PROCEEDINGS OF SCIENCE

PoS(NOW2024)093

# Ultra-low background physics: lessons from Borexino and future steps

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The Borexino experiment concluded the data acquisition at the end of 2021 and among the solar neutrino experiments it has been the only one capable of reconstructing the position and the energy on an event-by-event base, with an energy threshold of 150 keV, thanks to its ultra-high radio-purity. The experimental techniques and analysis methods that allowed Borexino to reach such unprecedented levels of radio-purity are now a standard and the legacy that Borexino leaves to the next low energy neutrinos and rare event searching experiments. This contribution is aimed to present the methods and the main achievements of the Borexino and to summarize the broad experimental effort presently in progress in the field of ultra-low background physics to further improve the sensitivity with massive underground detectors and new techniques.

*NOW2024*
*2-8 September 2024*
*Otranto, Lecce, Italy*

## 1. The radio-purity challenge

Neutrinos from the Sun and from the Cosmos offer natural beams for fundamental physics and, at the same time, represent a unique probe of stars internal working and structure. The Borexino experiment came online in 2007 with high sensitivity to all solar neutrino components, particularly those below 2 MeV, an energy region at that time still poorly explored . This sensitivity was the result of a long-lasting effort devoted to the detector design, to the material selections, and to the scintillator purification systems [1–3].

The choice of a liquid scintillation detector (278 tons of pseudocumene doped with 1.5 g/l of PPO), was essential to achieve a good spatial and energy event reconstruction at low energy thanks to the high light yield ($\sim 10^4$photons/MeV). Unfortunately, scintillation light is isotropic and it does not provide directional capability: any radioactive decay of unstable isotopes represents a potential source of background. While external background could be reduced by concentric layers of high-purity materials surrounding the scintillator, internal background could only be cut down by means of liquid-scintillator purification. Key to success was therefore the development of cleaning procedures that could guarantee reliable operations over long time scale in multiton detectors operating undeground. The availability of on-site purification plants was a crucial point[3]. The pseudocumene, obtained from very old oil reservoir to reduce cosmogenic $^{14}$C, once refined, was quickly moved underground to reduce cosmic activation. It was then purified on site with ultra-filtration for particulates, 6 stages distillation, water extraction to remove water-soluble contaminants and gas stripping with ultra-clean nitrogen. All the detector and plants materials were carefully selected for low intrinsic radioactivity, low Rn emanation.

A small scale demonstrator, CTF, made of 5 tons of well-shielded liquid scintillator viewed by 100 PMTs was developed to demonstrate the reliability of the purification techniques, since the needed contaminants levels were below the sensitivity of existing instrumentation and never demonstrated.

The extreme care of all the details was well payed: a world-record radio-purity was finally achieved in Borexino. As an example, one gram of liquid scintillator contained less than $9.4 \cdot 10^{-20}$ grams of $^{238}$U and less than $5.7 \cdot 10^{-19}$ grams of $^{232}$Th (95% confidence level, C.L.), a concentration about ten orders of magnitude smaller than in any natural material on Earth[4]. This low level of background enabled the real-time detection of neutrinos with an energy threshold of 0.15 MeV, and allowed to perform the first complete spectroscopy of the pp chain neutrinos and to measure for the first time the CNO neutrino flux. Neutrinos from other sources, such as the anti-neutrinos emitted by the Earth, the so-called geo-neutrinos, were also observed[5]. In addition, Borexino set strong limits on cosmic neutrino fluxes and released other studies concerning neutrino physics in general, such as possible not-standard neutrino interactions and neutrino magnetic moment (for review, see [2]. In the following section the most important results on solar neutrinos are summarized.

## 2. Borexino: analysis methods and main achievements

The Borexino data were collected during three periods: the Phase-1 (mid 2007-2010) ended with the calibration campaigns; the Phase-2 started after further scintillator purification (water extraction + nitrogen stripping cycles) and lasted until 2016; the Phase-3 ran until October 2021 with the highest radio-purity thanks to the thermal insulation of the detector. A crucial point was the capability to develop accurate analysis techniques that enabled to get rid of the residuals backgrounds[4, 6, 7]. As an example, particle identification algorithms (PID), also based on neural networks, were implemented to disentangle $\beta/\alpha$ or $e^+/e^-$ particles, based on the different time profile of the emitted light. A specific method, called, three-fold coincidence was developed to tag the cosmogenic $^{11}$C decays[4]. Event selection criteria for solar neutrino studies and PID methods are reviewed in [2, 4]. The solar neutrino components in the energy region 0.19 to 16 MeV were separated with a simultaneous binned likelihood multivariate fit is performed on the energy distribution of events (Figure 2)[4], on the distribution of a pulse shape parameter tuned to discriminate between positrons and electrons, and on the radial distribution of events Above 3 MeV, the $^8$B neutrino signal was extracted by fitting only the radial distribution of events within an enlarged FV and no assumption was therefore made on the energy spectral shape.

