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Real-time detection of solar neutrinos with Borexino

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Summary. — Solar neutrinos have been fundamental in the discovery of neutrino flavor oscillations and are a unique tool to probe the nuclear reactions that fuel the Sun. The Borexino experiment, located in the Gran Sasso National Laboratory, is an ultra-pure liquid scintillator detector conceived for the real time spectroscopy of low energy solar neutrinos. Thanks to its unprecedented background levels, Borexino could measure in real time the fluxes of different components of the solar neutrino spectrum, thus probing both solar neutrino oscillations and the Standard Solar Model. We review these fundamental results and also discuss the prospects for the Phase-II of Borexino, which is entering the precision era of solar neutrino measurements.

1. – Solar neutrinos and Borexino

The study of low-energy solar neutrinos with a ultra-pure liquid scintillator technique is relevant both for testing the predictions of the Standard Solar Model and for investigating the MSW-LMA neutrino oscillation scenario in an energy range that is not accessible to water Cherenkov detectors [1, 2]. In fact, up to a few years ago, spectroscopic measurements were performed by water Cherenkov detectors above $\sim 5\,\text{MeV}$ and concerned only ^{8}B neutrinos for less than the 1% of the total flux. The bulk of neutrinos at lower energies were detected only with radiochemical experiments, unable to resolve the individual components. The theoretical spectrum of solar neutrinos is shown in fig. 1.

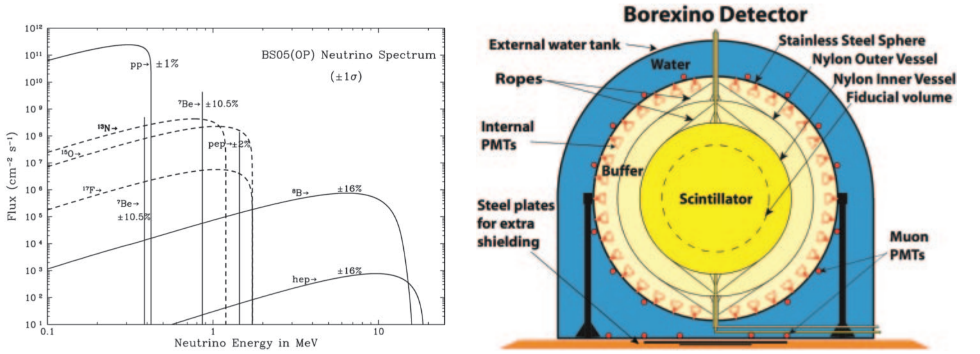

Fig. 1. – Left Panel: Solar neutrino spectrum [5]. Right Panel: Sketch of the Borexino detector.

The original main goal of Borexino [3, 4] was the precise measurement of the rate induced by the monochromatic electron neutrinos (862 keV) produced by the electron capture decay of ^{7}Be in the Sun. However, the very high radio purity of the scintillator made it possible for Borexino to largely exceed the expected performance and broaden the original physics program.

The Borexino detector [6] is sketched in fig. 1. It is located at the Gran Sasso National Laboratories (LNGS) in central Italy, at a depth of 3800 m.w.e. The active mass consists of 278 tons of pseudocumene (PC), doped with 1.5 g/l of PPO. The scintillator is contained in a thin (125 μm) nylon Inner Vessel (IV), 8.5 m in diameter. The IV is surrounded by two concentric PC buffers doped with a light quencher. The scintillator and buffers are contained in a Stainless Steel Sphere (SSS) with a diameter of 13.7 m. The SSS is enclosed in a Water Tank (WT), containing 2100 tons of ultra-pure water as an additional shield against backgrounds from the laboratory environment. The scintillation light released upon particle interaction in the pseudocumene is detected by 2212 8$''$ PhotoMultiplier Tubes (PMTs) uniformly distributed on the inner surface of the SSS. Additional 208 8$''$ PMTs instrument the WT and detect the Cherenkov light radiated by cosmic muons that cross the water shield.

The Borexino scintillator has a light yield of $\sim 10^4$ photons/MeV, resulting in ~ 500 detected photoelectrons/MeV. The fast time response of the scintillating mixture allows to reconstruct the events position by means of a time-of-flight technique with a good precision. The signature of ^{7}Be neutrinos is a Compton-like shoulder at 665 keV in the electron recoil spectrum. The energy resolution (1σ) at the ^{7}Be energy is as low as 44 keV (roughly $5\%/\sqrt{\mathrm{MeV}}$).

2. – Borexino results on solar neutrinos

^{7}Be neutrinos. The measurement of the flux of ^{7}Be neutrinos was the primary goal of Borexino. The first observation was published in the summer of 2007, after only 3 months of data taking. Subsequent refinements of the analysis and increase of statistics brought to a very precise evaluation of the rate of the neutrino-electron elastic scattering interactions from 862 keV ^{7}Be solar neutrinos, which resulted of $46.0 \pm 1.5(\mathrm{stat}) \pm 1.5(\mathrm{syst})$ counts/(day $\cdot$ 100 ton), [7]. This corresponds to a ν_e-equivalent ^{7}Be solar neutrino flux of $(3.10 \pm 0.15) \times 10^9\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and, under the assumption of ν_e transition to other active neutrino flavors, yields an electron neutrino survival probability of 0.51 ± 0.07 at

862 keV. The no flavor change hypothesis is ruled out at 5.0σ. Borexino also investigated the eventual day-night asymmetry in the ^{7}Be solar neutrino interaction rate. The measured asymmetry is 0.001 ± 0.012 (stat) $\pm$ 0.007 (syst) [8], in agreement with the prediction of MSW-LMA solution for neutrino oscillations. This result disfavors MSW oscillations with mixing parameters in the LOW region at more than 8.5σ. This region is, for the first time, strongly disfavored without the use of reactor anti-neutrino data and therefore the assumption of CPT symmetry.

