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Results and perspectives of the Borexino experiment

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Summary. — Borexino is a large-volume liquid scintillator experiment designed for low energy neutrino detection, installed at the National Laboratory of Gran Sasso (LNGS) and operating since May 2007. This contribution presents the very rich physics program that the Borexino experiment has already achieved in the neutrino physics fields. The physics potentialities and the future perspectives of the so-called "Borexino phase 2" are also shortly described.

PACS 14.60.Lm – Ordinary neutrinos.
PACS 14.60.St – Non-standard-model neutrinos, right-handed neutrinos, etc..
PACS 26.65.+t – Solar neutrinos.
PACS 91.35.-x – Earth's interior structure and properties.

1. – Introduction

Borexino is an experiment originally designed for real-time detection of low-energy solar neutrinos. It is installed at the underground National Laboratory of Gran Sasso (Assergi, Italy) where the average rock cover is about 1400 m resulting in a shielding capacity against cosmic rays of 3800 meter water equivalent (m.w.e.): at the LNGS, the muon flux is reduced by a factor 10^6 with respect to the surface.

In Borexino, neutrinos are detected via elastic scattering of the liquid scintillator electrons. The active target consists of 278 tons of pseudocumene (1,2,4-trimethylbenzene) doped with 1.5 g/L of a fluorescent dye (PPO, 2,5-diphenyloxazolo) and it converts the energy deposited by neutrino interactions into light. The detector is instrumented with photomultiplier tubes that can measure the intensity and the arrival time of this light, allowing the reconstruction of the energy, position and time of the events.

The Borexino detector was designed exploiting the principle of graded shielding: an onion-like structure allows to protect the inner part from external radiation and from radiation produced in the external shielding layers. The requirements on material radiopurity increase when moving to the innermost region of the detector [1].

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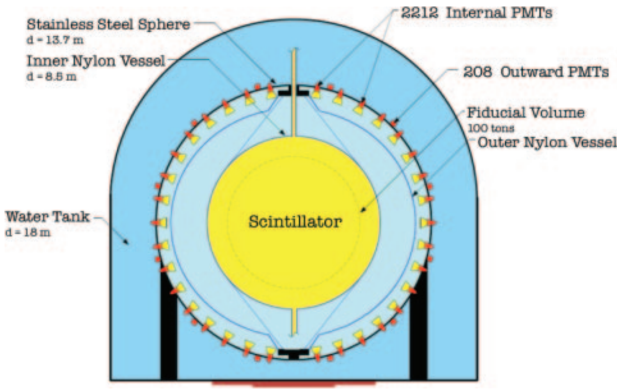

Fig. 1. – A schematic view of the Borexino detector.

The scintillator is contained in a thin nylon vessel (see fig. 1) and is shielded by two concentric PC buffers which in turn are separated by a second nylon vessel to prevent diffusion of radon towards the scintillator.

The scintillation light is detected via 2212 8″ photomultipliers tubes uniformly distributed on the inner surface of a Stainless Steel Sphere (SSS). The SSS in enclosed in a domed Water Tank (18 m diamater, 16.9 high), containing 2100 tons of ultra-pure water as an additional shield.

2. – The Borexino results

The physics potential of Borexino strongly depends on the unprecedented requirements of low-level background. During 2011 several purifications campaigns were perfomed and, at present, Borexino is characterized by an exceptional radiopurity: ^{238}U and ^{232}Th have been measured at the level of $(1.6\pm0.1)\times10^{-17}$ g/g and $(6.8\pm1.5)\times10^{-18}$ g/g, respectively.

So far, Borexino's main results are the first, direct measurement of the ^{7}Be solar neutrino signal rate, the first measurement of the pep solar neutrino flux and the observation of geo-neutrinos signal. Moreover, Borexino confirmed the LMA-MSW solution of the neutrino oscillation scenario by providing new data about the neutrino survival probability as a function of the neutrino energy and proving the absence of a day-night asymmetry in the ^{7}Be neutrino signal.

