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First evidence of \textit{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 \textit{pep} solar neutrino interactions in Borexino to be $3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{syst}} \text{ counts/(day \cdot 100 ton)}$. Assuming the \textit{pep} neutrino flux predicted by the Standard Solar Model, we obtained a constraint on the CNO solar neutrino interaction rate of $<7.9 \text{ counts/(day \cdot 100 ton)}$ (95% C.L.). The absence of the solar neutrino signal is disfavored at 99.97% C.L., while the absence of the \textit{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 $(1.6 \pm 0.3) \times 10^{8} \text{ cm}^{-2} \text{s}^{-1}$ and $<7.7 \times 10^{8} \text{ cm}^{-2} \text{s}^{-1}$ (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 \textit{pep} neutrino signal and the strongest constraint of the CNO solar neutrino flux to date.

1. Introduction

Two distinct processes, the main \textit{pp} fusion chain and the sub-dominant CNO cycle, are expected to produce solar-$\nu_{e}$ with different energy spectra and fluxes. Until now only fluxes from the \textit{pp} chain have been measured: $^{7}$Be, $^{8}$B, and, indirectly, \textit{pp}. Experiments involving solar-$\nu$ 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-$\nu$ rate and of the upper limit of the CNO-$\nu$ 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-$\nu$ at the best-fit rate is shown for comparison.

reactor $\bar{\nu}_e$ have shown that solar-$\nu_e$ 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 $\sim$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-$\nu$ spectroscopy below 2 MeV. Its potential has already been demonstrated in the precision measurement of the 0.862 MeV $^7$Be solar-$\nu$ 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 11C
(lifetime: 29.4 min). 11C is produced in the scintillator by cosmic muon (µ) interactions with
12C nuclei. The muon flux through Borexino is ∼4300 µ/day, yielding a 11C production rate of
∼27 counts/(day·100 ton). In 95% of the cases at least one free neutron is spalled in the 11C
production process [6], and then captured in the scintillator with a mean time of 255 µs [7].

11C 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 11C rejection and optimal preservation of exposure results in a 11C 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
11C 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.

References

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.

<table>
<thead>
<tr>
<th>Component</th>
<th>counts/(day·100 ton)</th>
</tr>
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<tbody>
<tr>
<td>pep</td>
<td>3.1 ± 0.6stat ± 0.3syst</td>
</tr>
<tr>
<td>CNO</td>
<td>&lt; 7.9 (&lt; 7.1stat only)</td>
</tr>
<tr>
<td>85Kr</td>
<td>19±5</td>
</tr>
<tr>
<td>210Bi</td>
<td>55±5</td>
</tr>
<tr>
<td>11C</td>
<td>27.4 ± 0.3</td>
</tr>
<tr>
<td>10C</td>
<td>0.6 ± 0.2</td>
</tr>
<tr>
<td>6He</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>40K</td>
<td>&lt; 0.4</td>
</tr>
<tr>
<td>234mPa</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Ext. γ</td>
<td>2.5 ± 0.2</td>
</tr>
</tbody>
</table>
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.