First evidence of pep solar neutrinos by direct detection in Borexino

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We observed, for the first time, solar neutrinos in the 1.0–1.5 MeV energy range. We measured the rate of pep solar neutrino interactions in Borexino to be \((3.1\pm0.6_{\text{stat}}\pm0.3_{\text{syst}})\) counts/(day\cdot100\ ton) and provided a constraint on the CNO solar neutrino interaction rate of \(<7.9\) counts/(day\cdot100\ 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. This unprecedented sensitivity was achieved by adopting novel data analysis techniques for the rejection of cosmogenic \(^{14}\)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 \((1.6\pm0.3)\times10^6\ cm^{-2}\ s^{-1}\) and \(<7.7\times10^6\ cm^{-2}\ s^{-1}\) (95\% C.L.), respectively, in agreement with the Standard Solar Model. These results represent the first measurement of the pep neutrino flux and the strongest constraint of the CNO solar neutrino flux to date.

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Over the past 40 years solar neutrino experiments \cite{1–5} have proven to be sensitive tools to test both astrophysical and elementary particle physics models. Solar neutrino detectors have demonstrated that stars are powered by nuclear fusion reactions. Two distinct processes, the main \(pp\) fusion chain and the sub-dominant CNO cycle, are expected to produce solar neutrinos 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 neutrinos and reactor anti-neutrinos \cite{6} have shown that solar neutrinos undergo flavor oscillations.

Results from solar neutrino experiments are consistent with the Mikheyev-Smirnov-Wolfenstein Large Mixing Angle (MSW-LMA) model \cite{7}, which predicts a transition from vacuum-dominated to matter-enhanced oscillations, resulting in an energy dependent \(\nu_{ee}\) survival probability, \(P_{ee}\). Non-standard neutrino interaction models formulate \(P_{ee}\) curves that deviate significantly from MSW-LMA, particularly in the 1–4 MeV transition region, see e.g. \cite{8}. The mono-energetic 1.44 MeV pepp neutrinos, which belong to the \(pp\) chain and whose Stan-
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 process that is believed to fuel massive stars (>1.5\(M_\odot\)). Furthermore, its measurement may help to resolve the solar metallicity problem [9] [10]. The energy spectrum of neutrinos from the CNO cycle is the sum of three continuous spectra with end point energies of 1.19 (<sup>13</sup>N), 1.73 (<sup>15</sup>O) and 1.74\text{MeV} (<sup>17</sup>F), close to the pep neutrino energy. 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 modeling, being 40% higher in the High Metallicity (GS98) than in the Low Metallicity (AGSS09) solar model [9].

Neutrinos interact through elastic scattering with electrons in the \(\sim 278\) ton organic liquid scintillator target of Borexino [11]. The electron recoil energy spectrum from pep neutrino interactions in Borexino is a Compton-like shoulder with end point of 1.22\text{MeV}. High light yield and unprecedentedly low background levels [5] [12] make Borexino the only detector presently capable of performing solar neutrino spectroscopy below 2\text{MeV}. Its potential has already been demonstrated in the precision measurement of the 0.862\text{MeV} \(^7\text{Be}\) solar neutrino flux [5] [13]. The detection of pep and CNO neutrinos is even more challenging, as their expected interaction rates are \(\sim 10\) times lower, a few counts per day in a 100 ton target.

We adopted novel analysis procedures to suppress the dominant background in the 1–2\text{MeV} energy range, the cosmogenic \(\beta^+\)-emitter \(^{11}\text{C}\) (lifetime: 29.4 min). \(^{11}\text{C}\) is produced in the scintillator by cosmic muon interactions with \(^{12}\text{C}\) nuclei. The muon flux through Borexino is \(\sim 4300\)\text{µ}/day, yielding a \(^{11}\text{C}\) production rate of \(\sim 27\) counts/(day·100 ton). In 95% of the cases at least one free neutron is spalled in the \(^{11}\text{C}\) production process [14], and then captured in the scintillator with a mean time of 255\text{µs} [15]. The \(^{11}\text{C}\) background can be reduced by performing a space and time veto after coincidences between signals from the muons and the cosmogenic neutrons [16] [17], discarding exposure that is more likely to contain \(^{14}\text{C}\) due to the correlation between the parent muon, the neutron and the subsequent \(^{11}\text{C}\) decay (the Three-Fold Coincidence, TFC). The technique relies on the reconstructed track of the muon and the reconstructed position of the neutron-capture \(\gamma\)-ray [15]. The rejection criteria were chosen to obtain the optimal compromise between \(^{11}\text{C}\) rejection and preservation of fiducial exposure, resulting in a \(^{11}\text{C}\) 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 (Fig. 1 top) corresponds to a fiducial exposure of 20\text{409 ton·day}, consisting of data collected between January 13, 2008 and May 9, 2010.

