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Recent analysis of the Borexino experiment: *pp chain* solar neutrino spectroscopy

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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. The main procedures for the solar neutrino analysis of Borexino Phase-II data (2011–2016) are briefly described.

1. – Solar neutrinos

Solar neutrinos are generated in the innermost layers of the Sun through series of nuclear fusion reactions. They provide a unique and direct way to study the interior regions of our star. The main contribution to the solar luminosity (∼99%) comes from the so-called *pp chain* reactions, while the *CNO cycle*, according to the current models, should

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be a secondary contributor. 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 flavor 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 and disentangling them.

2. – Borexino detector

Borexino is a large volume liquid-scintillator detector whose primary purpose is the real-time measurement of low-energy solar neutrinos [1]. 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 an extremely high muon flux suppression. Borexino has been taking data for more than ten years, achieving important results for what concerns the solar neutrino spectroscopy [2], such as detecting and then precisely measuring the flux of the ^{7}Be solar neutrinos and of the other *pp* chain components, ruling out the day-night asymmetry of their interaction rate [3], and setting the tightest upper limit so far on the flux of CNO solar neutrinos.

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) at a concentration of 2.5 g/l. The main scintillator mass is about 278 tons and is contained in a 125 μm thick spherical nylon Inner Vessel (IV) of approximately 4.25 m radius. 2212 internal photo-multipliers are mounted on a Stainless Steel Surface (SSS) in order to collect scintillation light. The energy, position, and pulse shape of each event are reconstructed through the number of detected photons and their detection times.

3. – Data analysis

The Borexino Phase-II analysis is based on data collected between December 14th, 2011 to May 21st, 2016, corresponding to an exposure 1.6 times the one of Phase-I. This most recent phase follows an extensive detector purification campaign, with the goal of further reducing many radioactive contaminants mainly coming from the natural radioactive chains.

The events selection is a crucial point for a solar neutrinos analysis. Muons are removed applying a 300 ms or 2 ms veto for internal or external candidate events respectively, to suppress cosmogenic backgrounds. The definition of a fiducial volume cut (FV) via software allows to avoid background events coming from sources external to the scintillator: this selects an innermost region of the scintillator which is expected to be more radiopure. The low-energy region, that is found below 300 keV, is affected by the unavoidable ^{14}C background; it is due to the employment of an organic scintillator and decays β^- with a 156 keV Q-value. Neutrinos from *pp* reaction are found almost in this energy region. *pep* and CNO neutrinos instead are found in the same energy region of the cosmogenic isotope ^{11}C: the related events can be removed through the use of techniques as the Three-Fold Coincidence (TFC) and the e^+-e^- pulse shape discrimination, which are accurately described in ref. [4] and ref. [2].

Two complementary procedures have been followed to construct the signal and background reference spectral shapes used in the fit. The first one relies on an analytical description of the detector response function, while the second one is based on Monte Carlo simulations. The analytical approach models the full detector energy response, including details as the ionization quenching, the Cherenkov effects (impacting at a $\sim$1% level) and the homogeneity and resolution of the reconstructed energy. The tuning of several parameters relies on the Monte Carlo description of the detector and on independents measurements, while other ones have to be necessarily left free in the fit (*e.g.*, the scintillator light yield, the non-uniformity parameter for the energy resolution, and other effective parameters). Clearly, the neutrino species rates and the background rates are considered as free parameters of the fit. The second approach is based on the Monte Carlo description of the Borexino detector [5], performed with a simulation package developed by the Collaboration. It takes into account all the processes occurring from the beginning of a physics event: the particle interaction in the detector, the scintillation photons emission, the photons propagation along with the possible optical processes occurring, and so on. The response of the electronics chain, along with their possible evolution in time, is also fully described.

The events are generated following the theoretical spectra and then are processed, binned and normalized, building the PDFs that are eventually used in the fit. In contrast to what has been done for the analytical approach, the only free fit parameters in the Monte Carlo approach are the interaction rates of all species. The success of the Monte Carlo fitting has a double importance: it confirms both the accuracy of the Borexino Monte Carlo simulation package and the stability of the detector response.

A crucial role in the analysis is played by the systematic errors, that have been studied accurately. For example, using the two different methods we can estimate the systematic errors associated to the approach itself, comparing their results and including the differences results as systematics. Instead the systematics related to the fitting procedures can be estimated fitting the data in several fit configurations and settings.

Beyond this low-energy spectrum measurements, a complementary work has been performed on the ^{8}B solar neutrino rate [6]. The simultaneous, precise measurement of the ^{7}Be and ^{8}B solar neutrino interaction rates allows to test the SSM predictions and to investigate the metal composition of the Sun (solar metallicity problem). This measurement has been obtained with $\sim$11.5 times the statistics used in the previous analysis, and relies on many substantial changes, as the Monte Carlo description of the detector improved and the lower ^{208}Tl background rate in the scintillator after the purification phase.

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