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First direct detection of CNO neutrinos: The multivariate fitting strategy

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Summary. — Borexino is a large organic liquid scintillator detector with unprecedented level of radiopurity, located at the LNGS in Italy. Designed for real-time solar neutrino spectroscopy, during more than ten years data collection Borexino measured all the neutrino fluxes produced in the pp chain. The last stages of its life were devoted to the first experimental detection of neutrinos emitted from the CNO cycle. In the following, the detection strategy and the main results will be presented.

1. – Solar neutrino physics

The study of neutrinos is providing a formidable impulse to fundamental knowledge in the fields of particle physics and astrophysics. Over the years, detection of neutrinos from various sources allowed to prove the neutrino flavour oscillation, which represents the first experimental evidence of physics beyond the Standard Model. Moreover, studies based on neutrinos detection have broadened significantly our understanding of the functioning mechanism of stars.

In general, stellar energy production is accounted for by two nuclear fusion sequences devoted to the conversion of hydrogen into heavier atoms in the core of a star: the proton-proton (pp) chain and the carbon-nitrogen-oxygen (CNO) cycle. Their relative contribution depend on stellar mass and on its metallicity, defined as abundance of elements heavier than helium in the core. According to the Solar Standard Model predictions [1], the Sun produces most of its energy ($\sim$99%) through the pp chain, with the subdominant CNO cycle accounting for the remaining $\sim$1%. Both processes include several reactions leading to the emission of electron-flavour neutrinos, the so-called *solar*

(*) *Present address*: Forschungszentrum Jälich and RWTH Aachen University - Aachen, Germany. E-mail: `l.pelicci@fz-juelich.de` *neutrinos*, whose detection is the main goal of solar neutrinos experiments. Over the last few decades, many experiments worldwide have focused on the detection of neutrinos emitted from the Sun by the pp chain. Until now, the CNO cycle has been the missing piece for the complete understanding of processes fueling stars. Even though its contribution in the Sun is expected to be marginal, for stars with $M > 1.5\ M_\odot$ the CNO cycle is hypothesised to be the dominant mechanism for stellar energy production. Moreover, since it is catalyzed by elements heavier than helium, the corresponding neutrino fluxes are the most sensitive to the chemical composition of the Sun, thus representing the best available approach to tackle the so-called "metallicity problem" [2].

2. – Borexino detector

Borexino is a large organic liquid scintillator detector placed in the Hall C of the Laboratori Nazionali del Gran Sasso (LNGS), in Italy, below a natural shield of about 1400 m of rock (∼3800 m of water equivalent). The detection of neutrino events in Borexino is performed exploiting the production of scintillation light by recoiling electrons, as a result of elastic scattering with solar neutrinos. The detection material employed consists of ∼280 tons of ultra-clean organic scintillator [3], a mixture of pseudocumene (PC, 1,2,4-trimethylbenzene) as solvent and PPO (2,5-diphenyloxazole) as fluor at a concentration of 1.5 g/l. The liquid scintillator (LS) is contained in a spherical nylon vessel of 8.5 m diameter and 125 μm thickness. The type of LS mixture was chosen to ensure an energy resolution of ∼5% at 1 MeV of deposited energy. The active core of the detector is surrounded by a series of concentric shells made of material with radio-purity increasing towards the inside, to achieve maximal radiopurity in the inner scintillating core. On the external surface, the detector is equipped with a set of 2112 photomultiplier tubes (PMTs), which functions to measure the number and arrival time of detected photoelectrons, thus allowing the reconstruction of energy and position of recoiling electrons.

Borexino was mainly designed for the real-time measurement of solar neutrinos at low energies, in the sub-MeV and MeV energy range. Given the unprecedented level of radio-purity achieved, combined with the high light yield ($\sim 10^4$ photons/MeV), it has achieved several important results in solar and neutrino physics. Collecting data for more than ten years, it was possible to precisely measure the flux of the ^{7}Be neutrino, excluding the possibility of day-night asymmetry of neutrino interaction rate [4], claim the discovery of pep-ν, rejecting at 5σ significance the hypotesis of absence of the pep reaction within the pp chain [5], and finally perform the simultaneous measurement of the interaction rates of pp-ν, ^{7}Be-ν and pep-ν [5].