^{8}B neutrinos. Borexino could measure for the first time ^{8}B solar neutrinos with an energy threshold of only 3 MeV. The rate of ^{8}B solar neutrino-induced electron scattering events above this energy in Borexino is 0.217 ± 0.038(stat) $\pm$ 0.008(syst) counts/(day·100 ton [9], which corresponds to a flux of $(2.4 \pm 0.4) \times 10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, in good agreement with the measurements from SNO and SuperKamiokaNDE.

pep and CNO neutrinos. Thanks to the development of novel data analysis techniques for the rejection of the cosmogenic ^{11}C (the main background in the 1–1.5 MeV region), the rate of pep solar neutrino interactions in Borexino could be measured, with the result of 3.1 ± 0.6(stat) $\pm$ 0.3(syst) counts/(day·100 ton) [10]. Also, the strongest constraint on the CNO solar neutrino interaction rate (<7.9 counts/(day·100 ton), at 95% CL [10]), could be obtained. The absence of the solar neutrino signal is disfavored at 99.97% CL, while the absence of the pep signal is disfavored at 98% CL.

pp neutrinos. The pp reaction in the core of the Sun is the keystone process for the energy production and is the source of the largest component of the neutrino flux. Its measurement is a major experimental milestone in solar neutrino physics, and paves the way to a deeper understanding of the Sun dynamics. This measurement was made possible by the very low radioactive background, particularly in ^{85}Kr, achieved after an extensive purification campaign performed in 2010–2011 and thanks to the extremely good performance of the detector as a whole. The solar pp neutrino interaction rate measured by Borexino is 144 ± 13(stat.) ± 10(syst.) counts/(day·100 ton) [11]. The absence of pp solar neutrinos is excluded with a statistical significance of 10σ. Once statistical and systematic errors and the latest values of the neutrino oscillation parameters are taken into account, the measured solar pp neutrino flux is $(6.6 \pm 0.7)\ 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, in accordance with the Standard Solar Model.

3. – Other Borexino measurements

Borexino is a "big" ultra-pure calorimeter and, apart from solar neutrinos, could investigate many other rare processes. Other results include the study of solar and other unknown anti-neutrino fluxes [12], a 5.9σ observation of geo-neutrinos with a 98% CL evidence of a signal from the mantle [13, 14], a measurement of neutrino velocity [15], searches for solar axions [16], experimental limits on heavy neutrinos [17], and a test of the electric charge conservation and electron decay [18].

4. – Outlook

The high impact of Borexino on neutrino physics is very well summarized by fig. 2, where the survival probability of solar neutrinos is plotted as a function of the neutrino energy. For all the solar neutrino components that Borexino measured, the trend is in good agreement with the MSW-LMA prediction.

Apart from the result on the pp solar neutrinos flux, which has been obtained after the purification campaign, all the other solar neutrino components were measured with

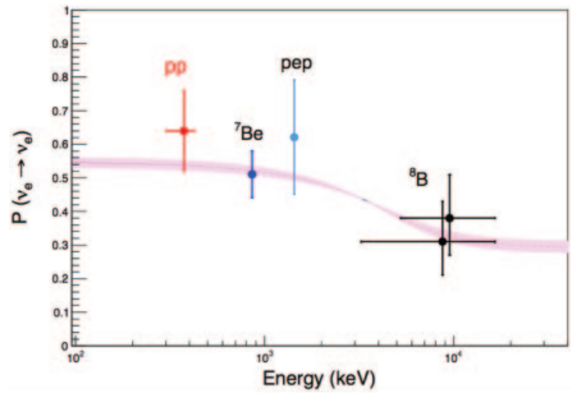

Fig. 2. – Survival probability of electron-neutrinos produced by the different nuclear reactions in the Sun. All the experimental numbers are from Borexino's measurements. The violet band corresponds to the $\pm 1\sigma$ prediction of the MSW-LMA solution.

data sets coming from the so-called Borexino Phase-I [19]. The Phase-II, which started right after the purification campaign at the end of Phase-I, is now close to its end, and this will hopefully lead to a general improvement of all the measurements of the solar neutrino fluxes. Particularly, the efforts of the Collaboration are pushing to achieve the best possible result (either an eventual measurement or an improvement of the limit) regarding the CNO flux determination. This would be of extreme importance, since the CNO flux has not been observed yet, and could solve the Solar Metallicity puzzle [20].

The Borexino detector will also be used to search for sterile neutrinos by means of and artificial anti-neutrino source in the framework of the SOX project [21].

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