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Solar Neutrino Results and Future Opportunities with Borexino

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Abstract. The Borexino experiment, located in the Laboratori Nazionali del Gran Sasso in Italy and widely known for its rich Solar Neutrino physics program, has recently celebrated the 10 years of data taking. Among the achievements of the Borexino experiment solar program are: a precision measurement of ^{7}Be neutrino flux with uncertainty of 3%, limit on its day/night asymmetry, first spectral measurement of pp-neutrinos, first evidence of monoenergetic *pep* neutrinos at 5 sigma, ^{8}B neutrinos detection with the lowest visible energy threshold of 3 MeV, observation of season modulation of the ^{7}Be solar neutrino rate at 3.8 sigma and the best current limit on CNO neutrino flux.

Borexino is now in its high-purity Phase II data taking, thanks to intense purification campaigns of scintillator in 2010-11 that were very successful in further reducing the already low backgrounds. The advanced tecniques of data analysis were improved, allowing to maximize the signal/noise ratio. The detector was thermally insulated in order to improve the fluid stability. As an outcome, quality of the data has significantly increased leading to new levels of sensitivity to all solar neutrino fluxes. This allows a more sensitive probe for CNO neutrinos relevant to the solar metallicity problem.

1. Solar neutrino

The stars are powered by nuclear fusion reactions. Two distinct processes are expected to fuel the Sun and produce solar neutrinos with different energy spectra and fluxes: the main *pp* fusion chain, responsible for 99% of solar energy, and the sub-dominant CNO cycle, responsible for 1% of the Sun's luminosity. The study of neutrinos emitted by the Sun with energies below 3 MeV (low-energy solar neutrinos) is a science at the intersection of elementary particle physics

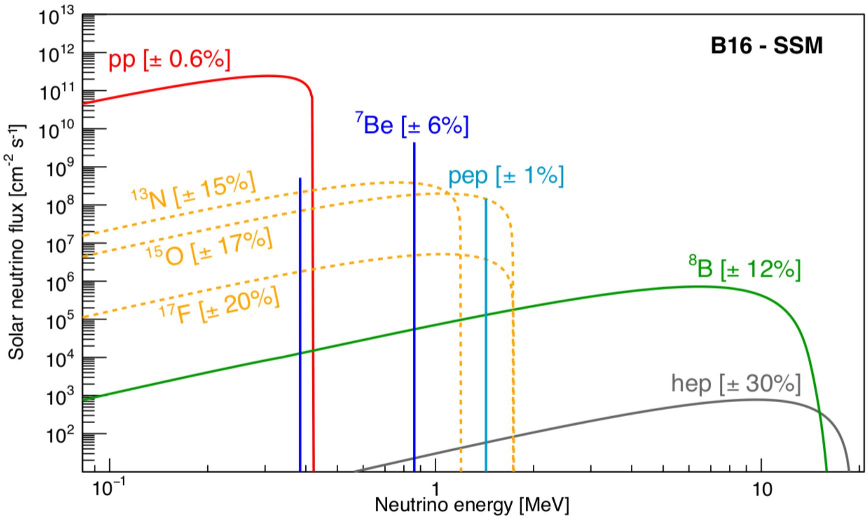

Figure 1. (Figure coloured online) Spectrum of electron neutrinos (ν_e) generated in the core of the Sun. The vertical axis reports the flux in $cm^{-2}s^{-1}(10^3keV)^{-1}$ for the continuous neutrino spectra, while in $cm^{-2}s^{-1}$ for the monochromatic lines (^{7}Be-ν at 384 and 862 keV, shown as dark (blue) lines, and *pep*-ν at 1440 keV, shown as a light grew (light blue) continuous line). The numbers in parentheses represent the theoretical uncertainties on the expected fluxes.

