RECENT RESULTS FROM BOREXINO

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The neutrino probability to interact is so faint that every attempt to detect the neutrino signal is an experimental challenge. Neutrinos freely escape from remote galaxies or from the deep of the Sun and they are natural carriers of precious information about regions otherwise unaccessible. Borexino is a large, unsegmented liquid-scintillator calorimeter built in the Laboratori Nazionali del Gran Sasso (LNGS) in Italy with the ambitious goal to study in real-time energy the single components of the solar neutrino spectrum. The record-low level of radioactive purity made possible to achieve an exceptional sensitivity especially at energies close and below few MeV. This contribution is aimed at reviewing the most important Borexino results and to discuss the future perspectives, emphasizing in particular the unique possibility of Borexino to aggress the measurement of the elusive CNO-neutrino component and to exploit the possible existence of a fourth sterile neutrino (SOX project).

1 The Borexino detector

The Borexino detector was build starting from 1996 in the underground hall C of the Laboratori Nazionali del Gran Sasso (LNGS) in Italy and it is taking data since May 2007. Its layout is based upon the principle of the graded shielding: the detector structure consists of a set of concentric shells, more inner the shell, higher the radiopurity. The core is made of ~ 280 tons of a liquid scintillator using pseudocumene (PC, 1,2,4-trimethylbenzene) as aromatic scintillation solvent, and a fluorescent dye (PPO, 2,5-diphenyloxazole) as solute at a concentration of 1.5 g/l. It is contained within a thin nylon transparent vessel with 4.25 radius and viewed by about 2000 photomultipliers (PMT). The scintillator is surrounded by a layer of non scintillating medium and by water working as Cerenkov detector for vetoing the residual muons and the muon induced events[1] .

The neutrinos are detected through the elastic scattering interaction with electrons in the organic liquid scintillator, Eq. 1:

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^- \quad (1)$$

This process is sensitive to all neutrino flavors, through the neutral current interaction, but the cross section for ν_e is larger than that for ν_μ and ν_τ by a factor of 5-6, due the combination of charged and neutral currents. Anti-neutrinos are conversely detected via the inverse neutron beta-decay on protons, a process with a threshold of 1.8 MeV:

$$\bar{\nu}_e + p \rightarrow e^+ + n \tag{2}$$

The event energy is measured through the number of hit PMT's or charge: several calibration campaigns [2] with radioactive sources allowed to establish the energy scale and to calibrate the Monte Carlo simulation code [3]. Depending on the type of the analysis, a fiducial volume is software defined within the 4.25 m sphere through the measured event position, obtained from the PMT's timing data via a time-of-flight algorithm. The choice of a liquid scintillator as target mass is especially important to observe the low energy events: the high light yield typical of Borexino scintillator ($\sim 10^4$ photons/MeV) makes it possible to get a good energy resolution ($\sim$ 5% at 1 MeV) and to set a very low energy threshold (50 keV). The drawback of a liquid scintillator is its isotropic light emission so that no event directionality is possible. It is also not possible to distinguish the electrons scattered off by solar neutrinos from electrons due to natural radioactivity.

For this reason, an extremely low level of radioactive contamination is mandatory and this has been one of the main tasks and technological achievements of the experiment. All the materials used in Borexino were specially selected for extremely low radioactivity and only qualified ultra-clean processes and careful surface cleaning methods were employed for the realization of the whole detector. The record-low level of radioactive purity and the related low background make Borexino a powerful instrument to search for many rare processes.

2 Solar neutrinos physics with Borexino

According to Standard Solar models (SSM) solar neutrinos are mainly produced in the so-called proton-proton cycle reactions and in the subdominant CNO cycle[4]: the predicted fluxes are shown in Fig.1 - left. In spite of their elusiveness, the study of solar neutrinos has been up to now very rewarding: on one hand, it has provided a sensitive test of the Standard Solar Model[4]; on the other hand, it has proved that neutrinos oscillate and therefore have mass.

