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The study of solar neutrinos and of non-standard neutrino interactions with Borexino

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Abstract. The Borexino liquid scintillator neutrino observatory has a unique capability to perform high-precision solar neutrino observations thanks to its exceptional radiopurity and good energy resolution (5% at 1 MeV). A comprehensive study of the pp-chain neutrinos was presented that includes the direct measurements of ^{7}Be, pp and pep neutrino fluxes with the highest precision ever achieved (down to 2.8% in the ^{7}Be component), the ^{8}B with the lowest energy threshold, the best limit on CNO neutrinos and the first Borexino limit on hep neutrinos. These results are important to validate the MSW-LMA oscillation paradigm across the full solar energy range and to exclude possible Non-Standard neutrino Interactions (NSIs). In particular the effects of neutrino-flavor-diagonal Neutral-Current (NC) interactions that modify the $\nu_e e$ and $\nu_\tau e$ couplings while preserving their chiral and flavor structures, have been investigated. At detection, the shape of the electron-recoil spectrum is affected by changes in the $\nu_e e$ and $\nu_\tau e$ couplings, quantified by the parameters $\varepsilon_e^{L/R}$ and $\varepsilon_\tau^{L/R}$. New bounds to all four parameters were obtained, quite stringent compared to the global ones. In particular, the best constraint to-date on ε_e^L was achieved. A comprehensive summary of all the recent results on solar neutrinos from Borexino is reported in the present paper.

1. Introduction

Solar neutrinos are a unique probe of the Sun's interior and at the same time they provide an intense natural beam for fundamental physics: they reach the Earth as a mixture of all neutrino flavours (electronic, muonic, and tauonic) owing to the flavour-conversion mechanism enhanced by the MSW effect. Borexino is a liquid-scintillator experiment [1] and it detects solar neutrinos by means of their weak elastic scattering off electrons. Given the tiny cross-section of neutrino interactions with electrons Borexino has a large target mass ($\sim$ 300 t) and is housed deep underground in the Laboratori Nazionali del Gran Sasso in Italy, under 3,800 m water equivalent of rock that suppresses the flux of cosmic radiation by a factor of approximately 10^6. This low level of background together with an unprecedented scintillator radio-purity has enabled real-time detection of solar neutrinos with an energy threshold of 0.19 MeV, and allowed to perform the complete spectroscopy of the pp chain.

2. Solar neutrino study and Borexino results

For each of the events detected in Borexino, the total amount of the light and its time distribution among photomultipliers provide three important quantities: its deposited energy, from the total number of detected photoelectrons; its position within the detector, from the analysis of the photons arrival times at each photomultiplier; and its particle identification, from a pulse-shape discrimination method that exploits the difference in time structure of liquid-scintillator light pulses induced by different particles [2]. In general, depending on the energy, distinct backgrounds are relevant and in the solar neutrino analysis two energy regions have been considered: a low-energy region (LER) of 0.19-2.93 MeV, to study the pp, ^{7}Be and pep neutrino interaction rates, and a high-energy region (HER) of 3.2-16 MeV, to measure ^{8}B neutrinos [3]. The LER analysis uses exclusively the more radiopoure Borexino Phase-II data, collected between December 2011 and May 2016, for a total exposure of 1,291 days $\times$ 71.3 t. Neutrino signals are disentangled from backgrounds by following a a multivariate approach, simultaneously fitting the energy spectrum, the spatial and the pulse-shape estimator distributions. The HER is above the natural, long-lived radioactive background and makes it possible to use all data collected between January 2008 and December 2016, for a total exposure of 2,062.4 days $\times$ 266.0 tons. In the HER a fit of the radial distribution of events is performed to separate the ^{8}B neutrino signal (uniformly distributed in the scintillator) from the external background. A detailed table of all the measured fluxes can be found in [3]. In general, the measured neutrino fluxes can be used either to probe our understanding of solar physics assuming the validity of the neutrino physics assumptions or, alternatively, to test the MSW-LMA paradigm assuming Standard Solar Model (SSM) flux predictions. Solar neutrinos are detected on Earth only about 8 min after their emission, therefore they provide a real-time picture of the Sun's core. By using the new Borexino results [3] we found L = $(3.89\pm0.35)10^{33}$ erg s^{-1}, in agreement with the luminosity calculated using the well known photon output, L = $(3.846\pm0.015)10^{33}$ erg s^{-1}. This result supports the nuclear origin of the solar power with the best precision achieved so far by a single solar-neutrino experiment and it proves that the Sun has been in thermodynamic equilibrium over a timescale of 10^5 years.