and astrophysics: on one hand these neutrinos allow the study of neutrino properties, and on the other they provide key information for accurate solar modelling. After the successful solution to the *Solar Neutrino Problem*, solar neutrinos continue to play a very important role in the Physics of the Sun. They provide the only currently available method to distinguish between different solar models, and solve the so called *Solar Metallicity Problem*, the recently observed disagreement between the helioseismology and the Sun photosphere observation. The spectrum of electron neutrinos (ν_e) generated in the core of the Sun is shown in Fig.1, resulting both from the reactions of the *pp* chain and the CNO cycle.
Borexino is the only experiment which performed the direct detection of the four main solar neutrino fluxes from the *pp* chain, thereby providing a clear evidence of the transition of the electron neutrino survival probability from vacuum to matter-dominated oscillations in the framework of the MSW-LMA solution. The future Borexino goal is the precision measurement of the CNO neutrino fluxes, that has the highest priority due to its fundamental astrophysical importance.

2. Borexino

Borexino is a real-time large-volume liquid scintillator detector installed in the underground halls of Laboratori Nazionali del Gran Sasso (LNGS) [1]. The bulk of the mountains of the Gran Sasso dItalia, under which the LNGS are located, provide 3600 meters of water-equivalent shielding against cosmic backgrounds. The original main goal of Borexino 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 broaden the original physics program.
The detector is filled with 278 tons of organic liquid scintillator of unprecedented radiopurity, which has the unique possibility to probe solar neutrinos in real time and in the sub-MeV region, but also to detect geo, reactor and supernova antineutrinos.
Its design is based on the principle of ultra-radiopure liquid scintillator and graded shielding

with the inner scintillating core surrounded by concentric vessels of decreasing radio purity from inside to outside. The Borexino detector is sketched in Fig.2.
The active scintillator is a solution of PPO (2,5-diphenyloxazole), which is a wavelength-shifter, at a concentration of 1.5g/l in pseudocumene (PC, 1,2,4 trimethylbenzene). The scintillator is contained in a 125 m thick spherical inner nylon vessel (IV) with 4.25 m radius. A second 5.5 m radius nylon outer vessel (OV) surrounds the IV, acting as a barrier against radon and other background contamination originating from outside. The region between the IV and the OV contains a passive shield composed of PC and a small quantity of DMP (dimethylphthalate), a material that quenches the residual scintillation of PC . The scintillation light is collected by 2212 8 inch PMTs. The scintillator and the PMTs are located inside a 18-meter-diameter stainless steel sphere which is contained in a water Cerenkov tank acting as active muon veto (efficiency greater than 99.99%). The Inner Detector is contained in a tank (9 m base radius, 16.9 m height) filled with ultrapure water. The total liquid passive shielding of the central volume from external radiation (such as that originating from the rock) is thus 5.5 m of water equivalent. The water tank (WT) serves also as an active veto [outer detector (OD)] allowing the detection of the Cherenkov light induced by muons in water. All the materials of the detector internal components (stainless steel, phototubes, cables, light concentrators, nylon) were specially selected for extremely low radioactivity.