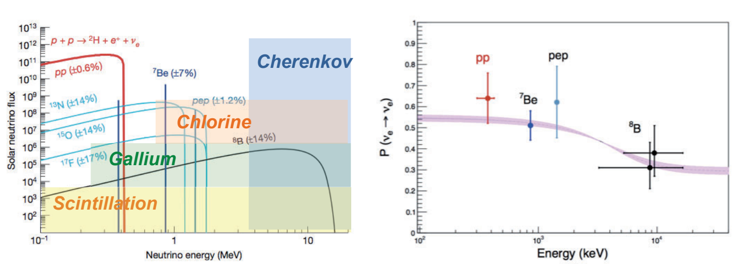

Figure 1 – Left: The solar neutrino energy spectra according to Serenelli et al. [4].The number in parenthesis represent the theoretical uncertainties and the colored areas highlight the sensitivity of the different experimental techniques. Right: the electron neutrino survival probability as measured by Borexino and compared with MSW-LMA predictions (purple band).

The phenomenology of lepton flavor changing neutrino oscillations has now been robustly established thanks to a join experimental effort pursued both with natural and with man-made neutrino beams. According to our present knowledge the left-handed flavor neutrino fields are unitary linear combinations of the massive neutrino fields as described by the Pontecorvo-Maki-Nakagawa-Sakata (PMKS) matrix [5], the leptonic analogous of the Cabibbo-Kobayashi-Maskawa matrix for quarks. Since the amplitudes of different mass components evolve differently with space and/or time, acquiring different quantum mechanical phases, it follows than flavor is a periodical function of time. The PMKS matrix is usually parametrized in terms of three mixing angles (θ_{12}, θ_{23}, θ_{13}) and one(three) phases depending on the Dirac (Majorana) nature of neutrinos. Relevant to oscillation are also two of the three mass differences, Δm^2_{12}, Δm^2_{23}, Δm^2_{13}.

Only two parameters (Δm^2_{12} and θ_{12}) are sufficient to describe well the main features of solar neutrino oscillations: Δm^2_{12}= 7.6±0.2 eV^2 and $\tan 2\theta_{12}$ = 0.47±0.05. These two values are known as the MSW-LMA (low mixing angle) solution to the solar neutrino problem and are obtained by combining the measurements of high energy ^{8}B solar neutrino fluxes, data from radiochemical experiments and the electron flavor survival probability measured by nuclear reactor experiments. The MSW-LMA model predicts an energy dependent survival probability P_{ee} of electron neutrinos traveling from the Sun to the Earth with two oscillation regimes, in vacuum at low energies and in matter at energies above few MeV with a transition regime in between. There do exist also several non standard neutrino interaction models [6,7,8], predicting P_{ee} curves that deviate significantly from the MSW-LMA paradigm particularly between 1 and 4 MeV. Low-energy solar neutrinos are thus a sensitive tool to test the MSW-LMA paradigm measuring P_{ee} versus neutrino energy.

Before Borexino only radiochemical experiments could observe solar neutrinos below 3 MeV, while real-time experiments were just sensible to the very small fraction of the solar neutrino spectrum represented by ^{8}B neutrinos. The very low energy threshold (down to 50 keV) allowed the Borexino experiment to perform an almost complete spectroscopy of solar neutrinos.

In the years 2007-2010 (Phase-I data taking) the following fundamental steps have been accomplished:

- the first direct measurement of the ^{7}Be solar neutrinos flux within a 4.2% error [9,10] which is smaller than the uncertainty of Solar Model predictions and therefore it is setting constraints to the models . Any significant day-night asymmetry of the ^{7}Be neutrinos interaction rate [11] was also ruled out;
- the first direct observation of the solar *pep* neutrinos [12] (with 20% precision);
- a new measure of ^{8}B neutrino flux with the lowest threshold achieved so far (3 MeV) and with 20% precision[13].

Thanks to the detector radio-purity the Compton edge at 661 keV due to ^{7}Be neutrino scattering off electrons is perfectly visible and overwhelming all the other backgrounds in the same energy region (see Fig.2-left) : the ^{7}Be flux has been deduced through an energy fit of the events collected within the fiducial volume. Under the assumption that the reduction in the apparent flux is the result of ν_e oscillation to ν_μ or ν_τ we found P_{ee}= 0.51±0.07 at 862 keV.

The extraction of the *pep* signal required conversely the development of new analysis tools to suppress the cosmogenic ^{11}C background dominating in the energy region around 1-2 MeV: the β^+ ^{11}C decays have been be recognized and rejected by exploiting the coincidence with the parent muon and the different pulse shape with respect to a β^- decay. The final result was based on a binned likelihood multivariate fit performed on the energy, pulse shape, and spatial distributions of selected scintillation events[12]. Under the assumption that the flux reduction is the result of ν_e oscillation we found P_{ee}=0.62±0.17 at 1.44 MeV. The most stringent limit on the CNO neutrino rate was also obtained as a by-product of this analysis: $\Phi_{CNO}<$ 7.9 cpd/100t at 95% C.L[12] .

