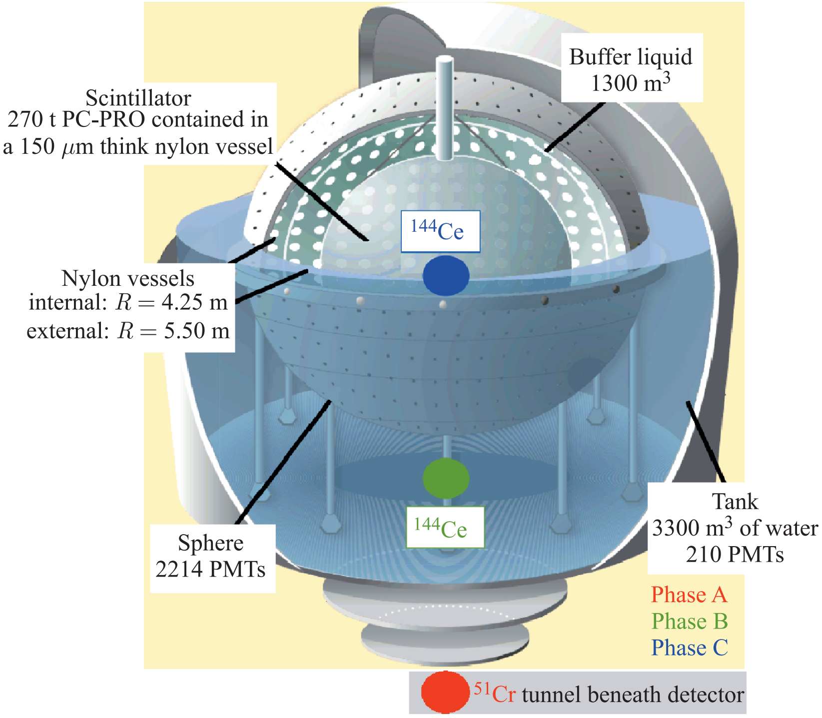

Fig. 3. Layout of the Borexino detector and the approximate location of the neutrino and antineutrino sources in the three phases

that can be in principle tackled thanks to the correlated nature of the $\bar{\nu}_e$ signal detection. In the Phase B this background, though still present, is mitigated by the shielding of the buffer liquid.

Borexino can study short distance neutrino oscillations in two ways: by comparing the detected number of events with expected value (disappearance technique, or total counts method), or by observing the oscillation pattern in the events density over the detector volume (waves method). In the last case, the typical oscillations length is of the order. The variations in the survival probability $P_{ee}$ could be seen on the spatial distribution of the detected events as the waves superimposed on the uniformly distributed background. Oscillation parameters can be directly extracted from the analysis of the waves. The result may be obtained only if the size of the source is small compared to the oscillation length. The $^{51}$Cr source will be made by about 10–35 kg of highly enriched Cr metal chips which have a total volume of about 4–10 l. The source linear size will be about 15–23 cm, comparable to the spatial resolution of the detector. The

$^{144}$Ce–$^{144}$Pr source is even more compact. All simulations shown below take into account the source size.

In the Phase A, the total counts method sensitivity is enhanced by exploiting the fact that the lifetime of the $^{51}$Cr is relatively short. In the Phases B and C, this time-dependent method is not effective because the source lifetime is longer (411 days), but this is compensated by the very low background and by the larger cross section. The total counts and waves methods combined together yield a very good sensitivity for both experiments. Besides, the wave method is independent of the intensity of the source, of detector efficiency, and is potentially a nice probe for unexpected new physics in the short distance behavior of neutrinos or antineutrinos.

