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Looking at the Sun's core. CNO and *pep* solar neutrino detection in Borexino

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Summary. — Both the first evidences and the first discoveries of neutrino flavor transformation have come from experiments which detected neutrinos from the Sun. Observation of solar neutrinos directly addresses the theory of stellar structure and evolution, which is the basis of the standard solar models (SSMs). The Sun as a well-defined neutrino source also provides extremely important opportunities to investigate nontrivial neutrino properties such as neutrino oscillations and Mikheyev-Smirnov-Wolfenstein (MSW) effect, because of the wide range of matter density and the great distance from the Sun to the Earth. The ultra-pure Borexino detector at Laboratori Nazionali del Gran Sasso is designed to perform low-energy solar neutrino spectroscopy. Recently, the Borexino experiment has obtained the first direct evidence of the rare proton-electron-proton (*pep*) fusion reaction in the Sun by the detection of the neutrinos emitted in the process. Borexino has also placed the strongest limit on the flux of the neutrinos emitted in the carbon-nitrogen-oxygen (CNO) cycle. In these proceedings I will summarise the novel techniques adopted in Borexino to reduce the cosmogenic and external background contributions and I will describe the physics results obtained.

PACS 95.55.Vj – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS 26.65.+t – Solar neutrinos.

1. – Introduction

Borexino is a real-time solar neutrino detector that is designed to detect low-energy solar neutrinos, such as the 862 keV mono-energetic ^{7}Be solar neutrinos [1,2]. One of the unique features of the Borexino detector is the very low background that allowed the first measurement of the ^{7}Be neutrinos immediately after the detector became operational in May 2007 [2]. This result was the first real-time spectroscopic measurement of low-energy solar neutrinos, and a technological breakthrough in low-background counting.

The detector is in data taking since May 2007. Recent solar neutrino results include a new high-precision measurement of ^{7}Be neutrinos [3], the measurement of the absence

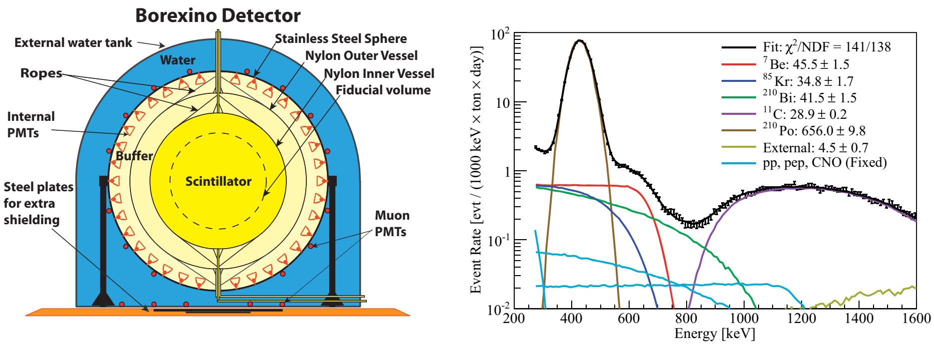

Fig. 1. – Left: The Borexino detector. Right: A Monte-Carlo–based fit over the energy region 270–1600 keV; the event energies are estimated using the number of photons detected by the PMT array.

of day-night asymmetry of ^{7}Be neutrinos [4], a measurement of ^{8}B solar neutrinos with a threshold recoil electron energy of 3 MeV [5], and the first time measurement of *pep* solar neutrinos and the strongest constraint up to date on CNO solar neutrinos [6]. Other recent results include the study of solar and other unknown anti-neutrino fluxes [7], observation of Geo-Neutrinos [8], searches for solar axions [9], and experimental limits on the Pauli-forbidden transitions in ^{12}C nuclei [10].

The motivating goal of low energy solar neutrino detection experiments is to directly probe the nuclear reaction processes in the Sun, and explore neutrino oscillations over a broader range of energies than has been done to date.

One of the features of neutrino oscillations that can be probed with Borexino is the transition from vacuum-dominated oscillation to matter-enhanced oscillations. In the Mikheyev-Smirnov-Wolfenstein (MSW) Large Mixing Angle (LMA) solution of solar-neutrino oscillations [12,13], vacuum-dominated oscillations are expected to dominate at low energies (≤ 0.5 MeV), while matter-enhanced oscillations should dominate at higher energies (≥ 3 MeV). Accurate measurements of neutrinos with energies below and above the transition region can probe this special aspect of MSW-LMA solution.

2. – The Borexino detector

The main features of the Borexino detector are illustrated schematically in fig. 1, left. The active detector is 278 tons of two-component liquid scintillator composed of pseudocumene (PC) and 2,5-diphenyloxazole (PPO), a wavelength shifter. The scintillator is contained in a thin nylon vessel, shielded by two PC buffers separated by a second nylon vessel. The scintillator and buffers are contained within a 13.7 m stainless-steel sphere that is housed in a 16.9 m domed water tank for additional shielding and muon veto [11].

