

## Recent results from Borexino and the first real time measure of solar pp neutrinos

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### Abstract

The Borexino detector was built starting from 1996 in the underground hall C of Gran Sasso National Laboratory (LNGS) in Italy under about 1400 m of rock (3800 m.w.e) and it is mostly aimed to the study in real-time of the low-energy solar neutrinos.

Since the beginning of data taking, in May 2007, the unprecedented detector radio-purity made the performances of the detector unique: a milestone has been very recently achieved with the measurement of solar  $pp$  neutrino flux, providing the first direct observation in real time of the key fusion reaction powering the Sun.

In this contribution the most important Borexino achievements to the fields of solar, geo-neutrino and particle physics are reviewed and the future perspectives discussed, emphasizing in particular the unique possibility of Borexino to cover at the end of its program the entire solar neutrino spectrum and to exploit the possible existence of a fourth sterile neutrino (SOX project).

**Keywords:** Solar neutrinos, Geo-neutrinos, Neutrino oscillations

## 1. Introduction

The Borexino experiment has been running since May 2007 at the LNGS laboratory in Italy with the primary goal to study in real-time the low-energy solar neutrinos, a research field at the crossover between astrophysics and elementary particle physics since solar neutrino provides key information both on solar physics and on neutrino properties like masses and mixing angles.

The detector [1] is a large unsegmented ultrapure liquid scintillator. Its layout is based upon the principle of graded shielding: the detector structure consists of a set of concentric shells, more inner the shell, higher the radio-purity. Borexino is divided into two main detectors: the Inner Detector (ID) filled with scintillator and the Outer Detector (OD) filled with water and detecting particles via Cherenkov effect. The core of ID is the innermost 278 tons of pseudocumene (1,2,4-trimethylbenzene) + PPO (2,5-diphenyloxazole) as fluor at a concentration of 1.5 g/l, enclosed by a 125  $\mu\text{m}$  thick nylon Inner Vessel (IV) with 4.25 m radius.

The choice of a liquid scintillator as target mass assures a light production high enough to observe low energy neutrino events via elastic scattering off electrons. This reaction is sensitive to all neutrino flavours through the neutral current interaction, but the cross section for  $\nu_e$  is larger than that for  $\nu_\mu$  and  $\nu_\tau$  by a factor of 5-6, since  $\nu_\mu$  and  $\nu_\tau$  do not interact via charged current.

The drawback of using a liquid scintillator is its isotropic light emission: the incoming neutrino direction cannot be reconstructed and the electrons scattered off by solar neutrinos cannot be disentangled on an event basis 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.

A detailed review of the Borexino backgrounds is reported in [2]. The present levels of  $^{238}\text{U}$  ( $<0.8 \cdot 10^{-19}$  g/g at 95% C.L.) and  $^{232}\text{Th}$  ( $<1.0 \cdot 10^{-18}$  g/g at 95% C.L.) contaminations are a factor 100 better than the target values at the time of the proposal.

The Borexino collaboration started taking data in May 2007 and after only 3 months (47.4 live days) it was able to extract the  $^7\text{Be}$  signal from the background [3]. Thanks to the detector radio-purity, the Compton edge at 661 keV due to  $^7\text{Be}$  neutrino scattering off electrons was perfectly visible and overwhelming all the other background in the same energy interval (see Fig.1).

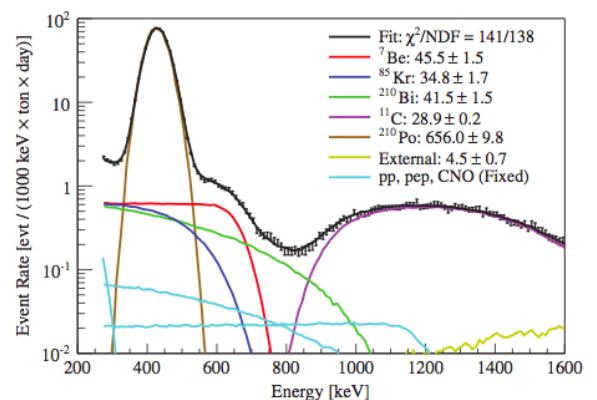


Fig. 1 The Borexino energy spectra with a 153.6 ton·year exposure: the  $^7\text{Be}$  shoulder is clearly visible; the peak at  $\sim 420$  keV is due to the  $^{210}\text{Po}$  contamination (for details see [4]).