2˙1. *The measurement of* ^{7}Be *neutrino flux and of its day-night asymmetry*. – The ^{7}Be neutrino interaction rate has been measured by analyzing 740.7 live days (after cuts) of data. Two indipendent methods were used, one Monte Carlo based (fig. 2, left) and the other relying on an analytic description of the detector response. In both cases, we performed a spectral fit which includes the characteristic Compton-like shape of the signal and the spectral shapes of the residual background components: ^{85}Kr, ^{210}Bi, ^{210}Po, and ^{11}C. The weights of the other solar neutrino components as pp, pep, CNO, and ^{8}B were fixed to the Standard Solar Model (SSM [2]) high-metallicity [3] predictions, assuming MSW-LMA oscillations. The best estimate for the ^{7}Be neutrino interaction rate in Borexino is found [4] to be $46 \pm 1.5(\mathrm{stat})^{+1.5}_{-1.6}(\mathrm{syst})$ cpd/100 tons, in agreement with the SSM MSW-LMA predictions.

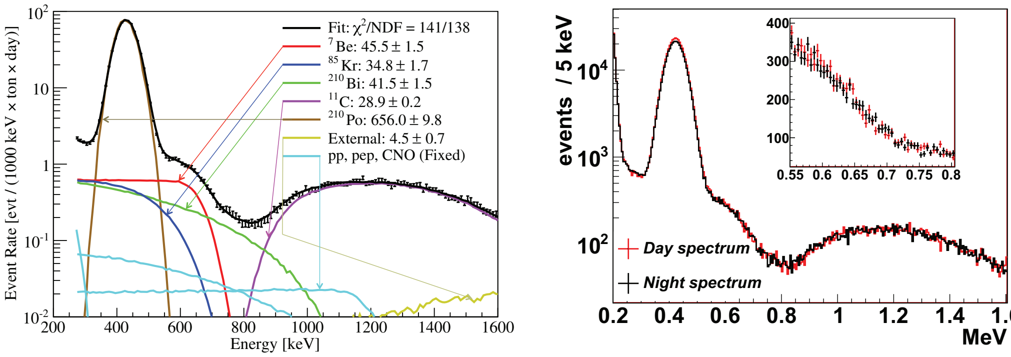

Fig. 2. – On the left, an example of the spectral fit used to extract ^{7}Be signal from data. On the right, the day spectrum (red) and night spectrum (black) of ^{7}Be signal normalized to the same live-time.

This result corresponds to the neutrino flux $\Phi(^7\mathrm{Be}) = (2.78 \pm 0.13) \times 10^9\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. In order to observe a potential ν_e rigeneration while crossing the Earth at nigh and therefore the associated matter effects, we split the data sample into "day" and "night" subsets (fig. 2, right). These subsets, once properly corrected for the Zenith angle and for the detector livetime, were analyzed and differences between the two spectral shapes have been excluded [5], rejecting at more the 8.5σ the LOW oscillating region and strongly confirming the MSW-LMA solution.

2·2. *The first observation of pep neutrinos.* – The pep neutrinos belong to the so-called "pp" cycle and are monochromatic neutrinos with $E = 1.44\,\mathrm{MeV}$. They were never directly observed before because of their tiny flux and low energy. Nevertheless Borexino succeded and has been the first experiment able to observe this class of neutrinos. The observation of pep neutrinos posed a special experimental challenge mainly because of the cosmogenic ^{11}C background. In Borexino, this background is rejected via the so-called "Three-Fold-Coincidence" (TFC) technique. The TFC exploits the fact that, in at least 90% of the cases, the cosmic muon which generates ^{11}C in the scintillator also produces a neutron. This makes possible the space-time correlation between the muon signal, the neutron capture gamma signal and the positron emitted by ^{11}C. The residual ^{11}C component is then identified exploiting the formation of the ortho-positronium bound state (as it happens in 50% of the cases). These analysis techniques and the Borexino detector features allow to measure [6] the pep neutrino interaction rate as $3.1 \pm 0.6(\mathrm{stat}) \pm 0.03(\mathrm{syst})$ cpd/100 tons, corresponding to the neutrino flux $\Phi(\mathrm{pep}) = (1.6 \pm 0.3) \times 10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This value is in agreement with the SSM MSW-LMA predictions (fig. 3).