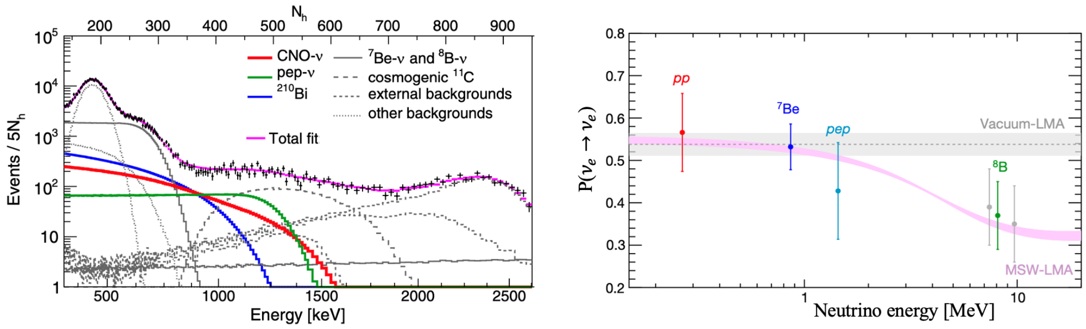

**Figure 1:** *(Left) Results of the multivariate fit including directionality constrain and $^{210}$Bi pull term [10]; (Right) The electron neutrino survival probability as measured by Borexino [4].*

The quest for the CNO-$\nu$ signal asked for a further analysis effort since the CNO, pep and $^{210}$Bi-$\beta$ spectra are very similar. While the pep rate can be precisely constrained by the solar luminosity and by the known ratio of pep and pp fluxes, the CNO and $^{210}$Bi-$\beta$ spectra are highly degenerate, and the fit can only correctly return their sum. Therefore, it was essential to recognize new independent constrains. Two analysis approached have been exploited: in the first method, the $^{210}$Bi rate was independently obtained by measuring the steady-state rate of $^{210}$Po, the $\beta$ daughter, as the asymptotic value of its decay profile and assuming it is in secular equilibrium with $^{210}$Bi[8]. The thermal stabilization was essential to avoid $^{210}$Po leaking from the vessel into the scintillator, so making unreliable the determination. The second method was based on the observation that for each event, the very first detected photons are likely to be due to faster Cherenkov light[9]: the position of the corresponding PMTs was then used to trace back the Cherenkov light direction and therefore the neutrino direction. This second method provided an evaluation of the CNO flux perfectly consistent with the first. In the final analysis, the two method were combined: the constraint accounting for directionality information was added to the standard multivariate likelihood function together with the multiplicative pull terms for the independent constraints on pep and $^{210}$Bi[10]. The final result for the CNO neutrino flux is $6.7^{+1.2}_{-0.7}\cdot 10^8$ cm$^{-2}$ s$^{-1}$ with the no-CNO hypothesis rejected at $8\sigma$ CL[10].

From the point of view of the particle physics, Borexino allowed to test the MSW-LMA paradigm over a very broad energy range, from a few hundred keV up to about 15 MeV. The survival probability, $P_{ee}$, was measured in the vacuum regime ($P_{ee} \sim 0.55$) with pp and $^7$Be neutrinos, and in the matter regime ($P_{ee} \sim 0.32$) with $^8$B neutrinos. Constant $P_{ee}$ was rejected at 98% CL. The transition region was also probed with limited sensitivity with pep neutrinos (26% flux uncertainty)[4] and CNO. No day/night rate asymmetry of the $^7$Be solar neutrino interaction rate was found and this singles out the LMA solution without the reactor antineutrino result from KamLAND, that means without invoking CPT symmetry. The $^7$Be solar neutrinos annual modulation was observed during a period of 10 years and resulted in perfect agreement with the astronomical measurement of the Earth's orbit eccentricity: the eccentricity measured with neutrinos is $\epsilon = 0.0184 \pm 0.0032$ (stat. + syst.).

From the point of view of solar physics, the measured fluxes allowed to determine the Sun's neutrino luminosity and to verify the excellent agreement with the photon luminosity. This provided an important test of the fundamental assumptions in the standard solar models [4, 6] . With the observation of CNO neutrinos, Borexino demonstrated for the first time the existence of the CNO cycle in the Sun: the CNO is believed to be dominant cycle in the massive stars and one of the most important process of energy burning in the universe; for this reason, its experimental confirmation was a milestone for experimental astrophysics. The CNO neutrinos measurement together with the $^8$B neutrino flux constraint from the global analysis (i.e. including other solar neutrino experiments) could also be exploited to determine the CN abundance in the Sun, avoiding the opacity-metallicity degeneracy. The CN abundance determined with this method, agrees very well with the high metallicity models, while exhibiting a mild tension ($\sim 2\sigma$) with low metallicity models[11]. This results pave the way for future experiments that can provide important clues to solve the longstanding metallicity puzzle of the standard solar model.

