Recent results from Borexino

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Abstract. We review the solar neutrinos results of Borexino and the limit on the charge conservation obtained in the context of the analysis of the low energy region of the energy spectrum.

1. Borexino and its physics

The Borexino detector is located in the Laboratory of G. Sasso (Italy) and it is collecting data since May 2007. The active medium is 280 tons of organic liquid scintillator [1] contained within a 100 μm thick nylon transparent bag with 4.25 radius and viewed by about 2000 photomultipliers (PMT). The scintillator acts as a unsegmented calorimeter. It is surrounded by a layer of non scintillating medium [2] and by water working as Cerenkov detector for vetoing muons and muon related events [3].

All the materials used in Borexino were specially selected for extremely low radioactivity and only qualified ultra–clean processes and careful surface cleaning methods were employed for the realization of the whole detector. The record-low level of radioactive purity and the related low background make Borexino a powerful instrument for the measurement of the flux of low energy (1-2 MeV or sub MeV) solar neutrinos and to search for many rare processes.

Solar neutrinos of all flavors are detected by means of their elastic scattering off electrons:

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^- \tag{1}$$

The energy associated to each event (elastic scattering of ν or background due to radiocative decay of residual contaminants) is measured through the number of detected PMT hit or charge. The PMTs work in single photoelectron regime but corrections for multiple hits must be considered.

A detailed calibration [4] with radioactive sources has been performed and it has allowed to establish the energy scale, to study the uniformity of the light collected as a function of the event position and to calibrate the Monte Carlo code and the analytical functions used in the data analysis [5]. Within the 4.25 m sphere a fiducial volume (FV) is software defined through the measured event position, obtained from the PMTs timing data via a time–of–flight algorithm. The choice of the optimal fiducial volume depends on the type of analysis.

The physics sectors on which Borexino provided results or is preparing the data taking are: 1) low energy solar neutrino physics; 2) geoneutrinos; 3) rare processes; 4) sterile neutrinos; 5) supernova detection. The detection of low energy solar neutrinos is the primary goal of Borexino: results and perspectives will be reviewed in the next section. Geoneutrinos detection with more than 3 σ C.L. is reported in [6] and we recently update the results [7] (see [8]). Several limits on rare processes have been established by Borexino [9] thanks to its low background: we will review the most recent one [10] about the charge conservation in the last section. Finally we recall that a measurement about sterile neutrinos is in preparation in Borexino (SOX project) [11] with a antiν radioactive source located below Borexino at short distance from the inner vessel. The data taking is expected to begin within about one year from now. The last item that we want to mention is the potential of Borexino for the detection of neutrinos and antineutrinos from a

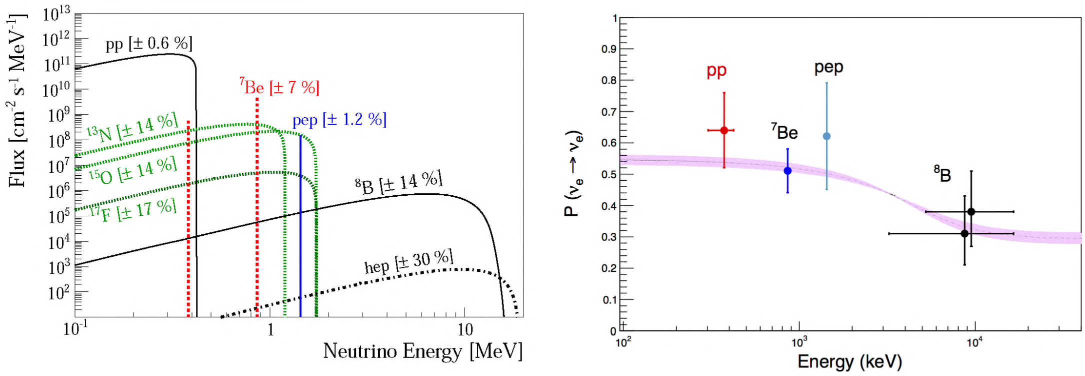

Figure 1. Left panel: Energy spectrum [13] of solar neutrinos. The numbers is parenthesis represent the theoretical uncertainties. For the monochromatic lines the vertical axis reports the flux in cm^{-2}sec^{-1}. Right panel: P_{ee} in the LMA-MSW model with all the Borexino results.

supernova. Liquid scintillator detectors are particularly powerful in the low energy region ([12]). Borexino is part of the SNEWS network.

