CNO and *pep* solar neutrino measurements and perspectives in Borexino

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Abstract. The detection of neutrinos emitted in the CNO reactions in the Sun is one of the ambitious goals of Borexino Phase-II. A measurement of CNO neutrinos would be a milestone in astrophysics, and would allow to solve serious issues in current solar models. A precise measurement of the rate of neutrinos from the *pep* reaction would allow to investigate neutrino oscillations in the MSW transition region. The *pep* and CNO solar neutrino physics, the measurement in Borexino Phase-I and the perspectives for the new phase are reviewed in this proceeding.

1. Introduction

Borexino is a real-time solar neutrino detector that is designed to detect low energy solar neutrinos [1, 2]. 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.

Mono-energetic (1.44 MeV) *pep* solar neutrinos, produced in the *pp* fusion chain, are an ideal probe to test the transition from vacuum-dominated oscillation to matter-enhanced oscillations predicted by the MSW-LMA model of the neutrino oscillations: the flux of *pep* predicted by from the Standard Solar Model has a small uncertainty (1.2%) due to the solar luminosity constraint. The detection of neutrinos resulting from the CNO cycle would have huge implications in astrophysics: it would be the first direct evidence of the nuclear processes that are believed to fuel massive stars ($>1.5\ M_\odot$). Furthermore, a measurement of the CNO neutrino flux may resolve the solar metallicity problem [3]. The total CNO flux 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 [3].

2. The Borexino detector

The features of the Borexino detector are described in detail in [1]. One of the unique features of the Borexino detector is the very low radioactive background. 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 [4].

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.

Borexino is in data taking since May 2007. Borexino Phase-I covers the period from May 2007 to May 2010. After the purification of the scintillator performed between May 2010 and August 2011, in November 2011 the Phase-II of Borexino started. Borexino Phase-II is expected to last until 2016, before the begining of SOX [5].

Borexino Phase-I solar neutrino results, described in detail in [2], include a high-precision measurement of ^{7}Be neutrinos [6], the measurement of the absence of day-night asymmetry of ^{7}Be neutrinos [7], a measurement of ^{8}B solar neutrinos with a threshold recoil electron energy of 3 MeV [8], and the first time measurement of *pep* solar neutrinos and the strongest constraint up to date on CNO solar neutrinos [9]. Other results include the study of solar and other unknown anti-neutrino fluxes [10], observation of geo-neutrinos [11, 12], measurement of neutrino velocity [13], searches for solar axions [14], and experimental limits on the Pauli-forbidden transitions in ^{12}C nuclei [15].

The direct real-time measurement of the solar neutrinos from the fundamental *pp* reaction [16] is the greatest achievement so far of Borexino Phase-II.

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

The Borexino collaboration reported in 2012 the first time measurement of the solar *pep* neutrino rate and the strongest limits on the CNO solar neutrino flux to date [9]. This measurement has been made possible by the combination of the low levels of intrinsic background in Borexino-I, and the implementation of novel background discrimination techniques.

The detection of *pep* and CNO solar neutrinos is challenging: their expected interaction rates are a few counts per day in a 100 ton target, and the main backgrounds, the cosmogenic β^+-emitter ^{11}C and radiogenic ^{210}Bi, are one order of magnitude more intense [9].

^{11}C is produced in the scintillator by cosmic muon interactions with ^{12}C nuclei. In 95% of the cases at least one free neutron is created in the ^{11}C spallation process and then captured in the scintillator [4, 17, 18]. The ^{11}C background can be reduced by applying 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). The rejection criteria were chosen to obtain the best compromise between ^{11}C rejection and preservation of exposure [2, 9].

The residual ^{11}C surviving the TFC cut is still a significant background. The pulse shape differences between e^- and e^+ were used 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. [19]. A pulse shape parameter was constructed using a boosted-decision-tree algorithm [2, 9].

The analysis is based on a binned likelihood multivariate fit performed on the energy, pulse shape, and spatial distributions of selected scintillation events. The non-uniform radial distribution of the external γ-ray background was included in the multivariate fit and strongly constrained its contribution [2, 9].

The best estimate for the interaction rate of *pep* solar neutrinos in Borexino is $(3.1 \pm 0.6\,(\text{stat}) \pm 0.3\,(\text{syst}))$ counts/(day·100ton). If this reduction in the apparent flux is due

Isotope	Specs for LS	BX Phase-I	BX Phase-II
^{238}U	$\leq 10^{-16}$ g/g	$(5.3 \pm 0.5) \times 10^{-18}$ g/g	$\leq 8 \times 10^{-20}$ g/g
^{232}Th	$\leq 10^{-16}$ g/g	$(3.8 \pm 0.8) \times 10^{-18}$ g/g	$\leq 9 \times 10^{-19}$ g/g
^{14}C/^{12}C	$\leq 10^{-18}$	$(2.69 \pm 0.06) \times 10^{-18}$	unchanged
^{40}K	$\leq 10^{-18}$ g/g	$\leq 0.4 \times 10^{-18}$ g/g	unchanged
^{85}Kr	≤ 1 cpd/100t	(30 ± 5) cpd/100t	≤ 7 cpd/100t
^{39}Ar	≤ 1 cpd/100t	$\ll\ ^{85}$Kr	$\ll\ ^{85}$Kr
^{210}Po	not specified	~ 700 cpd/100t (decaying)	~ 80 cpd/100t (decaying)
^{210}Bi	not specified	$\sim 20 - 70$ cpd/100 t	(25 ± 2) cpd/100t

Table 1. Residual radioactive contamination of the Borexino liquid scintillator before and after the purification performed in 2010-2011. ^{210}Po rate is a factor 100 less than at the begin of data taking. ^{210}Bi is a factor 2 less than in Phase-I.

to ν_e oscillation to ν_μ or ν_τ, we find $P_{ee} = 0.62 \pm 0.17$ at 1.44 MeV. Assuming MSW-LMA solar neutrino oscillations, the Borexino results can be used to measure the *pep* solar neutrino flux, corresponding to $\Phi_{pep} = (1.6 \pm 0.3) \times 10^8$ cm^{-2} s^{-1}, in agreement with the Solar Standard Model [2, 9].

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, Borexino Phase-I only provided an upper limit on the CNO neutrino interaction rate. Assuming MSW-LMA solar neutrino oscillations, the 95% C.L. limit on the solar CNO neutrino flux is 7.7 $\times 10^8$ cm^{-2} s^{-1}. The limit on CNO solar neutrino flux is 1.5 times higher than the flux predicted by the High Metallicity Solar Standard Model [2, 9].

4. Prospects in Borexino Phase-II
A new measurement of *pep* and CNO solar neutrinos is foreseen in Borexino Phase-II. The radioactive background levels in Borexino Phase-II are lower, thanks to a set of scintillator purifications performed after Phase-I. The residual background contaminations are summarised in table 1. The contamination of ^{210}Bi, which was the dominant radioactive background, is reduced of a factor ~ 3. New methods for pulse shape discrimination between e^- and e^+, and for constraining the residual rate of ^{210}Bi, are also under study.

5. Conclusions and outlook
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 by Borexino Phase II, since the next dominant background, ^{210}Bi, has been reduced by scintillator purification.

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