As will be briefly presented in the next section, the final phase (from July 2016 up to February 2020) of Borexino data taking was devoted to achieving another milestone in neutrino physics: the first experimental measurement of neutrinos emitted in the CNO cycle.

3. – Data selection and fitting strategy

Borexino closing goal was the extraction, for the first time, of a signal of solar neutrinos produced within the sub-dominant CNO cycle. Unfortunately, neutrino-induced events are intrinsically indistinguishable, on an event-by-event basis, from most of the β or γ radioactive backgrounds present in the detector. Therefore, to maximize the signal-to-noise ratio a set of selection cuts is applied, specifically devised to remove all the taggable backgrounds and non-physical events. Moreover, the backgrounds caused by radioactive materials in the apparatus outside the scintillator, the so-called *external backgrounds*, are drastically reduced by selecting events only in a specific software-defined portion of the scintillator. In Borexino, the fiducial volume for the CNO analysis corresponds to a sphere of 2.8 m radius with a cut on the vertical z-axis ($-1.8\,\mathrm{m} < z < 2.2$ m).

Another important source of background is represented by cosmogenic events. Specifically, the ^{11}C isotope dominates the energy region between 1.1 MeV and 1.8 MeV, thus impacting significantly CNO neutrino-detection. Since its interaction rate is very high (approximately six times higher than the CNO-ν rate predicted by SSM-HZ), in Borexino a dedicated tagging technique (known as Three Fold Coincidence, TFC) was adopted for the identification and removal of this contamination. In a nutshell, this algorithm rules out from data taking specific portions of the scintillator by exploiting the spatial and temporal coincidence of the events associated with the production of ^{11}C by cosmic muon spallation. Implementing this method, data are split in two distinct datasets: one enriched with ^{11}C (*TFC-tagged*) and the complementary one depleted in ^{11}C (*TFC-subtracted*).

Finally, to further disentangle neutrino-induced signals from residual backgrounds, a multivariate analysis was adopted, based on the fitting of the spectrum of Borexino events with MC-simulated reference shapes (PDFs). The PDFs are produced by means of complete GEANT4-based Monte Carlo simulations, taking into account all the physical and electronic processes occurring inside the detector. The likelihood function $\mathcal{L}(\vec{k},\vec{\theta})$ for the fit is set up based on a set of parameters $\vec{\theta}$ that defines the PDFs. This analysis is finalized to find the set of parameters that maximize $\mathcal{L}(\vec{k},\vec{\theta})$, and to use them to calculate the interaction rates of backgrounds and signals. In Borexino, the multivariate analyses are performed fitting simultaneously multiple likelihood with same parameters but related to different spectra: the energy spectrum (splitted in TFC-tagged and TFC-subrtacted) and the spectrum of radial distribution (RD). While for the first two the PDFs of neutrinos and contaminants are fitted, in the latter only two reference shapes are considered: the internal uniform component (neutrino-induced events combined with background distributed uniformly within the detector), and the external component.

The procedure results in a binned maximum likelihood that is the product of three distinct components accounting for the three different distribution depicted in fig. 1:

$$(1)\qquad \mathcal{L}(\vec{k},\vec{\theta}) = \prod_{j}\prod_{i=1}^{N_j} \frac{a_j \lambda_i^{k_i}(\vec{\theta})}{k_i!} e^{-a_j \lambda_i(\vec{\theta})}, \quad \text{where } j = \text{TFC-Tag, TFC-Sub, RD},$$