2. Solar neutrinos physics with Borexino

The construction of the first solar neutrinos detector began about 50 years ago for demonstrating that the Sun is powered by nuclear fusion processes and, surprisingly, the detection of solar neutrinos gave an impressive contribution on the discovery of the phenomenon of neutrino oscillations. This result established a bridge between the fields of astrophysics and fundamental particle physics. The first detectors (radiochemical experiments [15], [19], [20]) only measured the flux of solar neutrinos integrated over the energy of the neutrinos and time of observation (days). The next generation of water Cerenkov detectors [18], [21] preserved the information about the ν energy and the time of its interaction (real time experiments). Presently the real time solar neutrino detection is entered in the phase of precision energy spectroscopy and it has the potential to provide relevant input data both about details of the oscillation phenomenon and about the stellar physics enforcing the link between astrophysics and fundamental particle physics. Borexino is today the only real time detector specifically designed and built to measure the componenents of the flux of solar neutrinos with low energy (around 1-2 MeV and sub-MeV) and that is providing data on the whole solar spectrum.

The Standard Solar Model (SSM) identifies two distinct nuclear fusion processes occurring in the Sun: the main pp fusion chain and the the sub–dominant CNO cycle [13] [14]. Together they yield the neutrino fluxes in Fig. 1. The SSM has been continuously refined during the year including results about cross sections of relevant nuclear reactions at low energy [16]. An important confirmation come from Sun Elioseismology measurements [17]. Over the last decade, the development of three-dimensional radiation hydrodynamic models of the solar atmosphere has determined a revision of the solar composition (metallicity) determined from the analysis of the solar spectrum. Presently there is still open a scientific debate about this metallicity values so that there are basically two main models called High Metallicity and Low Metallicity. The precise measurements of the flux of solar neutrinos can help to resolve the controversy. Neutrinos from the CNO cycle are the ones offering the maximal sensitivity being the CNO flux 40% higher in high metallicity models [13] than in the low metallicity ones [14]. A measurement of solar neutrinos from the CNO cycle has important implications in solar physics and astrophysics more generally, as this is believed to be the primary process fueling massive stars ($>1.5 M_{Sun}$).

Lepton flavor changing neutrino oscillations have been detected by several experiments