The \(^{11}\text{C}\) surviving the TFC veto is still a significant background. We exploited the pulse shape differences between \(e^-\) and \(e^+\) interactions in organic liquid scintillators [18] [19] to discriminate \(^{11}\text{C}\) \(\beta^+\) decays from neutrino-induced \(e^-\) recoils and \(\beta^-\) 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 \(\gamma\)-rays, which present a distributed, multi-site event topology and a larger average ionization density than electron interactions. An optimized pulse shape parameter was constructed using a boosted-decision-tree algorithm [20], trained with a TFC-selected set of \(^{11}\text{C}\) events (\(e^+\)) and \(^{214}\text{Bi}\) events (\(e^-\)) selected by the fast \(^{214}\text{Bi}\)\text{α-β}\) decay sequence.

We present results of an analysis 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 fiducial volume (FV), i.e. less than 2.8 m from the detector center and with a vertical position relative to the detector center between -1.8 m and 2.2 m. We confirmed the accuracy of the modeling of the detector response function used in the fit by means of an extensive calibration campaign with α, β, γ and neutron sources deployed within the active target.

The distribution of the pulse shape parameter (Fig. 2) was a key element in the multivariate fit, where decays from cosmogenic 11C (and 10C) 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, Geant4-based Monte Carlo simulation, starting with the peripheral structure and propagating the particles into the active volume. We validated the simulation with calibration data from a high-activity 228Th source deployed in the outermost buffer region, outside the active volume. The non-uniform radial distribution of the external background was included in the multivariate fit and strongly constrained its contribution. Neutrino-induced e− recoils and internal radioactive backgrounds were assumed to be uniformly distributed. Fig. 3 shows the radial component of the fit.

We removed α events from the energy spectrum by the method of statistical subtraction. We excluded from the fit all background species whose rates were estimated to be less than 5% of the predicted rate from pep neutrinos in the energy region of interest. Furthermore, we constrained all rates to positive values. The thirteen species left free in the fit were the internal radioactive backgrounds 210Bi, 11C, 10C, 9Be, 40K, 85Kr, and 234mPa (from 238U decay chain), electron recoils from 7Be, pep, and CNO solar neutrinos, and external γ-rays from 208Tl, 214Bi, and 40K. We fixed the contribution from pp solar neutrinos to the SSM predicted rate (assuming MSW-LMA with tan²θ12=0.47±0.05, Δm²23=(7.6±0.2)×10⁻⁵ eV² [22]) and the contribution from 8B neutrinos to the rate from the measured flux [4]. We fixed the rate of the radon daughter 214Pb using the measured rate of 214Bi, 214Po delayed coincidence events.

Simultaneously to the fit of events surviving the TFC veto, we also fit the energy spectrum of events rejected by the veto, corresponding to the remaining 51.5% of the exposure. We constrained the rate for every non-cosmogenic species to be the same in both data sets, since only cosmogenic isotopes are expected to be correlated with neutron production.

Fits to simulated event distributions, including all species and variables considered for the data fit, returned results for the pep and CNO neutrino interaction rates that were unbiased and uncertainties that were consistent with frequentist statistics. These tests also yielded the distribution of best-fit likelihood values, from which we determined the p-value of our best-fit to the real data to be 0.3. Table I summarizes the results for the pep and CNO neutrino interaction rates. The absence of the solar neutrino signal was rejected at 99.97% C.L. using a likelihood ratio test between the result when the pep and CNO neutrino interaction rates were fixed to zero and the best-fit result. Likewise, the absence of a pep neutrino signal was rejected at 98% C.L. Due to the similarity between the electron-recoil spectrum from CNO neutrinos and the spectral shape of 210Bi, whose rate is ~10 times greater, we can only provide an upper limit on the CNO neutrino interaction rate. The 95% C.L. limit reported in Table I has been obtained from a likelihood ratio test with the pep neutrino rate fixed to the SSM prediction under the assumption of MSW-LMA, (2.80±0.04) counts/(day·100 ton), which leads to the strongest test of the solar metallicity. For reference, Fig. 4 shows the full Δχ² profile for pep and CNO neutrino interaction rates.