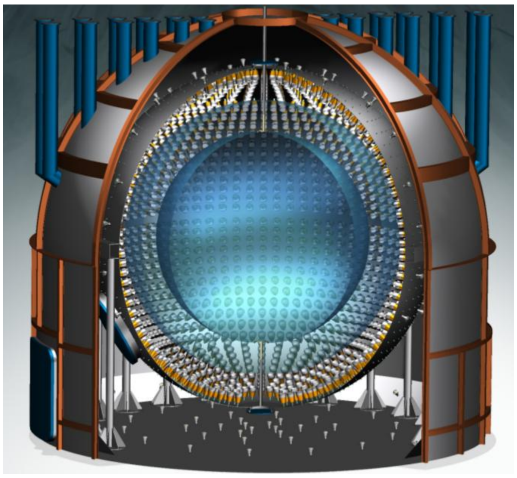

Figure 2. Schematic drawing of the Borexino detector

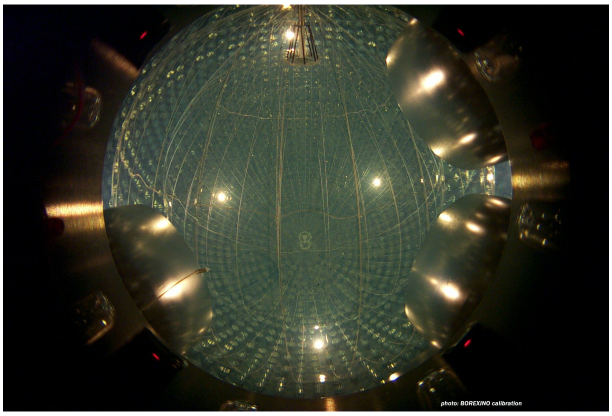

Figure 3. Picture of the Stainless Steel Sphere interior with visible the Inner and Outer nylon vessels and the PMTs.

The Borexino scintillator has a light yield $\sim 10^4$ photons/MeV resulting in 500 detected photoelectrons/MeV. The fast time response ($\sim$3 ns) allows to reconstruct the events position by means of a time-of-flight technique with $\sim$13 cm precision. Depending on the analysis, the fiducial volume is defined between 75 t and 150 t. Neutrinos are detected via elastic scattering on electrons in the target material while antineutrinos are detected thorough the Inverse Beta Decay (IBD) coincidence signal, which is almost background free.

3. Neutrino spectrum and results from PhaseI and Phase II

To measure the complex spectrum observed by Borexino, the analysis technique consists in fitting the spectra expected from both β-decay background contributions and electrons scattered by neutrinos, using the amplitudes as free parameters. From Phase-I [2], several results were achieved from the solar program: first direct spectroscopical observation of neutrino fluxes from ^{7}Be [3] [4] and *pep* [5] chains, new upper limit for neutrinos from CNO cycle [5] and neutrino spectrum from ^{8}B chain with an energy threshold of 3 MeV [6].

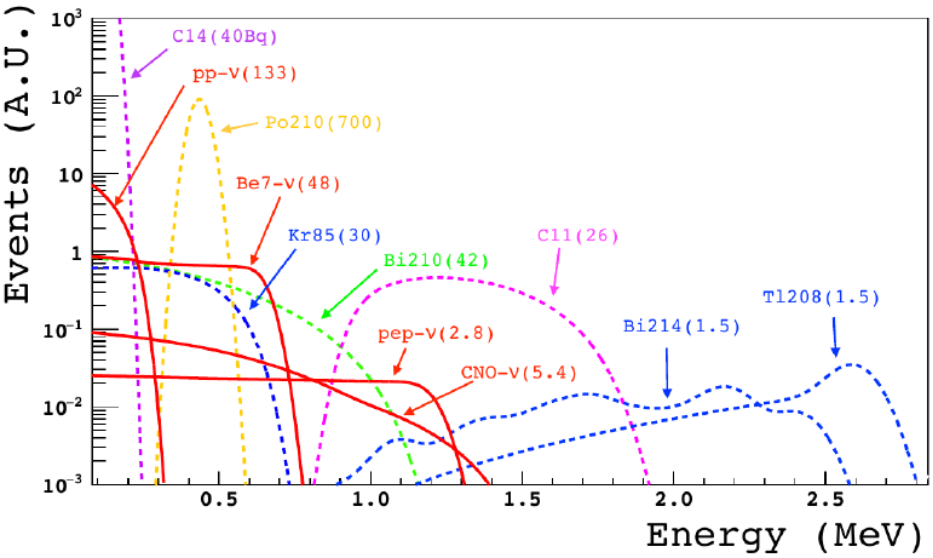

Figure 4. The Borexino detector spectrum components with their typical count rates. Values are expressed in terms of counts per day per 100 tons of liquid scintillator

After theses results, a scintillator purification process, done by means of water extraction and nitrogen stripping, substantially reduced the radioactive backgrounds. These purification campaings allow to achieve an unprecedented level of purity for ^{238}U ($< 9.5 \cdot 10^{-20}$ g/g at 95% Confidence Level) and ^{232}Th ($< 7.2 \cdot 10^{-19}$ g/g at 95% C.L.) and to further reduce the residual contamination of ^{85}Kr and ^{210}Bi by a factor ~ 4.6 and ~ 2.3 respectively. The main components of the Borexino spectrum (both the solar and the background fluxes) are shown in Fig. 4.