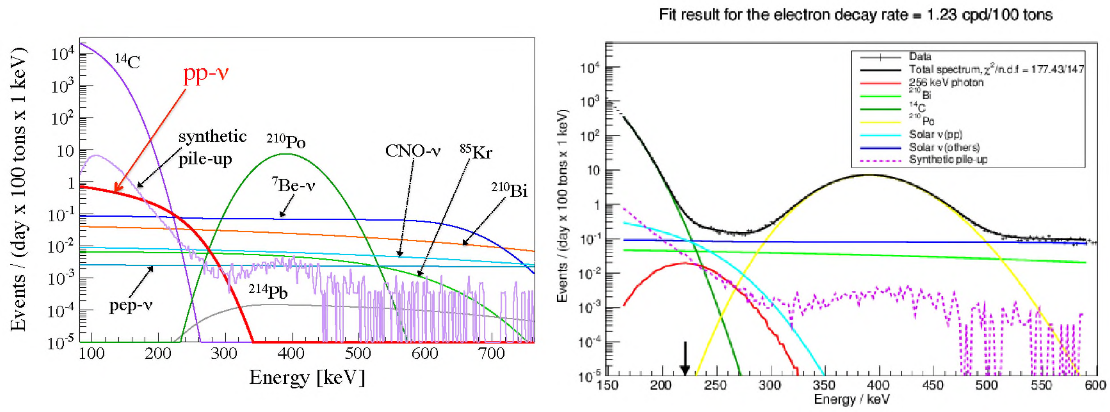

Figure 2. Energy spectrum in the low region used for the pp analysis (left panel) and for the electron decay search. The most prominent features are the ^{14}C β-spectrum (green), the peak at about 400 keV from ^{210}Po α-decays, and the solar neutrinos and the pile-up spectrum. The hypothetical mono–energetic 256 keV γ line is shown in red in the right plot at its 90% exclusion C.L. with an arrow indicating the mean value of the detected energy, which is lower than 256 keV because of quenching.

covering a wide range of source to detector distances and neutrino energies. Two parameters (Δm^2_{12} and θ_{12}) are sufficient to describe well the main features of solar neutrino oscillations [25]: $\Delta m^2_{12} = 7.6{\pm}0.2$ eV^2 and $tan^2\theta_{12} = 0.47^{+0.05}_{-0.04}$. Known as the MSW–LMA (low mixing angle) [23] solution, these two parameters are obtained combining the measurements of high energy ^{8}B solar neutrino fluxes, of the integrated solar neutrino fluxes from radiochemical experiments and the electron flavor survival probability measured versus the distance from the source of antineutrinos from nuclear reactors.

The MSW–LMA model accounts for the interaction of ν in the matter and predicts an energy dependent survival probability P_{ee} of electron solar neutrinos travelling from the Sun to the Earth with two oscillation regimes, in vacuum and in matter, and a transition region in between. MSW flavor transformation is an explicit prediction of the Standard Model and the model of neutrino oscillations. Non standard neutrino interaction models [24] predict P_{ee} curves that deviate significantly from the MSW–LMA particularly between 1 and 4 MeV. Low–energy solar neutrinos are thus a sensitive tool to test the MSW-LMA paradigm measuring P_{ee} versus neutrino energy.

The right panel of figure 1 shows the MSW-LMA prediction of the survival probability for solar neutrinos together with all the Borexino results.

The signal of the ^7Be solar neutrinos is extracted from the data through a fit of the energy spectrum of the events collected within the fiducial volume. There is not special signature other than the shape of the spectrum itself (the Compton like shoulder at 660 KeV) that allows to distinguish the signal from background. The resulting interaction rate [26] is ($R^{^7Be}$=46.0 $\pm$ 1.5 (stat) $^{+1.5}_{-1.6}$ (syst)) cpd / 100 t) corresponding to a ν_e equivalent ^{7}Be solar neutrino flux of (3.10 $\pm$ 0.15) $\times 10^9$ cm^{-2} s^{-1}. The main background is due to the radiocative decay of the isotopes ^{85}Kr, ^{210}Po, ^{210}Bi, and ^{11}C contaminating the scintillator.

The extraction of the pep [27] signal required a more complex analysis to suppress the background and special tools have been developed to suppress the cosmogenic ^{11}C dominating the region around 1-2 MeV. The final result has been obtained through a multivariate approach including a fit of the energy spectrum after the ^{11}C subtraction, the fit of the complementary spectrum, the radial distribution of the events (important to reject the external background which is the only component not uniformly distribuited in the volume) and a particular pulse shape parameter helping in the rejection of the residual ^{11}C. The measured pep interaction rate is $R^{pep} = 3.1 \pm 0.6_{stat} \pm 0.3_{syst}$ and the CNO rate is constrained to $R^{CNO} < 7.9$ cpd/100t at 95% C.L. This is the best current limit on the CNO flux. All details are in [5].