After these results, the scintillator was subjected in 2010-11 to extensive purification campaigns, based both on water extraction and nitrogen stripping processes, which have further brought down the background levels, especially the ^{85}Kr amount, now negligible.

Thanks to most radio-pure Phase II data, in 2014 a new milestone has been achieved with the measurement of the neutrinos emitted by the first reaction of the *pp* chain[14]:

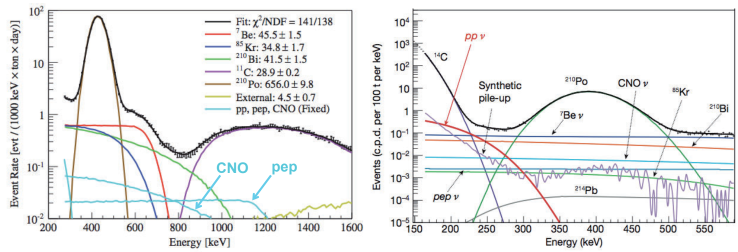

Figure 2 – Left: The Borexino energy spectra with a 153.6 ton · year exposure: the ^{7}Be shoulder is clearly visible; the peak at $\sim$ 420 keV is due to the ^{210}Po contamination (for details see [9]. Right: Borexino energy spectrum between 165 and 590 keV: the best fit *pp* neutrino component is shown in red (see [14]).

$$p + p \rightarrow^4 He + 2e^+ + 2\nu \qquad (3)$$

This reaction belongs to the proton-proton cycle and it is the keystone process for energy production in the Sun and responsible for 90% of the solar neutrino flux at Earth. The data set uses for this analysis ranges from January 2012 to May 2013 (408 days). The *pp* neutrino energy spectrum extends up to 420 keV, yielding in the scattering process a maximum electron recoil energy of 264 keV: particularly relevant to this analysis are the backgrounds due to ^{14}C, an α emitter intrinsic to the organic liquid scintillator whose energy spectrum extends up to 156 keV and its pile-up. ^{14}C and pp neutrinos exhibit however different energy spectra and independent analysis methods[14] have been developed to precisely constrain these sources of background.

The signal of the *pp* solar neutrinos was extracted from the data through a fit of the energy spectrum of the events collected in the 165-590 keV energy window. The solar *pp* neutrino interaction rate in Borexino was found to be of 144 $\pm$ 13 (stat.) $\pm$ 10 (syst.) counts/(day·100 t), corresponding to a survival probability of 0.64$\pm$0.12 and to a solar *pp* neutrino flux of (6.6$\pm$0.7) $\cdot$ 10^{10} cm^{-2} s^{-1}, according to the oscillation parameters reported in [15]. This result is a major experimental milestone in solar neutrino physics since it strongly confirms our understanding of the Sun. The *pp* neutrino flux measured by Borexino shows that neutrino and photon luminosities are equal within errors: on the right panel of Fig.1 the MSW-LMA prediction of the survival probability for solar neutrinos is compared to all Borexino results.

In spite of this huge effort, the study of solar neutrinos is far from being completed.

The SSM has been continuously refined during the years including new effects like the diffusion of elements or updated results about cross sections of the relevant nuclear reactions at low energies. A great success of the models was the capability to reproduce with great accuracy the heliosismological data like the sound speed profile in the outer layers of the Sun or the depth of the convective zone. In more recent years the development of three-dimensional hydrodynamic models of the solar atmosphere has determined a revision of the solar composition predicting in particular a lower amount of metals (i.e. of elements heavier the helium). Unfortunately solar models accounting the low metallicity values poorly reproduce heliosismological data. This tension is known as the high/low metallicity controversy. A precise measurements of the solar neutrino fluxes can help to resolve this issue: neutrinos from the CNO cycle offer the maximal sensitivity being the CNO flux 40% higher in High metallicity models (GS98) [4] than in the Low metallicity ones (AGS09) [16] The detection of neutrinos resulting from the CNO cycle would have huge implications in astrophysics: it would be the first direct evidence of the nuclear processes that are believed to fuel massive stars (>1.5 M_{sun}).