The assumed Sun's metallicity determines the plasma opacity and, as a consequence, regulates the central temperature and the branching ratios of the different pp-chain terminations. The Borexino measurements can be used to test the predictions of SSMs with different metallicity: in particular the ^{7}Be and ^{8}B neutrino fluxes are very different in the high metallicity (HZ) and the low metallicity (LZ) SSM theoretical predictions (differences of 9% and 18%, respectively) [4]. A frequentist hypothesis test based on a likelihood-ratio test statistics (HZ versus LZ) was performed by computing the probability distribution functions with a Monte Carlo approach. Our data disfavour LZ at 96.6% C.L., by assuming HZ to be true.

The ratio $R_{I/II}$ between the ^{3}He-^{4}He and the ^{3}He-^{3}He fusion rates constrains the relative intensity of the two primary terminations of the pp chain (pp-II and pp-I). This ratio can be quantified from the measured pp and ^{7}Be neutrino fluxes by the relation , $R_{I/II}$ = 2Φ(Be)/[Φ(pp) - Φ(Be)]. We found $R_{I/II}$= 0.178±0.027, that again looks in better agreement with the predicted values of $R_{I/II}$ = 0.180 ± 0.011 for the HZ respect to the LZ one, 0.161 ± 0.010.

Finally, the Borexino results can be used to simultaneously test neutrino flavour conversion both in the vacuum and in the matter-dominated regime. By assuming the HZ-SSM fluxes and standard neutrino-electron cross-sections, we obtained the electron neutrino survival probabilities for each solar-neutrino component: P_{ee}(pp, 0.267 MeV) = 0.57 ± 0.09, P_{ee}(^{7}Be, 0.862 MeV) = 0.53 ± 0.05, P_{ee}(pep, 1.44 MeV) = 0.43 ± 0.11 and P_{ee}(^{8}B-HER,8.1 MeV) = 0.37 ± 0.08. The quoted errors include the uncertainties on the SSM solar-neutrino flux predictions. Borexino supports the MSW-LMA paradigm (see Fig.1) and provides the most precise measurement of the P_{ee} in the LER, where flavour conversion is vacuum-dominated. At higher energy where flavour conversion is dominated by matter effects in the Sun, the Borexino results are in agreement with the high-precision measurements performed by SuperKamiokande and SNO. Borexino data disfavour the vacuum-LMA hypothesis at 98.2%.

3. Non-standard neutrino interactions

Some theories of physics beyond the Standard Model postulate the existence of Non-Standard Interactions (NSIs) which modify the chiral couplings of the neutrino and electron and the P_{ee}(E). On the base of the more radio-pure Phase II data, we searched for neutral-current (NC) interactions that modify the $\nu_e e$ and $\nu_\tau e$ couplings while preserving their chiral and flavor structures. In particular we restricted the analysis to neutrino-flavor-diagonal NSIs ν_e interactions to which Borexino is particularly sensitive. We neglected possible effects on ν_μ-e couplings, since they are already well constrained by the ν_μ-e scattering CHARM II experiment [5]. The monochromatic ^{7}Be-component plays a fundamental role in the Borexino analysis since both the shape and the normalization of the electron-recoil spectrum are well-constrained in the spectral fit. Given the 6%-uncertainty in the theoretical ^{7}Be neutrino flux, it provides the highest sensitivity to NSI's among all the neutrino components. In general NSIs can affect solar neutrinos at production, propagation, and detection. Neutrino production in the Sun might be affected via processes such as $\gamma e \to \nu\bar{\nu}e$, but the expected modification in the neutrino spectrum is at energies well below the detection threshold of Borexino (∼50 keV). The solar neutrino survival probability $P_{ee}(E)$ is also modified via the LMA-MSW mechanism as the neutrinos propagate through dense solar matter. The effect is stronger at ^{8}B neutrino energies but not particularly large at ^{7}Be neutrino energies, limiting the sensitivity of Borexino to such deviations. The effect of the NSI's to which Borexino is most sensitive is at detection, where the modified $\nu_e e$ and $\nu_\tau e$ interactions cause a shift of the coupling constants in the expression of the differential cross section:

$$g_{\alpha R} \quad \to \quad \tilde{g}_{\alpha R} \;=\; g_{\alpha R} + \varepsilon_\alpha^R\ , \tag{1}$$
$$g_{\alpha L} \quad \to \quad \tilde{g}_{\alpha L} \;=\; g_{\alpha L} + \varepsilon_\alpha^L\ . \tag{2}$$

