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First evidence of *pep* solar neutrinos by direct detection in Borexino

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Abstract. We observed, for the first time, solar neutrinos in the 1.0–1.5 MeV energy range. We determined the rate of *pep* solar neutrino interactions in Borexino to be $3.1\pm0.6_{\rm stat}\pm0.3_{\rm syst}$ counts/(day·100 ton). Assuming the *pep* neutrino flux predicted by the Standard Solar Model, we obtained a constraint on the CNO solar neutrino interaction rate of <7.9 counts/(day·100 ton) (95% C.L.). The absence of the solar neutrino signal is disfavored at 99.97% C.L., while the absence of the *pep* signal is disfavored at 98% C.L. The necessary sensitivity was achieved by adopting data analysis techniques for the rejection of cosmogenic ^{11}C, the dominant background in the 1–2 MeV region. Assuming the MSW-LMA solution to solar neutrino oscillations, these values correspond to solar neutrino fluxes of $(1.6\pm0.3)\times10^8\,\mathrm{cm^{-2}s^{-1}}$ and $<7.7\times10^8\,\mathrm{cm^{-2}s^{-1}}$ (95% C.L.), respectively, in agreement with both the High and Low Metallicity Standard Solar Models. These results represent the first direct evidence of the *pep* neutrino signal and the strongest constraint of the CNO solar neutrino flux to date.

1. Introduction

Two distinct processes, the main *pp* fusion chain and the sub-dominant CNO cycle, are expected to produce solar-ν_e with different energy spectra and fluxes. Until now only fluxes from the *pp* chain have been measured: ^{7}Be, ^{8}B, and, indirectly, *pp*. Experiments involving solar-ν and

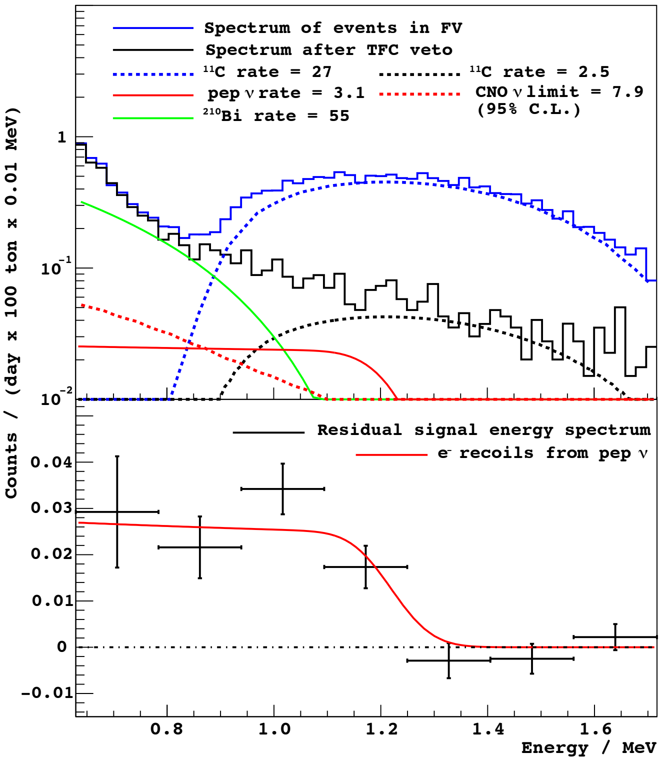

Figure 1. Top: energy spectra of the events in the FV before and after application of the TFC veto. The solid and dashed blue lines show the data and estimated ^{11}C rate before any veto is applied. The solid black line shows the data after the procedure, in which the ^{11}C contribution (dashed) has been greatly suppressed with the TFC veto. The next largest background, ^{210}Bi, and the e^- recoil spectra of the best estimate of the *pep*-ν rate and of the upper limit of the CNO-ν rate are shown for reference. Rate values in the legend are integrated over all energies and are quoted in units of counts/(day·100 metric ton). Bottom: residual energy spectrum after best-fit rates of all considered backgrounds are subtracted. The e^- recoil spectrum from *pep*-ν at the best-fit rate is shown for comparison.

reactor $\bar{\nu}_e$ have shown that solar-ν_e undergo flavor oscillations. The mono-energetic 1.44 MeV *pep* neutrinos, which belong to the *pp* chain and whose Standard Solar Model (SSM) predicted flux has one of the smallest uncertainties (1.2%) due to the solar luminosity constraint [1].