With the start of the Phase-II, the first direct measurement of the neutrino flux from the *pp* chain was achieved [7]. Recently, a simultaneous precision spectroscopy of ν-fluxes from *pp*, *pep* and ^{7}Be solar neutrinos is performed with an exposure of 1291.51 days x 71.3 ton [8]. The method used in analysis is the *spectral fit* that consist in the fit of known signal and background spectra to the data spectrum to extract neutrino rates. The presence of residual backgrounds (^{14}C, pile-up, ^{85}Kr, ^{210}Bi, ^{210}Po, cosmogenic ^{11}C, external background) makes it complex to extract the neutrino signal from our data. For this reason a novel technique was developed called *Multivariate fit analysis* (originally developed for *pep*-neutrino analysis in 2012), that includes further variables in the analysis fit: this allows to separate electron spectra from the overwhelming contribution of ^{11}C. The fit is then performed with a multivariate approach, fitting simultaneously two energy spectra (one with ^{11}C tagged and one with ^{11}C vetoed), the pulse shape discrimination variable (for β^{+}/β^{-} separation) and the radial distribution of the events (in order to decouple the uniformly distributed neutrino-like events from the external gammas). These results, together with a new ^{8}B measurement [9] and their implications (more stringent confirmation of the Solar Standard Model and the MSW-LMA , favouring the high metallicity assumption but not yet excluding the low metallicity scenario), have been published last year.

4. CNO challenge

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. This will provide the direct determination of the composition of the solar core being directly related to the abundances of C and N nuclei in the Sun, and clues for the solution of the *Solar Metallicity Problem*.
The total CNO solar neutrino flux is similar to the *pep* neutrino one (see Fig.**??**), but its predicted value is strongly dependent on the inputs of the solar modelling, being 40% higher in the High Metallicity than in the Low Metallicity solar model. The solar neutrino fluxes measured by Borexino agree, within the errors, but cannot distinguish between the two metallicities, due to the uncertainties of the model and the experimental errors. On the contrary, with a realistic CNO measurement it could be possible to determine the solar core composition because its neutrinos are the most sensitive to the difference in metallicity.
Despite the unprecedented low levels of background reached in the detector the CNO solar neutrinos detection remains a very challenging task because the expected flux is relatively low, with a continuous energy spectra with endpoints at 1.73 MeV. Moreover, since they are not monocromatic like the ^{7}Be and *pep* neutrinos, it is not possibile to distinguish them from the background by detecting the characteristic Compton-like edge in the ν_e-e scattered energy spectrum. In particular, the main background comes from ^{210}Bi, an emitting daughter of ^{210}Pb, whose β decay spectrum spans the energy range of interest for the CNO neutrinos signal and they are almost degenerate (Fig.**??**) so that spectral fits are only able to determine ^{210}Bi+CNO contribution.
A realistic measurement of CNO neutrinos can be performed only using a multivariate spectral fit on the ^{11}C subtracted spectrum (through the method of threefold coincidence) supported by a sensitive pulse shape discrimination between α and β for the ^{210}Po, and between e^+ and e^- for the ^{11}C beta emission. The ^{210}Bi background can be reduced by further purifications of the scintillator, but anyway it must be also constrained independently by measuring the rate of decay of the daughter nucleus, the ^{210}Po. The difficulty of this analysis lies both in the low signal to noise ratio and in the contamination of the ^{210}Po in the vessel, which diffuses towards the center of the detector. Such transport was strongly suppressed after the detector was equipped with thermal insulation yet this effect remains non-negligible.

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