Neutrinos are detected by their elastic scattering on electrons in the liquid scintillator. The scintillation light is detected with an array of 2200 photomultiplier tubes mounted on the inside surface of the stainless-steel sphere. The number of photomultipliers hit is a measure of the energy imparted to the electron, but has no sensitivity to the direction of the neutrino. The position of the scintillation event is determined by a photon time-of-flight method.

The scintillator is shielded from external gamma rays by a combination of high-purity water and PC buffer fluids. Additional shielding against gamma rays from the detector peripheral structures is accomplished by selecting an inner fiducial volume (FV). With the external background highly suppressed, the crucial requirement for solar neutrino detection is the internal background in the scintillator. The basic strategy employed for Borexino is to purify the scintillator with a combination of distillation, water extraction, and nitrogen gas stripping [1, 14-16]. The special procedures for scintillator purification and material fabrication resulted in very low internal backgrounds. Assuming secular equilibrium in the uranium and thorium decay chains, the Bi-Po delayed coincidence rates imply ^{238}U and ^{232}Th levels of $(1.6 \pm 0.1) \times 10^{-17}$ g/g and $(6.8 \pm 1.5) \times 10^{-18}$ g/g. The radon progenies ^{210}Po and ^{210}Bi however, are higher than expected and are out of secular equilibrium. Nevertheless, the current low background has made possible measurements of ^{7}Be solar-neutrino flux with high accuracy, detection of ^{8}B and *pep* solar neutrinos, and strong limits on CNO solar-neutrino flux.

3. – First evidence of *pep* solar neutrinos and limits on CNO solar-neutrino flux

Recent results from the Borexino Collaboration are the first-time measurement of the solar *pep* neutrinos rate and the strongest limits on the CNO solar neutrino flux to date [6]. This has been made possible by the combination of the extremely low levels of intrinsic background in Borexino, and the implementation of novel background discrimination techniques.

The mono-energetic 1.44 MeV *pep* neutrinos, produced in the *pp* fusion chain, are an ideal probe to test the transition region of the P_{ee} predicted by the MSW-LMA model of the neutrino oscillations, because the *pep* predicted flux from the Standard Solar Model has a small uncertainty (1.2%) due to the solar luminosity constraint [17]. The detection of neutrinos resulting from the CNO cycle has important implications in astrophysics, as it would be the first direct evidence of the nuclear processes that are believed to fuel massive stars ($> 1.5\ M_{\odot}$). Furthermore, its measurement may resolve the solar metallicity problem [17, 18]. The energy spectrum of neutrinos from the CNO cycle is the sum of three continuous spectra with end-point energies of 1.19 (^{13}N), 1.73 (^{15}O), and 1.74 MeV (^{17}F). The total CNO flux is similar to that of the *pep* neutrinos, but its predicted value is strongly dependent on the inputs to the solar modelling, being 40% higher in the high-metallicity (GS98) than in the low-metallicity (AGSS09) solar model [17].

The electron recoil energy spectrum from *pep* neutrino elastic scattering interactions in Borexino is a box-like shoulder with end point of 1.22 MeV. The detection of *pep* and CNO solar neutrinos is challenging, as their expected interaction rates are a few counts per day in a 100 ton target, and because of the background in the 1–2 MeV energy range, the cosmogenic β^{+}-emitter ^{11}C (lifetime: 29.4 min).

^{11}C is produced in the scintillator by cosmic muon interactions with ^{12}C nuclei. The muon flux through Borexino is $\sim$ 4300 muon/day [19], yielding a ^{11}C production rate of $\sim$ 27 counts/(day·100 ton). In 95% of the cases at least one free neutron is spallated in the ^{11}C production process and then captured in the scintillator with a mean time of 255 μs [11]. The ^{11}C background can be reduced by performing a space and time veto after coincidences between signals from the muons and the cosmogenic neutrons, discarding exposure that is more likely to contain ^{11}C due to the correlation between the parent muon, the neutron and the subsequent ^{11}C decay (the Three-Fold-Coincidence, TFC).