2. Borexino

Neutrinos interact through elastic scattering with electrons (e^-) in the ∼278 ton organic liquid scintillator target of Borexino [2]. The e^- recoil energy spectrum from *pep* neutrino interactions in Borexino is a Compton-like shoulder with end point of 1.22 MeV. High light yield and low background levels [3, 4] allow Borexino to perform solar-ν spectroscopy below 2 MeV. Its potential has already been demonstrated in the precision measurement of the 0.862 MeV ^{7}Be solar-ν flux [3]. The detection of *pep* and CNO neutrinos requires new analysis techniques, as their expected interaction rates are a few counts per day in a 100 ton target.

3. *pep* solar neutrinos

A full description of the results is available in Ref. [5].

In order to study neutrinos in the energy range 1–2 MeV, we adopted analysis procedures to suppress the dominant background in that energy range, the cosmogenic β^+-emitter ^{11}C (lifetime: 29.4 min). ^{11}C is produced in the scintillator by cosmic muon (μ) interactions with ^{12}C nuclei. The muon flux through Borexino is $\sim$4300 μ/day, yielding a ^{11}C production rate of $\sim$27 counts/(day·100 ton). In 95% of the cases at least one free neutron is spalled in the ^{11}C production process [6], and then captured in the scintillator with a mean time of 255 μs [7].

^{11}C background is primarily discarded from the data set by performing a space and time veto after coincidences between signals from the muons and the cosmogenic neutrons [8, 9] (the Three-Fold Coincidence, TFC). Optimization of the veto criteria between the competing requirements of strong ^{11}C rejection and optimal preservation of exposure results in a ^{11}C rate of (2.5±0.3) counts/(day·100 ton), (9±1)% of the original rate, while preserving 48.5% of the initial exposure. The resulting spectrum is shown in Fig. 1. In addition, we exploited the pulse shape differences between e^- and e^+ interactions in organic liquid scintillators [10], to discriminate ^{11}C β^+ decays from neutrino-induced e^- recoils and β^-decays [11]. 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 e^- interactions.

We extracted neutrinos signals from a multi-variate fit of the energy spectra, pulse-shape and spatial distributions of the events. Table 1 summarizes the results for the *pep* and CNO neutrino interaction rates as well as for the background sources.

We have achieved the necessary sensitivity to provide, for the first time, evidence of the signal from *pep* neutrinos and to place the strongest constraint on the CNO neutrino flux to date. This has been made possible by the combination of low levels of intrinsic background in Borexino and the implementation of novel background discrimination techniques.

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Table 1. Best estimates for the *pep* and CNO solar neutrino interaction rates, and for the the total rates of the background species included in the fit. For the backgrounds, the statistical and systematic uncertainties were added in quadrature. The statistical uncertainties for the neutrino rates are not Gaussian, as shown in Fig. 2.

Component	[counts/(day·100 ton)]
pep	$3.1 \pm 0.6_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}}$
CNO	< 7.9 ($< 7.1_{\mathrm{stat\,only}}$)
^{85}Kr	19^{+5}_{-3}
^{210}Bi	55^{+3}_{-5}
^{11}C	27.4 ± 0.3
^{10}C	0.6 ± 0.2
^{6}He	< 2
^{40}K	< 0.4
^{234m}Pa	< 0.5
Ext. γ	2.5 ± 0.2

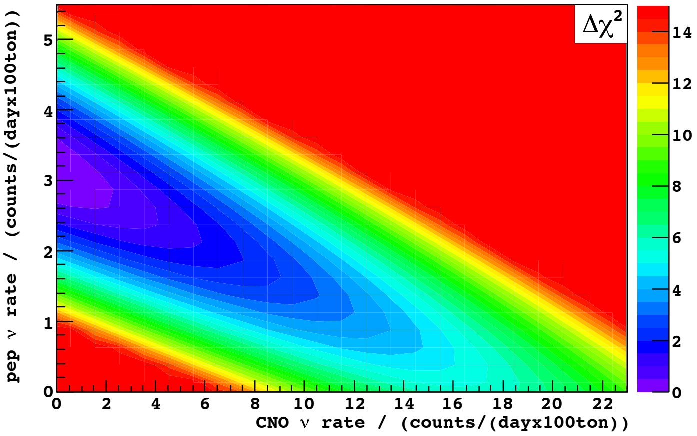

Figure 2. $\Delta\chi^2$ profile obtained from likelihood ratio tests between fit results where the *pep* and CNO neutrino interaction rates are fixed to particular values (other species are left free) and the best-fit result.

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