## 3. Future steps

Borexino enabled to make important steps forward in the knowledge of solar and particle physics but some open issues could only be settled with future more precise measurements: the "standard" LMA-MSW oscillation paradigm still need to be confirmed by an accurate determination of the neutrino survival probability in the upturn region. This last is very relevant to disclose possible non-standard physics effect such as oscillations into sterile neutrinos, non standard interactions (NSI), anomalous neutrino magnetic moment $\mu_\nu$ or neutrino decays. From the point of view of the solar physics, improved measurements of $^7$Be, $^8$B and especially CNO fluxes could help to definitely settle the metallicity puzzle. The small hep solar neutrino component still eluded the experimental observation because of the extremely low flux ($8{\cdot}10^3$ ($\nu$/cm$^2$/sec): it could be finally assessed with very large mass detectors thanks also to the high energy end point (19 MeV).

All large mass future detectors under construction are indeed multi-purpose experiments, aimed to study not only to solar-$\nu$ but also long baseline neutrino oscillations, neutrino-less double beta decay, reactors-$\nu$..): in particular, two very large neutrino detectors are close to start the data taking, in particular JUNO [12, 13] and Hyper-K[14].

JUNO is a sort of Borexino big brother, with a fiducial mass of 10 ktons of liquid scintillator, a factor ~100 larger that that of Borexino. It is located in Jiangmen (China) under an overburden of 700 m of rock and it should start the data taking in 2025. An excellent energy resolution of $\sim 3\%/\sqrt{E}$ could be achieved thanks to a total PMTs coverage of 77%, a factor two larger than

Borexino. The main goal is the study of the neutrino mass ordering with reactor neutrinos, but also solar-$\nu$, geo-$\nu$ and the diffuse relic supernovae neutrino background are among the possible research goals. Reaching the high level of radio-purity needed for low energy solar $\nu$ studies is challenging, and scintillator purification similar to the ones performed in Borexino are expected with the ultimate goal to achieve $10^{-17}$ g/g in U/Th. In any case, if the U/Th will result at least below $10^{-16}$ g/g, it will be possible to detect $^{8}$B neutrinos with a threshold of only 2 MeV[12], collecting $\sim 6{\cdot}10^4$ events in 10 years in the electron scattering channel . The day/night effect could therefore be established at $3\sigma$ in 10 years, and already after 2-3 years the $^{7}$Be and pep rates could be determined with a precision, respectively, below 1% and 10% and the CNO rate similarly to Borexino with possible improvements by exploiting the Cherenkov light directionality[13].

Hyper-K[14] is located in Tochibora Mine, ~ 8 Km far from the Kamioka mine: it should start the data taking in 2027, with a fiducial mass of 190 kton. It will be mainly focused to study the CP violating phase $\delta_{CP}$, the Neutrino Mass ordering (NMO) as far detector for the JPARC beam. It will be equipped by 40000 PMTs with high QE and improved time resolution, also including new types of PMTs, ex. a Multi-PMT module inspired by the KM3NeT design providing improved angular acceptance, intrinsic directional sensitivity and enhanced reconstruction for multi-ring events and near wall events. Depending on background in ~10 years it should study the D/N effect at 4-8$\sigma$, with the possibility to detect upturn at $5\sigma$ and to measure the hep neutrino flux at ~2-3$\sigma$.

Huge R&D activity is also in progress to develop new light sensors (LAPPD, SiPM) or new competitive detection media such as Hybrid Cherenkov/Scintillation detectors (Theia[15], JNE[16]), opaque scintillators (LiquidO), or Liquid Argon and Xenon Time Projection Chambers (DUNE,DS20k, DARWIN/XLZD[17]..) Hybrid detectors will allow to exploit simultaneously the advantages of scintillation (better energy resolution, low threshold) and Cherenkov light (directionality) to boost the sensitivity to solar and cosmic neutrinos. Already successful hybrid detection was demonstrated by experiments: SNO+ has achieved the first event-by-event directional reconstruction by using diluted liquid scintillator[18] while Borexino, as discussed, obtained the evidence for solar-$\nu$ directionality by using the first detected Cherenkov photons of the event. Liquid noble gas detectors have already shown to be very promising with the recent measurement of the $^{8}$B neutrinos signal at $2.73\sigma$ by means of the Coherent Elastic Neutrino with the XENONnT[19] dual-phase TPC. This is the first astrophysical neutrino measurement via CE$\nu$NS.

In conclusion, in 32 years of activity Borexino has pioneered techniques and methods that represent a new standard for ultra-low-background physics: very large mass experiments adopting these methods are close to start the data taking. New techniques are under study and most of them have already demonstrated to be successful: there are all the ingredients for future breakthrough in neutrino physics and astrophysics.

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