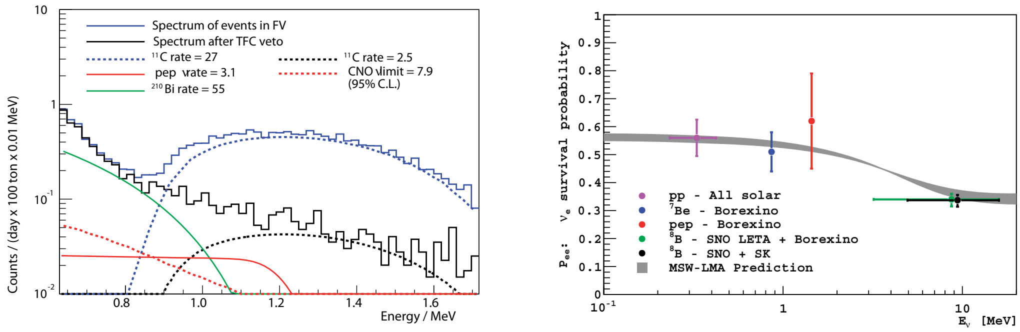

Fig. 2. – Left: Energy spectra of the events in the fiducial volume before and after the TFC veto is applied. The solid and dashed blue lines show the data and estimated ^{11}C background rate before any veto is applied. The solid black line shows the data after the procedure, in which the ^{11}C contribution (dashed) has been suppressed. Rate values in the legend are integrated over all energies and are quoted in units of counts/(day·100 ton). Right: Electron neutrino survival probability (P_{ee}) as a function of energy. The red line corresponds to the *pep* solar-neutrino measurement presented in [6]. The *pp* (magenta line) and ^{7}Be (blue line) measurements of P_{ee} given in [3] are also shown. The MSW-LMA prediction band is the 1σ range of the mixing parameters. Additional details can be found in [6].

The technique relies on the reconstructed track of the muon and the reconstructed position of the neutron-capture γ-ray [11]. The rejection criteria were chosen to obtain the best compromise between ^{11}C rejection and preservation of fiducial exposure, resulting in a ^{11}C rate of (2.5±0.3) counts/(day·100 ton), (9±1) % of the origninal rate, while preserving 48.5% of the initial exposure. The resulting energy spectrum is shown in fig. 2, left.

The residual ^{11}C surviving the TFC veto is still a significant background. We exploited the pulse shape differences between e^- and e^+ interactions in organic liquid scintillators [20] to discriminate ^{11}C β^+ decays from neutrino induced e^- recoils and β^- decays. A slight difference in the time distribution of the scintillation signal arises from the finite lifetime of ortho-positronium as well as from the presence of annihilation γ-rays, which present a distributed, multi-site event topology and a larger average ionization density than electrons interactions. An optimised pulse shape parameter was constructed using a boosted-decision-tree algorithm, trained with a TFC-selected set of ^{11}C events (e^+) and ^{214}Bi events (e^-) selected by the fast ^{214}Bi-^{214}Po α-β decay sequence [6].

The analysis is based on a binned likelihood multivariate fit performed on the energy, pulse shape, and spatial distributions of selected scintillation events whose reconstructed position is within the FV [6]. The distribution of the pulse shape parameter was a key element in the multivariate fit, where decays from cosmogenic ^{11}C (and ^{10}C) were considered e^+ and all other species e^-. The energy spectra and spatial distribution of the external γ-ray backgrounds have been obtained from a full, Geant-4–based Monte Carlo simulation. The non-uniform radial distribution of the external background was included in the multivariate fit and strongly constrained its contribution.

The species left free in the fit were the internal radioactive backgrounds ^{210}Bi, ^{40}K, ^{85}Kr, and ^{234m}Pa, cosmogenic backgrounds ^{11}C, ^{10}C, and ^{6}He, external γ-rays from ^{208}Tl, ^{214}Bi, and ^{40}K, and electron recoils from ^{7}Be, *pep* and CNO solar neutrinos. The contribution from *pp* solar neutrinos was fixed to the Standard Solar Model predicted rate and the contribution from ^{8}B neutrinos to the rate from the measured flux [5].

The best estimate for the interaction rate of *pep* solar neutrinos in Borexino is (3.1±0.6 (stat) ±0.3 (syst)) counts/(day·100 ton) [6]. The measured rate is to be compared to the predicted rate without neutrino oscillation, based on the Standard Solar Model, of (4.47± 0.05) counts/(day·100 ton); the observed interaction rate disfavours this hypothesis at 97% CL. If this reduction in the apparent flux is due to ν_e oscillation to ν_μ or ν_τ, we find $P_{ee} = 0.62 \pm 0.17$ at 1.44 MeV. This result is shown alongside other solar-neutrino P_{ee} measurements in fig. 2, right. Alternatively, by assuming MSW-LMA solar-neutrino oscillations, the Borexino results can be used to measure the *pep* solar-neutrino flux, corresponding to $\Phi_{pep} = (1.6 \pm 0.3) \times 10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, in agreement with the Standard Solar Model.

Due to the similarity between the electron-recoil spectrum from CNO neutrinos and the spectral shape of ^{210}Bi decay, whose rate is ~ 10 times greater, we can only provide an upper limit on the CNO neutrino interaction rate. Assuming MSW-LMA solar neutrino oscillations, the 95% CL limit on the solar-neutrino CNO flux is $7.7 \times 10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Our limit on CNO solar-neutrino flux is 1.5 times higher than the flux predicted by the high-metallicity Standard Solar Model [6, 17] and in agreement with both the high-metallicity and low-metallicity Standard Solar Models.

4. – Conclusions

Borexino has achieved the necessary sensitivity to provide, for the first time, evidence of the rare signal from *pep* solar neutrinos and to place the strongest constraint on the CNO solar neutrino flux to date. This result raises the prospect for higher precision measurements of *pep* and CNO solar neutrino interaction rates by Borexino, if the next dominant background, ^{210}Bi, is further reduced by scintillator repurification.

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