During the Phase-I (2007 - 2010), Borexino made the first independent measurements of  $^7\text{Be}$ ,  $^8\text{B}$  and  $pp$  fluxes as well as the first measurement of anti-

neutrinos from the earth: a new comprehensive review of all the final phase-I (2007-2010) results has been recently released [2].

In order to reduce the systematic uncertainties and to tune the reconstruction algorithm and Monte Carlo simulations, calibration campaigns were performed in 2009-10 introducing inside the Borexino detector several internal  $\alpha$ ,  $\beta$ ,  $\gamma$  and neutron sources, at different energies and in hundreds of different positions [5].

After successful purification campaigns in 2010-11 which have further brought down the background levels, a second high precision measuring phase is now in progress and it is smoothly approaching towards its completion: commenced on October 2011 it will go ahead until December this year, followed by few months of calibration campaigns whose output will be fundamental to perform the analysis of the new three years of data available by then.

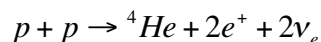
In the following sections we will review the main results of the first seven years of Borexino data taking.

## 2. Solar neutrinos physics results

### 2.1. The first real time measurements of solar $pp$ neutrinos

The Sun is an intense source of neutrinos, emitted in nuclear reactions of the p-p chain and of the CNO cycle: at the temperatures typical of the Sun centre ( $\sim 15.7 \cdot 10^6$  K) hydrogen is converted into helium predominantly via the p-p chain, releasing 26.73 MeV for each conversion of four protons into an helium nuclide.

The p-p chain begins with the fusion of two protons into a deuteron, which occurs 99.76% of the times by means of the reaction [6]:



The neutrinos emitted in this step are called  $pp$  neutrinos and constitute almost all the solar neutrino flux, largely dominating those produced in the other fusion reactions.

Solar neutrinos from secondary processes have already been observed, contributing to the discovery of neutrino masses and oscillations, while so far only radiochemical gallium experiment (Gallex and Sage) have been sensitive to the solar  $pp$  neutrinos ( $E < 420$

keV). These experiments measured indeed an integrated flux above a given threshold (233 keV) and the  $pp$  neutrino signal was inferred indirectly, by comparison with the other experiments.

Even though affected by some uncertainty, a direct measurement of the  $pp$  neutrino flux represents per se a milestone in experimental solar neutrino physics, since it provides the first direct observation in real time of the key fusion reaction which powers the Sun, essential to probe our knowledge of stellar modelling and energy production.

Photons emitted in the Sun's core by fusion reactions are subjected to many absorption/reemission and scattering processes as long as they travel towards the surface and they take at least a hundred thousand years to reach it. By combining neutrino and optical observations it is possible to test the Sun thermodynamic equilibrium over such a timescale.

Predictions for the expected  $pp$  neutrinos fluxes are given by the Standard Solar Models, one of the most recent is from A. Serenelli et al. [7]: according to this model the total flux of  $pp$  neutrinos at Earth could range from  $5.98 \cdot (1 \pm 0.006) \cdot 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$  to  $6.03 \cdot (1 \pm 0.006) \cdot 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$ , depending on the assumptions on the metallicity  $Z/X$  content of Sun outer layers [7].

The  $pp$  neutrino energy spectrum extends up to 420 keV, yielding in the scattering process a maximum electron recoil energy of 264 keV: a very low energy threshold and high energy resolution detector is mandatory to aggress the measure of this flux component.

This is the case of the Borexino scintillator whose high light yield ( $\sim 10^4$  photons/MeV) resulting in  $\sim 500$  detected photoelectrons/MeV, makes possible to reach a very low energy threshold (50 keV) and a good energy resolution (5% at 1 MeV). Moreover, the high transparency (the attenuation length is close to 10 m at 430 nm) and the fast time response (few ns) allow for a precise event spatial reconstruction and a good pulse shape discrimination capability between alpha and beta decays, very helpful in background rejection.

