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A strategy for the detection of CNO solar neutrinos with the Borexino experiment

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Summary. — Borexino is a large liquid scintillator detector with unprecedented intrinsic radiopurity levels, located at the LNGS laboratory in Italy. Its primary goal is to perform a real-time solar neutrinos spectroscopy, and the most recent result consists in the simultaneous measurement of the fluxes of neutrinos from the pp, ^{7}Be and pep reactions, from the pp chain. The current goal of the Borexino Collaboration consists in the detection of the solar neutrinos from the CNO cycle reactions: a general strategy to pursue this measurement will be outlined in the following.

1. – Solar neutrinos

Solar neutrinos are generated in the innermost layers of the Sun by means of two sequences of nuclear fusion reactions. The main contribution to the solar luminosity (∼99%) comes from the so-called *pp chain* reactions, while the *CNO cycle*, according to the Standard Solar Models predictions, should play a secondary role [1, 2].

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Neutrinos provide a unique and direct way to study the interior regions of our star. The study of solar neutrinos is important from a double point of view. From the solar physics side, it allows to investigate the Standard Solar Model (SSM) predictions; from the particle physics side, it has been crucial in order to discover and understand the neutrino flavour oscillations. The main goal of the solar neutrinos spectroscopy is the determination of the contribution of the several reactions involved (pp, ^{7}Be, pep, CNO, ^{8}B), measuring the associated fluxes.

Neutrinos emitted in the CNO cycle are the only undetected piece of the solar fusion mechanisms. Even though it is expected to contribute only for $\sim$1% to the solar luminosity, the CNO cycle is believed to be the main engine of very massive stars. Observing neutrinos from the CNO cycle reactions would have therefore a striking importance in astrophysics, since it would provide the first experimental proof of the existence of this important source of energy in the core of the stars. Moreover, since the CNO cycle is catalyzed by elements heavier than helium, the related neutrino flux is very sensitive to the metal abundance in the Sun: a precise experimental measurement of the CNO-ν flux could help to shed light on the solar metallicity abundance problem [1, 2].

2. – Borexino detector

Borexino is a large volume liquid scintillator detector, whose primary purpose is the real-time spectroscopy of low-energy solar neutrinos [3]. It is located deep underground (approximately 3800 meters of water equivalent) in the Hall C of the Laboratori Nazionali del Gran Sasso, in Italy. The Gran Sasso mountain natural shielding, combined with the detector structure, allows extremely high muon flux suppression. Borexino has been taking data for more than ten years, achieving crucial results for what concerns the solar neutrino spectroscopy [4], such as detecting and then precisely measuring the flux of the ^{7}Be solar neutrinos and of the other pp-chain components [5], ruling out the day-night asymmetry of their interaction rate [6], and setting the tightest upper limit so far on the flux of CNO solar neutrinos [5].

The Borexino design is driven by the principle of graded shielding: an inner scintillating ultra-pure core is found at the center of shielding concentric shells, with decreasing radio-purity from inside to outside. The extremely low intrinsic radioactivity achieved in Borexino, the strong cosmic ray shielding, the high photon yield have made a sensitive search for neutrinos in the sub-MeV and MeV energy range possible, measuring their energy and position through the elastic scattering with scintillator electrons. The scintillator is a solution of PPO (2,5-diphenyloxazole) in pseudocumene (PC, 1,2,4-trimethylbenzene) with a concentration of 2.5 g/l. The scintillator mass is about 278 ton and is contained in a 125 μm thick spherical nylon inner vessel (IV) of approximately 4.25 m radius. The detector is instrumented with 2112 photomultiplier tubes (PMTs) that measure the intensity and the arrival time of this light, allowing the reconstruction of the energy, position and time of the events.

Neutrino-induced events are intrinsically indistinguishable on an event-by-event basis from the most of backgrounds due to β or γ decays. Many selection cuts can be applied to partially remove several categories of backgrounds on an event-by-event basis: muons and muon-induced events, noise events, radioactive decays from delayed coincidences. The fiducial volume (FV) cut selects events in a central scintillator region reducing the external background. The cosmogenic events can be isolated via dedicated tagging techniques, exploiting the decay peculiarities of their products.