The detection CNO solar neutrinos is extremely challenging: the expected interaction rates are of the order of a few counts per day in a 100 ton target but the main backgrounds, the cosmogenic β^+-emitter ^{11}C and radiogenic ^{210}Bi, are one order of magnitude more intense[10]. As noticed in the *pep* neutrino analysis, the ^{11}C decays may be tagged and rejected by exploiting the coincidence with the parent muon and the different pulse shape with respect to a β^- decay: the fraction of background events surviving all these cuts is of the same order of the expected CNO signal and it may be discriminated because of the different energy shape. Conversely, because of the similarity between the electron-recoil spectrum from CNO neutrinos and the spectral shape of ^{210}Bi decay, CNO flux may be tackled only by finding a method to independently constrain the ^{210}Bi contamination.

We are presently pursuing the idea to constrain the ^{210}Bi content of the scintillator through the precise determination of the decay rate of the ^{210}Po successor: ^{210}Bi and ^{210}Po are both daughter of ^{238}U. ^{210}Bi is produced by the slow decay of ^{210}Pb which has a lifetime equal to τ_{Pb}= 32.3 y. It then undergoes a beta decay to ^{210}Po with a lifetime τ_{Bi} = 7.232 d. ^{210}Po is an α emitter with a lifetime τ_{Po}= 199.634 d: the decay rate in Borexino can be easily deduced from the prominent alpha peak in the event energy spectrum (see Fig.2 - left).

The relationship between the ^{210}Po and the ^{210}Bi abundances is given by:

$$\frac{dN_{Po}}{dt} = \frac{N_{Bi}(t)}{\tau_{Bi}} - \frac{N_{Po}(t)}{\tau_{Po}} \tag{4}$$

The two terms on the right side of Eq. 5 may be discriminated because of the different behavior as a function of time, provided that the time dependence of ^{210}Po decay rate is precisely recorded. The ^{210}Bi decay rate can, in turn, be used as input in the solar data energy fit with the aim of improving the actual CNO flux limit and eventually gaining sensitivity toward a measurement. If some external source of ^{210}Po is polluting the scintillator Eq. 4 modifies as:

$$\frac{dN_{Po}}{dt} = \frac{N_{Bi}(t)}{\tau_{Bi}} - \frac{N_{Po}(t)}{\tau_{Po}} + S_{Po}(t) \tag{5}$$

In such a case the method is not effective. Unfortunately because of temperatures changes in the experimental hall we observed small movements of the scintillator liquid that are supposed to be at root of transfer of dust and particulate sitting on the vessel towards the core of the Fiducial Volume, producing instabilities in the counting rate of the ^{210}Po. To measure the CNO flux a smooth and regular decay of the residual ^{210}Po must be guaranteed. In order to achieve such a good thermal stabilization of the detector, in 2015 the Collaboration pursued a huge effort by completing the application of an insulation material up to the top of the Water Tank, as well as installing an active thermal control system: the adopted strategy looks up to now very successful and the stable detector behavior observed so far is very promising in view of a CNO neutrino flux measurements.

3 Earth radiogenic heat and Borexino

Geo-neutrinos are electron antineutrinos released in the decays of radioactive elements with lifetimes comparable with the age of the Earth and distributed through the Earth's interior. They are mainly produced in the β decay of ^{40}K and of several nuclides in the chains of ^{238}U and ^{232}Th. All these isotopes are also known as Heat Producing Elements (HPE). Presently, geochemical and geodynamical models of the Earth predict that as much as 50% of the total heat radiated by the Earth comes from radiogenic decays. However, the predicted amount of HPE in the mantle is model dependent and we have no direct information in our hands. The heat released during the radiogenic decays is in a well fixed ratio with the total mass of HPE inside the Earth, thus, it is possible to extract from the measured geo-neutrino fluxes several geological information completely unreachable by other means: the observation of geoneutrinos is "the method" to directly measure the HPE in the mantle. Such a knowledge is conversely of critical importance for understanding complex processes such as the mantle convection, the plate tectonics, the geo-dynamo (the process of generation of the Earth's magnetic field), as well as the Earth formation process itself.