2·3. *The measurement of geo-neutrinos.* – Geo-neutrinos are electron antineutrinos produced in β decays of long-lived radioactive isotopes naturally present in the earth (^{238}U, ^{232}Th and ^{40}K). By measuring their fluxes it is possible to have a unique direct probe of our planet's interior, to reveal the terrestrial distribution of uranium and thorium and to assess the radiogenic contribution to the total heat balance of the earth. The Borexino experiment is one of the few which can perform a geo-neutrino analysis and in 2013 has released [7] the measurement of a geo-neutrino signal obtained from 1353 days of data (fig. 4). With a fiducial exposure of $(3.69 \pm 0.16) \times 10^{31}$ proton y^{-1} after all

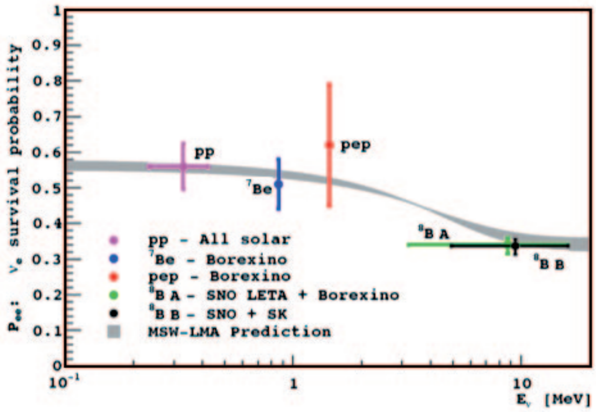

Fig. 3. – The survival ν_e probability as a function of the ν_e energy; the blue, red and green points represent the Borexino results on ^{7}Be, pep, and ^{8}B neutrino rate, assuming the SSM high-metallicity hypothesis. The purple point is the result for pp neutrinos and it is obtained by combining Borexino's and all other solar-neutrino experiments' results.

selection cuts and background subtraction, we detected (14.3 ± 4.4) geo-neutrino events assuming a fixed chondritic mass Th/U ratio of 3.9. This corresponds to a geo-neutrino signal $S_{\text{geo}} = (38.8 \pm 12.0)$ TNU with just a 6×10^{-6} probability for a null geo-neutrino measurement. Our measurement of $31.2^{+7.0}_{-6.1}$ reactor antineutrino events is in agreement with expectations in the presence of neutrino oscillations.

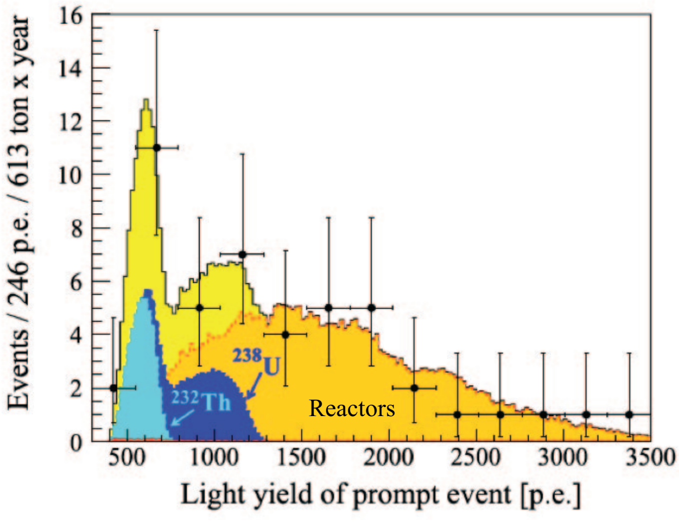

Fig. 4. – The light yield spectrum of the Borexino antineutrino candidates and the best fit. The yellow area isolates the contribution of the geo-neutrinos in the total signal. Dashed red line/orange area is the reactor antineutrino signal while dashed blue line is the geo-neutrino signal resulting from the fit. The contribution of background is almost negligible (red filled area). The conversion from p.e. to energy is approximately 500 p.e./MeV.