Attempts to measure  $pp$  neutrinos directly over the past 30 years have been hindered by the inability to sufficiently suppress radioactive backgrounds in this low-energy region.

Particularly relevant to this analysis are the backgrounds due to  ${}^{14}\text{C}$ , a  $\beta$  emitters intrinsic to the

organic liquid scintillator whose energy spectrum extends up to 156 keV and its ‘pile-up’.

$^{14}\text{C}$  and  $pp$  neutrinos exhibit however different energy spectra and can be therefore disentangled.

An independent and precise method to constrain  $^{14}\text{C}$  background and its pile-up was essential for  $pp$  neutrino analysis.

The  $^{14}\text{C}$  rate of  $(40 \pm 1)$  Bq/100 tons was accurately defined by looking at selected data such that the event causing the trigger was followed by a second event within the gate time acquisition window of 16  $\mu\text{s}$ : this second events bypassed threshold effects and allowed for a wider energy range fit of the  $^{14}\text{C}$  spectrum and precise decay rate determination.

The pile-up component was instead determined by using a data-driven method, called ‘synthetic pile-up’ that provides the spectral shape and the rate of the pile-up component: real events without any selection cuts are artificially overlapped with random data samples. The combined synthetic events are then selected and reconstructed using the same procedure applied to the normal data.

The data set used for the  $pp$  neutrino analysis range from January 2012 to May 2013 and it is based on the most radio-pure Phase II data (408 days).

The most important event selection cuts are: (a) no coincidence with muon events (a 2 ms veto after ‘external’ muons crossing only the water tank and a 300 ms veto after ‘internal’ muons crossing the scintillator) and (b) position reconstruction within the innermost volume of the detector (the fiducial volume of  $\sim 67$  tons).

The  $pp$  neutrino rate has been obtained [8] by fitting the measured energy spectrum of the selected events in the 165–590 keV energy window: the main components of the fit are the solar neutrino signal ( $pp$ ,  $^7\text{Be}$ , pep and CNO components), the  $^{14}\text{C}$  background, its pile-up, and the other relevant radioactive backgrounds ( $^{210}\text{Po}$ ,  $^{85}\text{Kr}$ ,  $^{210}\text{Bi}$  and  $^{214}\text{Pb}$ ).

The rates of the  $pp$  solar neutrinos and of the  $^{85}\text{Kr}$ ,  $^{210}\text{Bi}$  and  $^{210}\text{Po}$  backgrounds are free parameters of the fit. The  $^7\text{Be}$  neutrino rate is constrained to the value measured by Borexino [4] within the error, and pep and CNO neutrino contributions are fixed at the SSM predictions [7].

The measured solar  $pp$  neutrino interaction rate in Borexino is  $144 \pm 13$  (stat.)  $\pm 10$  (syst.) counts/(day  $\cdot$  100 t) and it corresponds to a solar  $pp$  neutrino flux of  $(6.6 \pm 0.7) \cdot 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$ , according to the oscillation parameters reported in [9]. This value is in good agreement with the SSM predictions and it

demonstrates that about 99% of the energy of the Sun is generated by the p-p fusion process.

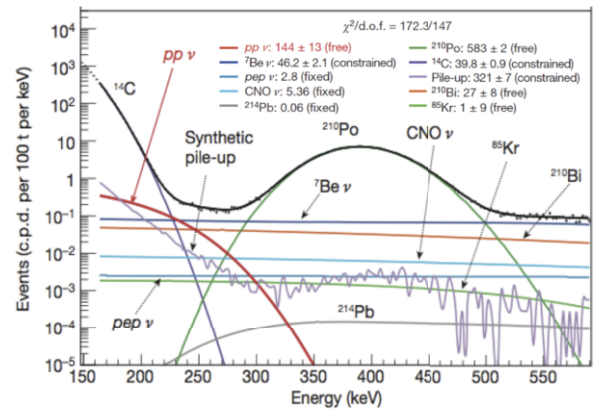


Fig.2 Borexino energy spectrum between 165 and 590 keV: the best fit  $pp$  neutrino component is shown in red (see [8]).