The idea of studying geoneutrinos dates back to 1966-1969 [17] but only in 1998 it was proposed the idea of using solar neutrino and reactor neutrino detectors[18]: currently, two large-volume, liquid-scintillator neutrino experiments, KamLAND in Japan [19,20,21] and Borexino in Italy [22,23,24], have been able to measure the geo-neutrino signal. Antineutrinos are detected in liquid organic scintillators by means of the Inverse Beta Decay on protons, a process having a threshold of 1.8 MeV(Eq. 2): only geo-neutrinos from U an Th decay chains are enough energetic to be detected. The cross-section of the inverse-beta decay detection interaction is very low ($\sigma \sim = 10^{-43}$ cm^2) and even a typical flux of the order of 10^6 geo-neutrinos cm^{-2} s^{-1} leads to only a hand-full number of interactions, few or few tens per year with the current-size detectors. This means, the geo-neutrino experiments must be installed in underground laboratories in order to shield the detector from cosmic radiation. Borexino made the first observation of the geo-neutrino signal in 2010 [22] already with a statistical significance of more than 4 σ, and it has recently released an updated result [24] based on the data collected between December 2007 and March 2015, corresponding to an efficiency corrected exposure after cuts of (907 $\pm$ 44) ton $\cdot$ year. The coincidence between the prompt positron signal and the delayed 2.2 MeV gamma due to neutron capture on protons makes the signature of this reaction very clean: energy, space/time correlation and pulse shape cuts are applied for an overall detection efficiency of (84.2 $\pm$ 1.5)%. Events occurring within 2 ms of every muon crossing the outer water Cherenkov detector and within 2 s of muons pass through the inner liquid scintillator detector are also rejected, to remove from the gold event sample, neutrons and long-lived cosmogenic radioactivity, respectively. Antineutrinos from nuclear reactor power plants are the main background to the geo-neutrino measurements. Since there are no nuclear power plants close by, the Gran Sasso laboratory is well suited for geo- neutrino studies. In the whole statistical sample, 77 antineutrino candidates were picked out [24], among which 47.4 $\pm$ 2.2 events expected from nuclear reactors and $0.78^{+0.13}_{-0.10}$ from the non-$\bar{\nu}_e$ backgrounds. The energy spectra of antineutrinos coming from nuclear reactors are more energetic respect to the geo-neutrino ones, therefore this background can be experimentally disentangled thanks to a maximal likelihood fit of prompt event energies (Fig.3 - left). An unbinned fit of the light-yield spectrum of prompt candidates was performed, with the Th and U mass ratio $m(Th)/m(U)$ fixed to 3.9 as suggested by the chondritic model [25]. The number of events from reactor antineutrinos was left as a free parameter, while all the other small backgrounds (accidental, cosmogenic and induced by (α,n) reactions) were constrained to the values determined by independent analyses. The best fit yielded: $S_{geo} = 23.7^{+6.5}_{-5.7}(stat)^{+0.9}_{-0.6}(sys)$ events [$43.5^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(sys)$ TNU] and $S_{react} = 52.7^{+8.5}_{-7.7}(stat)^{+0.7}_{-0.9}(sys)$ events [$96.6^{+15.6}_{-14.2}(stat)^{+4.9}_{-5.0}(sys)$ TNU] (1TNU= 1event/10^{32} protons/year). Borexino alone observes geoneutrinos with 5.9σ significance (Fig. 3-left) and the null hypothesis for geoneutrino observation has a probability equal to 3.6×10^{-9}.

The measured geoneutrino signal corresponds to $\bar{\nu}_e$ fluxes at the detector from decays in the U and Th chains of $\phi(U) = (2.7 \pm 0.7) \times 10^6$ cm^{-2}s^{-1} and $\phi(Th) = (2.3 \pm 0.6) \times 10^6$ cm^{-2}s^{-1}, respectively [24]. Our spectroscopical analysis method allows also for a separation of the contribution from uranium (the dark-blue area) and thorium (the light blue area): a general agreement with the expectations from the chondritic mass ratio of Th/U$\sim$3.9 was observed but the precision is still modest because of the limited statistics(see Fig. 3 - left).

The present data can also be used to constrain the signal from the mantle: by using a detailed computation of the contribution from the crust based on geological surveys and on 3D models of the crust up to the mantle boundary, it turned out that the expected geoneutrino signal is of S_{crust}=(23.4$\pm$ 12.8) TNU, corresponding to $\sim$13 events. The overall signal from Borexino is S_{geo}=$43.5^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(sys)$ TNU. Taking into accout the experimental likelihood profile for S_{geo} and a gaussian profile for S_{crust} we got: $S_{mantle} = S_{geo} - S_{crust}$=$20.9^{+15.1}_{-10.3}$ TNU. The hypothesis of S_{mantle}=0 is rejected by the present result at 98% C.L.