The estimated 7Be neutrino interaction rate is consis-
TABLE I. The best estimates for the pep and CNO solar neutrino interaction rates. For the results in the last two columns both statistical and systematic uncertainties are considered. Total fluxes have been obtained assuming MSW-LMA and using the scattering cross-sections from [22] and a scintillator $e^-$ density of $(3.307\pm0.003)\times10^{29}$ cm$^{-3}$ ton$^{-1}$. The last column gives the ratio between our measurement and the High Metallicity (GS98) SSM [9].

| Background | Interaction rate | Solar-$\nu$ flux | Data/SSM ratio |
|------------|-----------------|-----------------|----------------|
| $^8$B | $19.7^{+3.5}_{-3.2}$ | 30 $\pm$ 6 | [5] |
| $^{210}$Bi | $55^{+25}_{-23}$ | – | – |
| $^{11}$C | 27.4 $\pm$ 0.3 | 28 $\pm$ 5 | – |
| $^{10}$C | 0.6 $\pm$ 0.2 | 0.54 $\pm$ 0.04 | – |
| $^6$He | < 2 | 0.31 $\pm$ 0.04 | – |
| $^{40}$K | < 0.4 | – | – |
| $^{234}$mPa | < 0.5 | 0.57 $\pm$ 0.05 | – |
| Ext. $\gamma$ | 2.5 $\pm$ 0.2 | – | – |

TABLE II. The best estimates for the total rates of the background species included in the fit. The statistical and systematic uncertainties were added in quadrature. The expected rates for the cosmogenic isotopes $^{11}$C, $^{10}$C and $^6$He have been obtained following the methodology outlined in [25]. The expected $^{234}$mPa rate was determined from the $^{214}$Bi-$^{214}$Po measured coincidence rate, under the assumption of secular equilibrium. Ext. $\gamma$ includes the estimated contributions from $^{208}$Tl, $^{210}$Bi and $^{40}$K external $\gamma$-rays.

Table I summarizes the estimates for the rates of the other background species. The higher rate of $^{210}$Bi compared to [5] is due to the exclusion of data from 2007, when the observed decay rate of $^{210}$Bi in the FV was smallest.

Table III shows the relevant sources of systematic uncertainty. To evaluate the uncertainty associated with the fit methods we have performed fits changing the binning of the energy spectra, the fit range and the energy bins for which the radial and pulse-shape parameter distributions were fit. This has been done for energy spectra constructed from both the number of PMTs hit and the total collected charge in the event. Further systematic checks have been carried out regarding the stability of the fit over different exposure periods, the spectral shape of the external $\gamma$-ray background and electron recoils from CNO neutrinos, the fixing of $^{214}$Pb and $^{222}$Rn to their expected values, and the exclusion of minor radioactive backgrounds (short-lived cosmogenics and decays from the $^{232}$Th chain) from the fit.

Table I also shows the solar neutrino fluxes inferred from our best estimates of the pep and CNO neutrino interaction rates, assuming the MSW-LMA solution, and the ratio of these values to the High Metallicity (GS98) SSM predictions [9]. Both results are consistent with the predicted High and Low Metallicity SSM fluxes assuming MSW-LMA. Under the assumption of no neutrino flavor oscillations, we would expect a pep neutrino interaction rate in Borexino of $(4.47\pm0.05)$ counts/(day·100 ton); the observed interaction rate disfavors this hypothesis at 97% C.L. If this discrepancy is due to $\nu_e$ oscillation to $\nu_\mu$ or $\nu_\tau$, we find $P_{ee}=0.62\pm0.17$ at 1.44 MeV. This result is shown alongside other solar neutrino $P_{ee}$ measurements in Fig. 5. The MSW-LMA prediction is shown for comparison.

We have achieved the necessary sensitivity to provide, for the first time, evidence of the rare 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 the extremely low levels of intrinsic background in Borexino, and the implementation of novel background discrimination techniques. This result raises the prospect for higher precision measurements of pep and CNO neutrino interaction rates, if the next dominant background, $^{210}$Bi, is further reduced by scintillator purification.

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FIG. 5. Electron neutrino survival probability as a function of energy. The red line corresponds to the measurement presented in this letter. The pp and 7Be measurements of $P_{ee}$ given in [5] are also shown. The 8B measurements of $P_{ee}$ were obtained from [3, 4, 25], as indicated in the legend. The MSW-LMA prediction band is the 1σ range of the mixing parameters given in [22].