Going low: measurement of Solar pp-neutrino flux with liquid scintillator detector

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Going low: measurement of Solar pp-neutrino flux with liquid scintillator detector

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Abstract. Recently Borexino collaboration announced the first direct measurement of the low-energy neutrino flux from the pp-reaction in the Sun. Together with previous measurements of solar neutrino fluxes from $^7$Be, $^8$B and pep reactions the measurement completes the study of the neutrino fluxes from the pp-chain of solar reactions. Technical details of the analysis are presented, and results and implications are discussed.

1. Introduction
The solar photon luminosity $L_\odot = 3.846 \times 10^{26}$ W is measured for a precision of 0.4\% \cite{1, 2}. The energy lost by neutrinos adds $L_\nu = 0.023 \cdot L_\odot$ to this value \cite{3}. The solar luminosity constraint on the solar neutrino fluxes can be written as \cite{4}:

$$\frac{L_\odot}{4\pi (1\text{ a.u.})^2} = \sum \alpha_i \Phi_i$$

where 1 a.u. is the average Earth-Sun distance, the coefficient $\alpha_i$ is the amount of energy provided to the star by nuclear fusion reactions associated with each of the important solar neutrino fluxes, $\Phi_i$. The numerical values of the $\alpha$’s are determined to an accuracy of $10^{-4}$ and better.

The estimated uncertainty in the luminosity of the Sun corresponds to less than 3\% uncertainty in total solar neutrino flux.

Because of the relation (1) between the solar photon and neutrino luminosity, the measurement of the total neutrino luminosity will provide a test of the stability of the Sun at the time scale of 40000 years \cite{5}, the time needed for the radiation born at the center of the Sun to arrive to its surface. Finding a disagreement between $L_\odot$ and $L_\nu$ would have significant long term enviromental implications, and in the case of an agreement between the two measurements it would be possible to limit the unknown sources of the solar energy, different from the known thermonuclear fusion of light elements in the pp-chain and CNO-cycle.

The main neutrino sources in the Sun are the pp- and $^7$Be reactions, providing roughly 91 and 7\% of the total neutrino flux respectively. Borexino already measured the $^7$Be neutrino flux with 5\% precision \cite{6}, but till recent time the pp-neutrino flux was derived in a differential measurement using solar detectors data.
A number of projects aiming to perform pp-neutrino detection have been put forward in past two decades, but with all the time passed since the proposals, none of them started the operation facing the technical problems with realization. A possibility to use ultrapure liquid organic scintillator as a low energy solar neutrino detector for a first time was discussed in [7, 8]. The authors come to the conclusion that a liquid scintillator detector with an active volume of 10 tons is an appropriate tool to register the solar pp-neutrino if operated at the target level of radiopurity for Borexino and good energy resolution (5% at 200 keV) is achieved.

2. Solar pp-neutrino flux measurement with Borexino detector

The low-energy range, namely 165-590 keV, of the Borexino experimental spectrum has been carefully analyzed with the purpose of the pp-neutrino flux extraction [9]. The data were acquired from January 2012 to May 2013 and correspond to 408 live days of data taking.

The main features of the experimental spectrum, as can be seen in figure 1, are: a main contribution from the $^{14}\text{C}$ decays at low energies (below 200 keV) and the monoenergetic peak corresponding to 5.3 MeV $\alpha$-particles from $^{210}\text{Po}$ decay. The statistics in the first bins used in the analysis is very high, of the order of $5 \times 10^9$ events, demanding the development of a very precise model for the studies - the allowed systematic precision at low energy part should be comparable to the statistical fluctuations of 0.14%. The development of such a precise model was a main goal of the analysis. The adopted model for the analytical description of the energy response function was verified with MC simulations. It was confirmed that the main contribution to the shape of the response function is defined by the statistical part of the response and can be described well by the scaled Poisson distribution up to the necessary statistics.

As one can see from figure 1 the shapes of contributions to the spectrum from $^{14}\text{C}$ and other background components are quite different from the expected contribution of the electron recoil spectrum from the Solar pp-neutrino. This fact allows the extraction of the Solar pp-neutrino contribution from the data with a spectral fit.

3. Results and Implications

The solar pp-neutrino flux measured by Borexino is $\phi_{pp}(\text{Borex}) = (6.6 \pm 0.7) \times 10^{10}\text{ cm}^{-2}\text{s}^{-1}$, in a good agreement with the combined best fit value of the radiochemical and other solar experiments $\phi_{pp}(\text{other}) = (6.14 \pm 0.61) \times 10^{10}\text{ cm}^{-2}\text{s}^{-1}$ [10]. Both are in agreement with the expected value of $6.0 \times (1.000 \pm 0.006) \times 10^{10}\text{ cm}^{-2}\text{s}^{-1}$.

The survival probability for electron neutrino from pp-reaction is $P_{ee}(\text{Borex}) = 0.64 \pm 0.12$.

Taking into account that Borexino and other experiments measurements are independent, the results can be combined:

$$\phi_{pp} = (6.37 \pm 0.46) \times 10^{10}\text{ cm}^{-2}\text{s}^{-1}.$$  

The electron neutrino survival probability measured in all solar but Borexino experiment is $P_{ee}(\text{other}) = 0.56 \pm 0.08$, combining it with Borexino one we obtain:

$$P_{ee} = 0.60 \pm 0.07,$$

well compatible with theoretical prediction of the MSW/LMA model $0.561^{+0.030}_{-0.022}$.

The total energy production in the solar reactions calculated from the corresponding neutrino fluxes is $(4.04 \pm 0.28) \times 10^{26}\text{ W}\cdot\text{s}^{-1}$ in a good agreement with a total measured $L_\odot = 3.846 \times 10^{26}\text{ W}\cdot\text{s}^{-1}$ [2]. There is not much space left for the unknown energy sources, the 90% C.L. lower limit for the total energy production (conservatively assuming zero contribution from the not-observed reactions) is $L_{\text{tot}} = 3.68 \times 10^{26}\text{ W}\cdot\text{s}^{-1}$. If one assumes that such an unknown source exists, its total power with 90% probability can’t exceed $0.15 \times 10^{26}\text{ W}\cdot\text{s}^{-1}$. In other words no
Figure 1. Borexino energy spectrum between 165 and 590 keV (in black). The pp neutrino component is shown in red, the $^{14}$C spectrum in dark purple and the synthetic pile-up in light purple. The large green peak is $^{210}$Po $\alpha$-decays. $^7$Be (dark blue), pep and CNO (light blue) solar neutrinos, and $^{210}$Bi (orange) spectra are almost flat in this energy region.

more than 4% of the total energy production in the Sun is left for the unknown energy sources, confirming that the Sun shines due to the thermonuclear fusion reactions.

We can conclude that Borexino provided an independent measurement of the Solar pp-neutrino flux, which can be combined with measurements from other solar experiments. A comparison of the neutrino flux from the Sun with Solar luminosity in photons provides a test of the stability of the Sun on the $10^5$ years time scale, and allows to set a limit of no more than 4% of the total power production for the unknown energy sources in the Sun at 90% C.L..

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