Finally, the probability that  $pp$  neutrinos emitted in the Sun core preserve their electronic flavour once they arrive at the Earth was found to be  $P(\nu_e \rightarrow \nu_e) = 0.64 \pm 0.12$ : in fig.3 this result is compared with MSW-LMA expectations.

## 2.2. The first real time measurements of solar $^7\text{Be}$ neutrinos

Given the close link to the solar neutrino problem the precise measurement of the  $^7\text{Be}$  neutrino flux has been the primary goal of Borexino experiment since the time of the proposal. Thanks to the very low backgrounds, already in 2007, after 3 months of data taking, a best estimate for the  $^7\text{Be}$  neutrino rate of  $47 \pm 7$  (stat)  $\pm 12$  (syst) counts/(day  $\cdot$  100 ton) was released, where the systematic error was mainly due to the fiducial mass and energy scale definitions.

In order to significantly reduce the systematic uncertainties and to tune the position reconstruction algorithm and Monte Carlo simulations, calibration campaigns were performed in 2008-9 [5]: the overall systematic error due to the fiducial volume uncertainty was decreased from 5% to 1.3% and the energy scale uncertainty reduced from 6% to less than 1.5%.

The last and more precise result refers to the statistics from May 2007 to May 2010, with a fiducial exposure equivalent to 153.6 ton $\cdot$ year. The  $^7\text{Be}$  solar neutrino signal is extracted by spectral fit applied along with other neutrino and intrinsic background components such as  $^{85}\text{Kr}$ ,  $^{210}\text{Bi}$ ,  $^{14}\text{C}$ ,  $^{11}\text{C}$ : the measured rate is  $46.0 \pm 1.5$ (stat)  $\pm 1.3$  (syst) counts/(day  $\cdot$  100

ton) with a total uncertainty of only 4.3%, for the first time lower than the theoretical uncertainty quoted by solar models (7%) [7]. This rate corresponds to a flux of  $(3.10 \pm 0.15) \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$  and a survival probability of  $(0.51 \pm 0.07)$  at 862 keV.

In 2010 the absence of a significant day/night asymmetry was also demonstrated and an alternative MSW solution to the solar neutrino problem, called LOW, still allowed at  $3 \sigma$  level, was ruled out at more  $8.5 \sigma$  C.L. [10].

Finally the  $^7\text{Be}$  flux annual modulation due to Earth orbit eccentricity is presently under study with the purest phase II data [2].

### 2.3. The pep neutrinos flux and limits to CNO neutrinos

The ideal probes to test the solar models  $pp$  neutrinos given their intimate link with the solar luminosity constraint [7]. The mono-energetic 1.44 MeV  $pep$  neutrinos are closely related from the theoretical point of view to the fundamental  $pp$  neutrinos and therefore their flux is predicted with small uncertainty (1.2%) [7].

The detection of  $pep$  and CNO neutrinos is even more challenging, as their expected interaction rates are a few counts per day in a 100 ton target, 10 times lower the ones of  $^7\text{Be}$  neutrinos. The CNO neutrinos exhibit continuous energy spectra up to few MeV.

To detect  $pep$  and CNO neutrinos the Borexino Collaboration adopted a novel analysis procedure to suppress the dominant background in the 1–2 MeV energy range, due to the cosmogenic  $\beta^+$ -emitter  $^{11}\text{C}$  continuously produced within the scintillator by muon interacting with  $^{12}\text{C}$  nuclei.

This background can be reduced by performing a space and time veto, discarding exposure that is more likely to contain  $^{11}\text{C}$  due to the correlation between the parent muon, the neutron and the subsequent  $^{11}\text{C}$  decay (the Three-Fold Coincidence, TFC). To further discriminate  $^{11}\text{C}$ - $\beta^+$  decays from neutrino-induced electrons recoils, a multivariate analysis based on event energy, distance from the center and the pulse shape differences between  $e^-$  and  $e^+$  interactions in organic liquid scintillators was exploited. In fact a small difference in the time distribution of the scintillation signal arises from the finite lifetime of ortho-positronium as well as from the presence of annihilation  $\gamma$ -rays, which present a distributed, multi-

site event topology and a larger average ionization density than electron interactions.