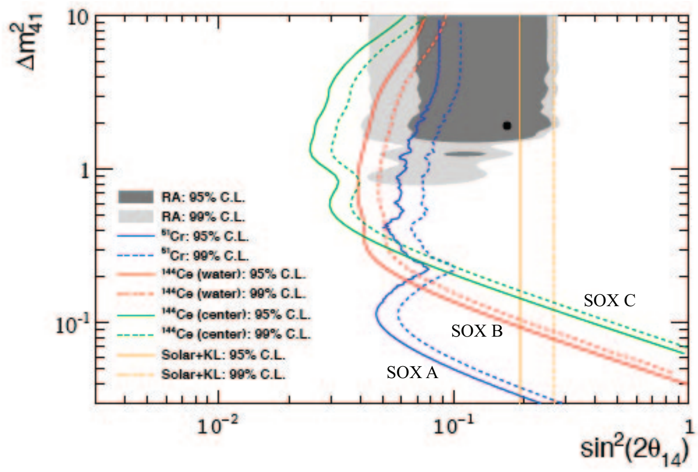

Fig. 5. – The Borexino-SOX project: sensitivity of the Phase A (^{51}Cr external, blue), of Phase B (^{144}Ce-^{144}Pr external, red) and Phase C (^{144}Ce-^{144}Pr center, green). The grey area is the one indicated by the reactor anomaly, if interpreted as oscillations to sterile neutrinos. Both 95% and 99% C.L. are shown for all cases. The yellow line indicates the region already excluded in [8].

3. – The Borexino Phase 2: status and perspectives

In the solar neutrino field, one of the Borexino Phase 2 goals is the direct observation of neutrinos from the CNO cycle: this group of reactions contributes less than 1% to our Sun luminosity but is believed to be the main source of energy for more massive stars and therefore its detection with Borexino would be of exceptional astrophysical interest. Another goal for Borexino Phase 2 is the first direct measurement of neutrinos coming from the pp reactions: these neutrinos provide more than 90% of the total solar neutrino flux but have never been directly observed because of their very low energy ($E < 0.42\,\mathrm{MeV}$).

In addition to these solar targets, Borexino is now in the so-called SOX project ("*Short distance neutrino Oscillations with BoreXino*"). Oscillations between the three neutrino flavours are well-estabilished and have received many experimental confirmations. On the other hand, there are several experimental anomalies which cannot be accomodated in a simple three flavour scenario, but require the existence of one or more non-active neutrinos. These hints which point towards new physics deserve to be investigated thoroughly in order to either confirm or definitely disprove the sterile neutrino existence. Borexino is in an excellent position to do so by performing a short baseline experiment using an high activity neutrino source placed either outside or inside the detector. The first phase of the SOX project (SOX-A) will be able of exploring a large portion (fig. 5, blue curves) of the oscillation parameters (Δm^2_{14}, $\sin^2 2\theta_{14}$) allowed by the reactor and gallium anomalies, since the characteristic L/E will be of the order of $1\,\mathrm{eV}^2$. The experiment will work in a standard disappearance mode by observing (or not) a deficit of neutrinos and at the same time will exploit Borexino's capability of measuring the event position to possibly observe an oscillation pattern within the active volume. SOX-A is planned to start by the beginning of 2015. More details on SOX can be found in [9].

4. – Conclusions

Borexino is the only experiment so far able to perform a real-time solar-neutrino spectroscopy by detecting neutrinos from almost all the different reactions happening in the Sun. For what concerns solar neutrino physics, in the next years Borexino will not only improve all the results here reported but will also face the direct measurement of the pp and CNO neutrino fluxes. In parallel to this program, the Borexino detector will be the base for the SOX project, a short baseline experiment, aiming at investigating the sterile neutrino hypothesis.

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