Even after the application of the selection cuts, background is still present. To disentangle the neutrino signal components from the background ones, a multivariate analysis is performed. It involves the simultaneous fit to the distributions of three physical quantities of interest: the event reconstructed energy, the radial and the β^+/β^- pulse-shape parameter distributions. The reference distributions for these three quantities are built using either analytical models or Monte Carlo simulations. Then, the model is fitted against data to extract the interaction rates of each background and neutrino signal.

The Phase-II data taking (December 2011 - May 2016), which followed a purification campaign, allowed to perform the complete spectroscopy of solar neutrinos from the pp-chain, as described in ref. [5]. The most relevant result is the simultaneous measurement of the interaction rates of pp-ν, ^{7}Be-ν, pep-ν in an extended energy range (0.19–2.93) MeV. All the pp-chain flux precisions have been improved with respect to the Phase-I analysis (2007–2010), reaching 2.7% for ^{7}Be-ν and 9.5% for pp-ν. The pep-ν discovery is claimed, rejecting at $> 5\sigma$ significance the hypothesis of absence of the pep reaction in the Sun.

3. – A strategy for the CNO neutrinos detection with Borexino

The current goal of Borexino is a measurement of the CNO-ν signal, analyzing the data taken from half 2016 on. The preliminary step towards the detection of a CNO-ν signal is to study via Monte Carlo simulations the sensitivity of Borexino under realistic conditions: this allows to define which are the elements playing the most relevant roles and therefore to elaborate a strategy for the analysis.

The Borexino sensitivity to a CNO-ν signal is driven by two main factors. The first is the low signal/background ratio for CNO-ν interaction rate in Borexino. According to the SSM predictions [1], indeed, the CNO-ν reactions are expected to play a secondary role in the solar reaction framework: this translates into a faint neutrino flux, and therefore into a very low counting rate in Borexino. The expected CNO-ν interaction rate in Borexino, according to the high-metallicity (HZ) and low-metallicity (LZ) scenarios, is $R^{\mathrm{HZ}}(\text{CNO-}\nu) = 4.92 \pm 0.56\,\text{cpd/100t}$ or $R^{\mathrm{LZ}}(\text{CNO-}\nu) = 3.56 \pm 0.37\,\text{cpd/100t}$, respectively. In the CNO-ν energy region of interest, the leading contributions in Borexino are instead provided by ^{7}Be-ν, ^{210}Bi and ^{11}C.

The CNO-ν, pep-ν and ^{210}Bi spectral shape similarity is the second and most critical factor preventing a straightforward CNO-ν detection in Borexino. Figure 1 shows the simulated energy spectra of e^- scattered by CNO-ν, pep-ν and produced in the ^{210}Bi decay (respectively, red line, blue line and green line), overlapped to Borexino Phase-II data (black). The CNO-ν events energy shape in Borexino does not show any prominent structure but, on the contrary, a smooth featureless profile, similar to the one of ^{210}Bi background and pep-ν. This shape similarity prevents the multivariate fit from distinguishing and isolating separately the interaction rates of the three contributions and, consequently, drastically reduces the sensitivity to a CNO-ν signal.

Dedicated sensitivity studies show that Borexino has the chance to isolate a CNO-ν signal with relevant significance only if this ^{210}Bi-CNO-pep correlation is broken. The only way to do this consists in the determination of the ^{210}Bi background and pep-ν rate independently of the fit, to constrain them in the multivariate analysis itself.