These background rejection techniques came out to be successful and Borexino published [11] the first direct observation  $pep$  neutrinos with a rate of  $3.1 \pm 0.6$  (stat)  $\pm 0.3$ (sys) counts/(day 100 ton) corresponding to a flux of  $(1.6 \pm 0.3) \cdot 10^8 \text{ cm}^{-2} \text{ s}^{-1}$  and a survival probability of  $0.62 \pm 0.17$ . With the same analysis the best existing upper limits on CNO neutrinos flux was set ( $< 7.9$  counts per day/100 tons at 95% C.L.).

### 2.4. The measurements of solar $^8\text{B}$ neutrinos flux

Among the solar neutrino components the  $^8\text{B}$  neutrinos are the most interesting to test the LMA solution to the solar neutrino problem in the vacuum-matter transition. The transition is expected to be smooth but there are models predicting different behaviour (Non Standard Neutrino Interactions models). The very good energy resolution achieved in the Borexino detector allows study the solar  $^8\text{B}$  neutrinos starting practically from the energies of the so-called Thallium limit of 2.8 MeV. The analysis reported in [12] is based on a two-year statistics (345 days of live-time). The measured rate above the 3 MeV energy threshold, is  $(0.22 \pm 0.04$  (stat)  $\pm 0.01$  (syst) counts/ (day  $\cdot$  100 t) and it corresponds to the flux of  $2.4 \pm 0.4$  (stat)  $\pm 0.1$  (syst)  $\cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ . The mean electron neutrino survival probability at effective energy of 8.6 MeV is  $0.29 \pm 0.10$ .

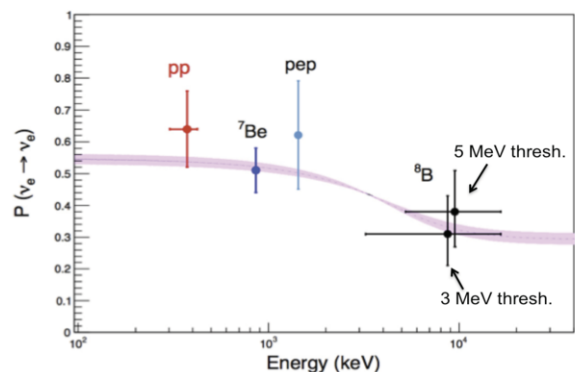


Fig.3 The electron neutrino survival probability as measured by Borexino: the grey region shows the expectations according to the LMA-MSW model.

### 2.5. Survival probability after Borexino

The survival probability of solar electron neutrinos once they get to the Earth, according to the Borexino results, is reported in Fig.3. To better improve the knowledge of the transition region at 1-3 MeV two

possibilities are currently pursued with Borexino phase II data: to increase the precision on pep neutrino flux or to lower lowering the threshold on  $^8\text{B}$  neutrino to observe the expected upturn.

### 3. Geo-neutrinos

Geo-neutrinos are electron antineutrinos produced in the decays of radioactive elements with lifetimes comparable with the age of the Earth and distributed through the Earth's interior.

The present availability of low background/large mass neutrino detectors has opened the door to a new inter-disciplinary field, the Neutrino Geoscience: geo-neutrinos are in fact direct messengers of the abundances and distribution of radioactive elements within our planet. By measuring their flux and spectrum it is possible to reveal the distribution of long-lived radioactivity in the Earth and to assess the radiogenic contribution to the total heat balance of the Earth.

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: only geo-neutrinos from U and Th decay chains are enough energetic to be detected.