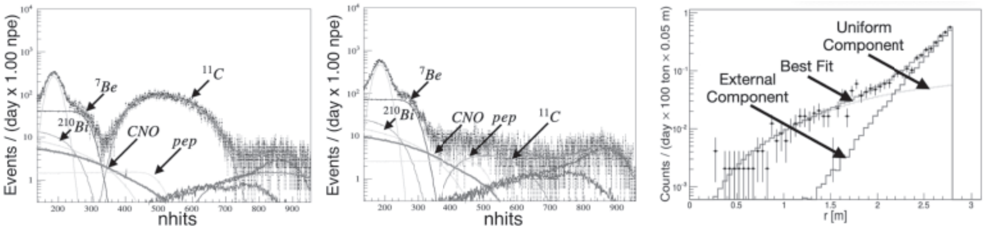

Fig. 1. – Fit of the distribution of the three physical quantities employed in the multivariate analysis. Left and middle panel: distributions of the electron recoil energy for the TFC-tagged and TFC-subtracted data sample. Right panel: radial distribution of external and internal events.

where the product runs over the N bins of the spectrum, λ is the expected number of entries in the i-th bin and $\vec{k}$ represents the set of experimental data. The effective parameter a is called "scaling factor" and it is introduced in the radial likelihood to account for potential double counting of entries in different histograms.

The major obstacle of the CNO analysis is the strong anti-correlation between the spectra of the CNO-ν and the β^- ^{210}Bi background, and to a lesser extent the pep-ν. To break this correlation and make Borexino sensitive to a CNO-ν signal [6], the contribution of these two species needs to be determined independently and constrained in the multivariate fit. The pep-ν rate can be safely constrained to the SSM predictions, according to the preferred metallicity scenario.

The independent constraint on the ^{210}Bi contaminant is the most compelling aspect of the analysis. Its estimation is carried out tagging its daughter isotope, the ^{210}Po, which α decays giving a unique and easily recognizable signature. Unfortunately, this measurement is complicated by additional ^{210}Po contributions not in secular equilibrium with ^{210}Bi. Among others, the most problematic contribution is given by the contamination on the nylon vessel (called *source term*), which can be carried inside the fiducial volume by convective currents triggered by temperature gradients in the liquid scintillator. To mitigate them, in 2016 the collaboration succeeded to thermally insulate the detector with a 20 cm thick layer of mineral wool. Having found a region of the detector with marginal ^{210}Po source term contribution, it is possible to extract an upper limit for the interaction rate of the ^{210}Bi contamination: $R(^{210}\mathrm{Bi}) < 11.5 \pm 1.3\,\mathrm{cpd/100t}$, ref. [7].

The multivariate analysis was performed in the (0.32–2.64) MeV energy range, constraining in the fit both pep-ν and ^{210}Bi interaction rates. The best fit value is found at 7.2 cpd/100t with an asymmetric confidence interval of $-1.7/+2.9\,\mathrm{cpd/100t}$ at 68% C.L. (statistical error only), with a good p-value of the fit (0.3). Many possible sources of systematic error have been investigated, varying fitting parameters or simulating millions of pseudo-experiments with deformed PDFs to be fitted with the regular ones. Among all, the main ones considered include: light yield, spectral shape of ^{210}Bi, detector energy response and deviations of the energy scale from the Monte Carlo model. The total amount of statistical error thus calculated is $-0.5/0.6\,\mathrm{cpd/100t}$.

In summary, considering both statistical and systematic error the final CNO interaction rate is $7.2^{+3.0}_{-1.7}\,\mathrm{cpd/100t}$. The significance of the result in rejecting the hypothesis of absence of CNO is evaluated by means of the log-likelihood profile and the *test statistic* $q = -2\log\frac{\mathcal{L}(\mathrm{CNO}=0)}{\mathcal{L}(\mathrm{CNO})}$, where $\mathcal{L}$ is the maximum likelihood obtained by keeping the CNO rate fixed to zero or free. Both these methods allow to reject the no-CNO hypothesis with a significance better than 5.0σ.

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