The pep-ν rate can be safely constrained to the Standard Solar Model predictions. Along with the pp-ν reaction, it starts the pp chain sequence; its neutrino flux, and therefore the related interaction rate in Borexino, are estimated at the 1% precision level; accounting also for the error on the flavour oscillation parameters, the expected rate in

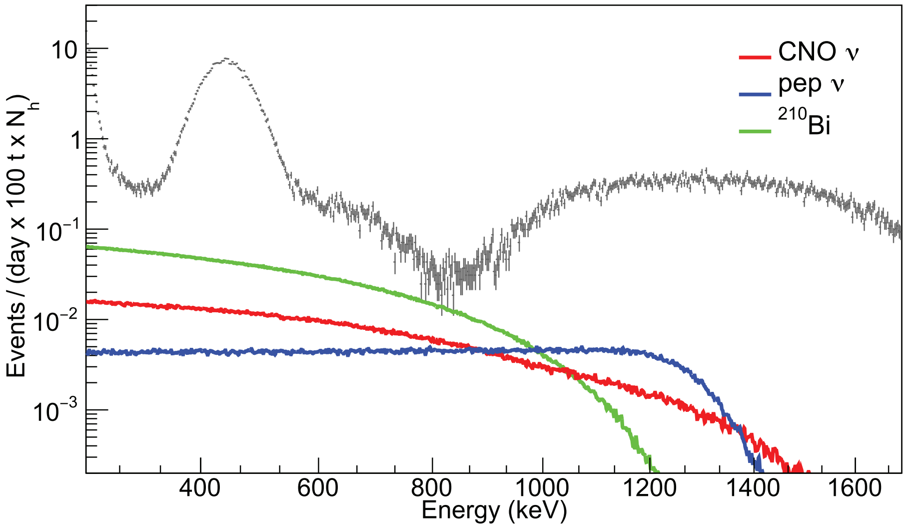

Fig. 1. – Simulated energy spectra of e^- scattered by CNO-ν, by pep-ν and produced in the ^{210}Bi decay (respectively, red line, blue line and green line), overlapped with Borexino Phase-II data (black). Injected rates for CNO-ν and pep-ν are matched to the HZ-SSM predictions, while ^{210}Bi one has been selected from Phase-II results [5].

Borexino is $R^{\mathrm{LZ}}(\text{pep-}\nu) = 2.78 \pm 0.04\,\text{cpd/100t}$ or $R^{\mathrm{HZ}}(\text{pep-}\nu) = 2.74 \pm 0.04\,\text{cpd/100t}$, depending on the metallicity scenario.

The independent constraint on ^{210}Bi is a crucial key of the CNO-ν analysis; in particular, its rate must be determined independently with a precision better than ~10%–15% in order to reach a median sensitivity for a CNO-ν signal of 3σ or more. The proposed strategy is based on the tagging with its daughter isotope ^{210}Po, which decays emitting a mono-energetic α of 5.3 MeV, quenched in the scintillator to an equivalent energy of approximately 400 keV. α events can be distinguished from β ones by means of pulse-shape discrimination techniques, which exploit the different time distributions of photons emitted by α and β in the scintillator. In a nutshell, the signature of this class of events in Borexino is a very clear Gaussian-like peak, which is easily recognizable with respect to events originated in β decays.

If the chain $^{210}\text{Pb} \to {}^{210}\text{Bi} \to {}^{210}\text{Po}$ is in secular equilibrium, the activity of ^{210}Po is *de facto* the same as the ^{210}Bi one, making the measurement straightforward. Unfortunately, this strategy is complicated by additional ^{210}Po contributions out of equilibrium, which are present in the detector. In particular, the most annoying ^{210}Po contribution is given by the contamination present on the inner vessel, which can detach from the nylon and can be carried inside the innermost region of the scintillator (the fiducial volume in which the analysis is done) by convective currents.

Analyzing the ^{210}Po evolution in time, along with its spatial distribution in the fiducial volume, it has been observed that these convective currents are triggered by variations in the temperature profile of the scintillator, mainly due to the season changes. In order to minimize this effect, the detector has been thermally insulated starting from 2015. A 20 cm thick layer of mineral wool have been installed around the detector; the insulation was completed at the end of 2015. In addition, in 2016 a Temperature Active Control System (TACS) has been installed on the top ring of the Water Tank. It provides heat to compensate for the seasonal cooling in Fall and Winter time and it is useful to further decouple the upper part of the detector from the Hall C temperature variations. In spite of this, ^{210}Po motions due to convection have not stopped completely and a dedicated study of the spatial profile of the ^{210}Po distribution is needed to extract the supported term which is directly related to ^{210}Bi.

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