Their typical fluxes are of the order of  $10^6 \text{ cm}^{-2} \text{ s}^{-1}$  and only few or few tens of events per year are expected with the current-size ( $\sim 1$  kton) detectors. This means that 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 [13] already with a statistical significance of more than  $4 \sigma$ , and it has recently released an updated result [14] based on the data collected between December 2007 and August 2012, corresponding to an exposure after cuts of 613 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. The overall selection efficiency is of  $\sim 84\%$ : 46 antineutrino candidates were picked out, among which  $33.3 \pm 2.4$  events expected from nuclear reactors and  $0.70 \pm 0.18$  from the non- $\nu_e$  backgrounds. An unbinned maximal likelihood fit of the light-yield spectrum of prompt candidates was

performed, with the Th/U mass ratio fixed to the chondritic value of 3.9, and with the number of events from reactor antineutrinos left as a free parameter. As a result, the number of observed geo-neutrino events is  $14.3 \pm 4.4$  in  $(3.69 \pm 0.16) \cdot 10^{31}$  proton  $\cdot$  year exposure. This signal corresponds to  $\nu_e$  fluxes from U and Th chains, respectively, of  $\phi(\text{U}) = (2.4 \pm 0.7) \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$  and  $\phi(\text{Th}) = (2.0 \pm 0.6) \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$  and to a total measured normalized rate of  $(38.8 \pm 12)$  TNU (1TNU= 1event/ $10^{32}$  protons/year).

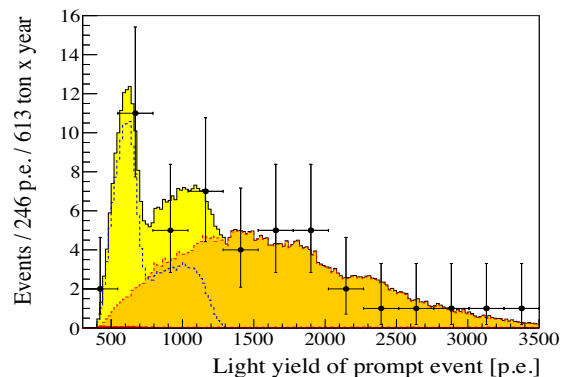


Fig.4 Geo-neutrino event prompt energy spectra: the area in yellow is the signal attributed by the fit to geo-neutrino while in orange is the reactors antineutrino component.

The Borexino result is in agreement to what is expected from Bulk Silicate Earth models but the precision is not yet enough to discriminate among different Earth models.

### 4. The future

The lower  $^{85}\text{Kr}$  and  $^{210}\text{Bi}$  contaminations achieved with the purification campaigns, are now making possible with Borexino phase II data, to further improve the precision on  $^7\text{Be}$ , pep,  $^8\text{B}$  solar neutrino fluxes and possibly to aggress the more elusive CNO neutrinos.

In the recent years several indications have emerged also from cosmological observations in favour of the possible existence of a fourth sterile neutrino. The experimental evidences obtained so far are not so strong to make a claim but by sure they deserve further investigations. Among them 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 ( $\sim 100$  m), eventually consistent with an oscillation into the fourth species with  $L/E \sim 1\text{m}/\text{MeV}$ .

In such a scenario, by using a neutrino source with energy of  $\sim 1$  MeV, the oscillation length would be smaller than the Borexino detector dimensions ( $\sim 10$  m) and larger than its spatial resolution ( $\sim 12$  cm), allowing for an observation of rate wiggles as a function of the distance from the source.

In 2015-16 the Borexino collaboration foresees to deploy a  $^{144}\text{Ce}$ - $^{144}\text{Pr}$  and a  $^{51}\text{Cr}$  source (SOX project) [15]. The sources are going to be placed in a pit just below the detector, excavated for this purpose at the times of detector construction, at a distance of 8 m from its center.

$^{144}\text{Ce}$ - $^{144}\text{Pr}$  is a  $\beta$  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 antineutrino reaction signature allowing for an almost background free measurement: a source activity of  $\sim 100$  kBq is therefore adequate.

In the case of  $^{51}\text{Cr}$  a source intensity of 1 MBq is required since the expected signal has to overwhelm both the solar neutrinos and intrinsic backgrounds:  $^{51}\text{Cr}$  neutrinos are emitted with energies of 430 keV (10%) and 750 keV (90%) and a relatively short decay time ( $\tau \approx 40\text{d}$ ). Contacts with reactor facilities in Oakridge (USA) and Mayak (Russia) are at a good stage, and the  $^{144}\text{Ce}$ - $^{144}\text{Pr}$  source production at Mayak has already started.

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.

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