As presently stated, the Earths energy budget is a fundamental question for understanding the plate tectonics and mantle convection. The present data best fit corresponds to 23-36 TW of radiogenic heat. By adopting the chondritic mass ratio[25] and a potassium-to-uranium mass ratio m(K)/m(U) = 10^4, the total measured terrestrial radiogenic power is $P(U+Th+K)= 33^{+28}_{-20}$TW, to be compared with the global terrestrial power output P_{tot} =47±2 TW. In conclusion, the two independent geo-neutrino measurements from the Borexino and KamLAND experiments have opened the door to a new inter-disciplinary field, the Neutrino Geoscience: we have a new tool for improving our knowledge on the Earth energy budget. The very low background level achieved in Borexino allows us to perform a real time spectroscopy of geo-neutrinos, currently limited only by the size of the detectors..

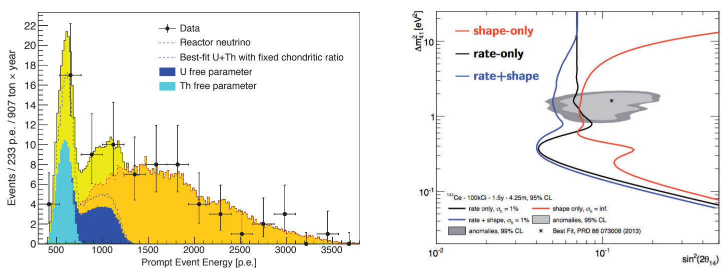

Figure 3 – **Left**: prompt light yield spectrum, in units of photoelectrons (p.e.), of antineutrino candidates and best-fit. The best-fit shows the total contribution of geoneutrino, reactor neutrino and background (yellow colored area) and reactor neutrino (orange colored area) assuming the chondritic ratio. The result of a separate fit with U (blue colored area) and Th (light-blue colored area) set as free and independent parameters is also shown. **Right**: the sensitivity of the Borexino-Sox project to the sterile neutrino oscillation parameters, considering a 100 kBq ^{144}Ce-^{144}Pr source[27] deployed in the tunnel below the detector .

4 The detection of rare processes

The conservation of charge is thought to be a fundamental law as a direct consequence of Maxwell's equations and the unbroken U(1) gauge symmetry of the electroweak theory and, of course, any experiment proving otherwise would point to physics beyond the standard model. In 2015 the tools developed for the *pp* neutrino analysis have offered the possibility to set a new improved limit on the possible electron decay into a neutrino and a monochromatic photon of 256 keV energy: such a photon would induce in our detector a signal equivalent to that of an electron of 220 $\pm$ 0.4 keV due to the ionization quenching of the scintillator: since the energy shape is similar and strongly correlated with the pp-neutrino spectrum, treating the *pp* rate as a free parameter in the fit would lead to non-physical values. To break the degeneracy, the *pp*-neutrino rate was constrained in the analysis to the value measured by radiochemical experiments, as far as the they are not sensitive to the electron decay. Then the fit was performed with a procedure similar to the one yielding the pp result. The non observation of the 256 keV signal allowed to set the limit on the lifetime of this decay of $\tau > 6.6\ 10^{28}$ years, improving by two order of magnitude the literature limit[26]. The sensitivity was such that a 5 σ discovery signal would have been possible with an electron lifetime of $1.9 \cdot 10^{28}$ yr.