The sensitivity of SOX with respect to oscillation into sterile neutrino was evaluated with a toy Monte Carlo. Expected statistical samples (2000 events) were generated for each pair of oscillation parameters. We assume a period of 15 weeks of stable data taking before the source insertion in order to accurately constrain the background. The background model includes all known components, identified and accurately measured during the first phase of Borexino. We built the confidence intervals from the mean $\chi^2$ for each couple of parameters with respect to the nonoscillation scenario. The result is shown in Fig. 4,

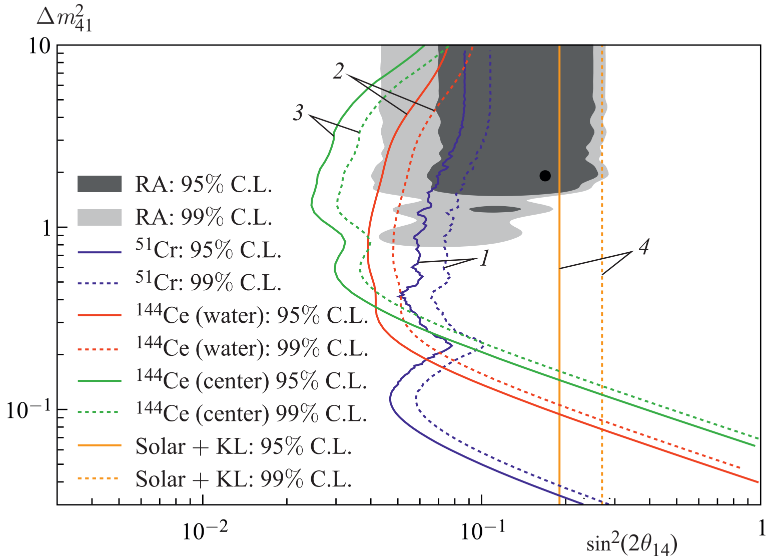

Fig. 4 (color online). Sensitivity of the Phase A ($^{51}$Cr external, blue *1*), Phase B ($^{144}$Ce–$^{144}$Pr external, red *2*) and Phase C ($^{144}$Ce–$^{144}$Pr center, green *3*). The gray area is the one indicated by the reactor anomaly, if interpreted as oscillations to sterile neutrinos. Both 95 and 99% C.L. are shown for all cases. The yellow lines *4* indicate the region already excluded in [14] as one can see from the figure the reactor anomaly region of interest is mostly covered.

The simulation for the Phase A is shown for a single irradiation of the $^{51}$Cr source up to the initial intensity of 370 PBq (10 MCi) at the site. A similar result can be obtained with two irradiations of about 200 PBq if higher intensity turns out to be beyond the technical possibilities. The single irradiation option is preferable and yields a slightly better signal to noise ratio.

The physics reach for the $^{144}$Ce–$^{144}$Pr external (Phase B) and internal (Phase C) experiments, assuming 2.3 PBq (75 kCi) source strength and one and a half year of data taking, is shown in the same figure (Fig. 4).

The $\chi^2$ based sensitivity plots are computed assuming significantly bigger volume of liquid scintillator (spherical vessel of 5.5 m radius), compared to the actual volume of liquid scintillator (limited by a sphere with 4.25 m radius) used for the solar phase. Such an increase will be possibly made by the addition of the scintillating fluor (PPO) in the inner buffer region (presently inert) of the detector. We have also conservatively considered exclusion of the innermost sphere of 1.5 m radius from the analysis in order to reject the gamma and bremsstrahlung backgrounds from the source assembly. Under all these realistic assumptions, it can be noted from Fig. 4 that the intrinsic $^{144}$Ce–$^{144}$Pr sensitivity is very good: for example, the 95% C.L. exclusion plot predicted for the external test covers adequately the corresponding reactor anomaly zone, thus ensuring a very conclusive experimental result even without deploying the source in the central core of the detector.

## CONCLUSIONS

Borexino achieved its main goal, but is still a challenging detector. Due to achieved level of purification (much higher than it was needed for $^{7}$Be neutrino detection), some measurements of solar neutrino fluxes beyond the original program were performed. Borexino-II is operating with repurified LS, at new levels of radiopurity, two years data are collected and are being analyzed aiming the *pp*-neutrino flux and CNO neutrino flux measurement. Borexino is also an ideal detector to test the sterile neutrinos through the disappearance/wave effects. The proposed staged approach ($^{51}$Cr source at the first stage and two $^{144}$Ce–$^{144}$Pr experiments) is a comprehensive sterile neutrino search which will either confirm the effect or reject it in a clear and unambiguous way. In particular, in the case of one sterile neutrino with parameters corresponding to the central value of the reactor anomaly, SOX will surely discover the effect, prove the existence of oscillations and measure the parameters through the oscillometry analysis.

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