^{8}B solar neutrinos are measured with high statistic by the water Cerenkov detectors. However, despite of the smaller active mass, Borexino can probe the ^{8}B solar ν spectrum with lower energy threshold. A 3 MeV threshold (electron recoil) has been achieved by Borexino [28]. This value is determined by the count rate of γ from the external background particularly the ones of ^{208}Tl with 2.6 MeV energy. Due to the finite energy resolution they give a contribution also at higher energies.

After these results (obtained during a period called called Phase 1) a scintillator purification process, done by means of water extraction and nitrogen stripping, substantially reduced the radioactive backgrounds. In particular, ^{85} Kr concentration is now compatible with zero (from $\simeq$ 35 cpd/100 t in Phase 1), and the ^{210}Bi content was reduced by a factor 4 , to about 20 cpd/100 t. ^{238}U and ^{232}Th concentrations were at a record low, $< 10^{-19}$ g/g.

The full analysis of the new set (called Phase 2) of data is in progress. First results obtained with these Phase 2 data concern the very low energy part of the spectrum (see figure 2): in fact the reduction of all the background has opened the sensitivity to pp neutrinos, the ones that are produced in the primary fusion reaction of 4 protons in the Sun.

The pp neutrino energy spectrum extends up to 420 keV, yielding a maximum electron recoil energy of of 264 keV. The expected interaction rate is 131 ± 2 cpd/100t but most of the signal is hidden by the background due to the β decay of ^{14}C with 256 keV end point. The ^{14}C rate (40 $\pm$ 1 Bq/100t) was determined independently from the main analysis, by looking at a sample of data in which the event causing the trigger is followed by a second event within the acquisition time window of 16 microsec. A particular effort was performed in modeling the pile-up events: occurrences of two uncorrelated events so closely in time that they cannot be separated and are measured as a single event. The spectral shape of pileup events is similar to the pp one: the rate of pile-up events was determined independently, using a data-driven method described in [29].

The low energy region of the spectrum is fitted constraining the rate of the solar neutrinos either than pp at the value found by Borexino in the different energy range or fixed at the prediction of the SSM. The ^{14}C rate and the pileup are constrained at the value found in independent measurements mentioned before. The normalization factors for other background components were mainly left free. The light yield and two energy resolution parameters entering in the analytical model used for the fit are left free. The position of the ^{210}Po is also left free in the analysis, decoupling it from the energy scale. The result is 144 $\pm$ 13 (stat.) $\pm$ 10 (syst.) c.p.d. per 100 t which corresponds to a measured ν flux of (6.6 $\pm$0.7) $\cdot 10^{10}$ $cm^{-2}s^{-1}$.

3. Limit on charge conservation

Conservation of charge is thought to be a fundamental law of nature, so any experiment proving otherwise would upend the standard model of particle physics and perhaps point physicists to new theories.

The tools developed for the pp analysis have offered the possibility to set the best limit on the existence of the decay of the electron without conserving charge into two neutral particles (a neutrino and a photon with 256 keV energy).

The non observation of the 256 γ signal has allowed to set the limit on the lifetime of this decay of $\tau > 6.6 \cdot 10^{28}$ years. This result improves the previous limit by two order of magnitudes. The 256 KeV γ should produce a scintillation signal equivalent to that of one electron with 220 ± 0.4 keV due to the ionisation quenching of the scintillator. Only a fraction of the total response for the mono-energetic 256 keV γ enters into the analysis window above threshold, which makes the signal look similar to the pp-spectrum and produces a strong correlation to it. To break the degeneracy, the pp-neutrino rate can be constrained either by the value measured by experiments other than Borexino or at that predicted by LMA-MSW theory. We chose to use data from radiochemical experiments only to obtain a model- independent result. Then the fit was performed with a procedure similar to the one yielding the pp result.

The sensitivity is such that a 5 σ discovery signal would have been possible with an electron lifetime of $1.9 \cdot 10^{28}$ yr.

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