5 The future

The very stable detector behavior together the record-low contaminant levels after the purification campaigns, enable us with phase II data, to further improve the precision on solar neutrino fluxes, to aggress the more elusive CNO neutrinos and to extend the range of investigation to new effects: several experimental indications have recently emerged also from cosmological observations in favor of the possible existence of a fourth sterile neutrino. These evidences are not so strong to make a claim but by sure they deserve further investigations. One of the most popular is the so called reactor neutrino anomaly, a 6% deficit in the observed reactor antineutrino rate measured with short baseline detectors (∼100 m), possibly consistent with an oscillation into the fourth species with L/E ∼ 1m/MeV. In such a scenario, by using a neutrino source with energy of few MeV, the oscillation length would be smaller than the detector dimensions (∼10 m) and larger that its spatial resolution (∼10 cm), allowing for an observation of rate wiggles as a function of the distance from the source. The effect of oscillations will be further investigated by comparing the overall interaction rate with expectations. In 2016-17 the Borexino collaboration foresees to deploy in a pit just below the detector, at a distance of 8 m from its center, at first a ^{144}Ce-^{114}Pr and later a ^{51}Cr source (SOX project)[27]. ^{144}Ce-^{114}Pr is an emitter of antineutrinos with energies up to 3 MeV and a decay time of 411 days. The inverse beta decay on protons gives a clean signature allowing for an almost background free measurement: a source activity of ∼ 100 kCi is therefore adequate (Fig. **??**-right) . In the case of ^{51}Cr a source intensity of 5 MCi is required since the expected signal has to overwhelm both the solar neutrinos and intrinsic backgrounds: ^{51}Cr neutrinos are emitted with energies of 430 keV (10%) and 750 keV (90%) and a relatively short decay time (∼ 40d) . The ^{144}Ce-^{114}Pr source production at Mayak reactor facility (Russia) is at a good stage. In case of the existence of a fourth sterile neutrino with the parameters highlighted by the reactor anomaly, Borexino-SOX will be able to discover the effect and to measure the oscillation parameters [27].

References

1. H.O. Back et al. (Borexino collaboration), *Nucl. Instr. Meth. A*, **609** (2009) 58.
2. H. Back et al. (Borexino Collaboration), *JINST* **7** 10 (2012) P10018.
3. G. Bellini et al. (Borexino Collaboration) *Phys. Rev. D* **89** (2014) 112007.
4. A. Serenelli, W.C. Haxton, C. Pena-Garay, *Astrophys. J.* **743** (2011) 1.
5. K.A. Olive et al. (Particle Data Group), *Chin. Phys. C* **38** (2014) 090001.
6. M.C. Gonzales-Garcia, M. Maltoni , *Phys. Rep.* **460** (2008) 1-129.
7. A. Frieland, C. Lunardini, C. Pena-Garay *Phys. Lett. B* **594** (2004) 347-354.
8. P.C. de Holanda, A.Y. Smirnov, *Phys. Rev. D* **83** (2011) 113011.
9. C. Arpesella et al. (Borexino collaboration), *Phys. Lett. B* **658** (2008) 101.
10. G. Bellini et al. (Borexino collaboration), *Phys. Rev. Lett.* **107** (2011) 141302.
11. G. Bellini et al. (Borexino collaboration), *Phys. Lett. B* **707** (2012) 22.
12. G. Bellini et al. (Borexino collaboration), *Phys. Rev. Lett.* **108** (2012) 051302.
13. G. Bellini et al. (Borexino collaboration), *Phys. Rev. D* **82** (2010) 1-10.
14. G. Bellini et al. (Borexino collaboration), *Nature* **512** (2014) 383-386.
15. J. Beringer et al. (Particle Data Group), *Phys. Rev. D* **86** (2012) 010001.
16. M. Aspund et al., *Ann. Rev. Astron. Astrophys.* **47** (2009) 481.
17. G. Eder, *Nucl. Phys.* 78 (1966). G. Marx, Czech J. Phys. B **19** (1969).
18. R.S. Raghavan et al., *Phys. Rev. Lett.* **80** (1998) 635, C.G. Rotschild, F. Calaprice and M. Chen, *Geo. Res. Lett.* **25** (1998) 1083.
19. T. Araki et al. (KamLAND collaboration), *Nature* **436** (2005) 499.
20. S. Abe et al. (KamLAND collaboration), *Phys. Rev. Lett.* **100** (2008) 221803.
21. A. Gando et al. (KamLAND collaboration), *Phys. Rev. D* **88** (2013) 033001.
22. G. Bellini et al. (Borexino collaboration), *Phys. Lett. B* **687** (2010) 299.
23. G. Bellini et al. (Borexino collaboration), *Phys. Lett. B* **722** (2013) 295.
24. M. Agostini et al. (Borexino collaboration), *Phys. Rev. D* **92** (2015) 031101(R).
25. J. Blichert-Toft er al, *Earth Planet. Sci. Lett.* **300** (2010) 152.
26. M. Agostini et al. (Borexino collaboration), *Phys. Rev.Lett* **115** (2015) 231802.
27. G. Bellini et al., (Borexino Collaboration), *Journal of High Energy Physics* **8** (2013) 38.