Both the shape of the electron-recoil spectrum and the absolute number of events are expected to be modified. The parameters $\varepsilon_\alpha^{L/R}$ ($\alpha = e, \tau$) quantify the strength of the NSI's interactions. In the Borexino analysis, the events have been selected as for the solar neutrinos LER study and the same multivariate fit procedure was applied. The spectra of ^{210}Bi and ^{85}Kr backgrounds overlap with the ^{7}Be electron-recoil spectrum leading to a modification of its shape. This reduces the sensitivity to the right-handed NSI parameter $\varepsilon^R_{e/\tau}$. In the multivariate fit the solar neutrino fluxes were constrained to the prediction of the SSMs with the LMA-MSW oscillation mechanism by adding penalty factors in the likelihood function. SSMs with both high- (HZ) and low-metallicity (LZ) were considered. Systematic effects related to the characterisation of

Table 1. The limits on the flavor-diagonal NSI parameters ε_e^R, ε_e^L, ε_τ^R and ε_τ^L as obtained by Borexino. All limits are 90% C.L. (1 d.o.f.).

	ε_e^R	ε_e^L	ε_τ^R	ε_τ^L
HZ-SSM	[−0.15, +0.11]	[−0.035, +0.032]	[−0.83, +0.36]	[−0.11, +0.67]
LZ-SSM	[−0.20, +0.03]	[−0.013, +0.052]	[−0.42, +0.43]	[−0.19, +0.79]

the target mass of the detector and the choice of oscillation parameters were taken into account. The 90% C.L. (1 d.o.f.) bounds on the flavor-diagonal NSI parameters (Table 1) were obtained by varying only one NSI parameter at-a-time, while the remaining three NSI parameters were fixed to zero. Borexino is particularly sensitive the ε_e^L parameter: the best up to date constrain has been obtained (Table 1). More details on the analysis can be found in [6].

The 2D allowed region for $\varepsilon_e^{L/R}$ is reported in Fig.2 together with the other literature results. The allowed contour of Borexino is quite distinct with respect to other νe or $\overline{\nu} e$ scattering experiments, also sensitive to the same NSI's, such as TEXONO [7] and LSND [8]. Borexino's contour intersects the allowed regions for both experiments at a certain angle, and the three experiments complement each other, strongly reducing the overall allowed region of the parameters.

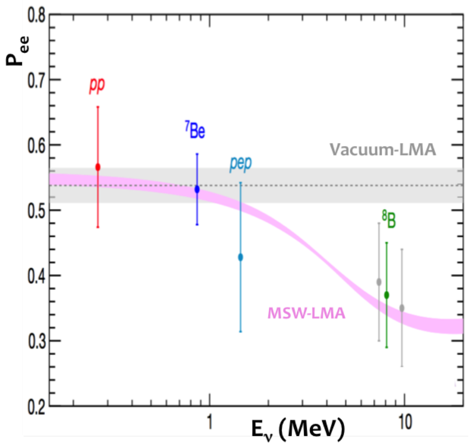

Figure 1. Electron neutrino survival probability P_{ee} as a function of neutrino energy. The pink band is the $\pm 1\sigma$ prediction of MSW-LMA [3].

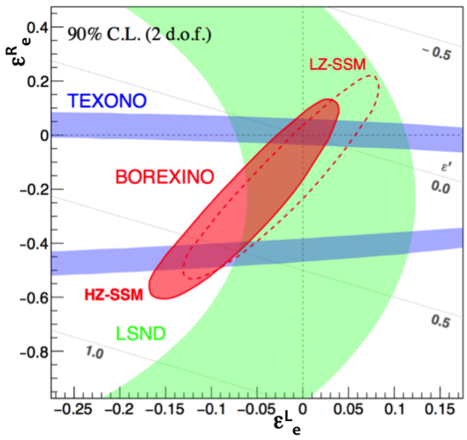

Figure 2. Allowed region for NSI parameters in $\varepsilon_e^{L/R}$ by Borexino [6]. The bounds from TEXONO [7] and LSND [8] are provided for comparison.

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