PROCEEDINGS OF SCIENCE

Borexino: from the Sun to the Earth

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Borexino is a liquid scintillator detector primary designed to observe solar neutrinos. Thanks to the intrinsic radiopurity achieved in the scintillator, Borexino already measured the rate of neutrinos coming from the *pp*, *pep*, ^{7}Be and ^{8}B processes which take place inside the Sun. Due to its low background level as well as its position in Italy, a nuclear free country, Borexino is also sensitive to geo-neutrinos. Borexino is leading this interdisciplinary field of neutrino geoscience by studying electron antineutrinos which are emitted from the decay of radioactive isotopes present in the crust and the mantle of the Earth.

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1. From the Sun...

Borexino is a liquid scintillator detector, located in the Laboratory Nazionali del Gran Sasso, primary designed to observe solar neutrinos. A special effort made on the radiopurity allowed to achieve a 10^{-18} g contamination on ^{238}U and ^{232}Th per gram of liquid scintillator, making low energy solar neutrinos accessible.

Solar neutrinos are electron neutrinos which are produced inside the Sun by nuclear reactions. They are detected through their elastic scattering on electrons inside the liquid scintillator target of the detector. The components of the solar neutrino energy spectra, from the ^{8}B, the ^{7}Be and the *pep* processes, have been measured by Borexino in the past years. Details on such results can be found in [1, 2, 3] and are summarized in Figure 1 (*left*).

I will focus on the latest result achieved by Borexino, the real time measurement of the *pp* neutrinos [4], which represents a new milestone in solar neutrino spectroscopy since they contribute to almost the entire solar neutrino flux.

The dominant background in the *pp* neutrinos energy region of observation, *i.e.* below $\sim$ 400 keV, is the ^{14}C β decay with a rate of 40 Bq per 100 ton, more than 20,000 higher than the expected signal from *pp* neutrinos. Such a high rate is also responsible of an important pile-up effect, whose rate is of the same order of magnitude of the signal.

Figure 1 (*left*) shows the energy spectra for both solar neutrino and radioactive background components. With a data set taken from January 2012 to May 2013, the *pp* solar neutrino interaction rate has been found to be 144 ± 13 (stat) ± 10 (syst) counts/(day $\times$ 100 ton). The Borexino result on *pp* neutrinos agreed with the prediction of the Standard Solar Model (SSM) with the MSW-LMA oscillation solution. The probability that *pp* neutrinos are not transformed into muon or tau neutrinos has been found to be $P(\nu_e \rightarrow \nu_e) = 0.64 \pm 0.12$ and is reported in Figure 1 (*right*).

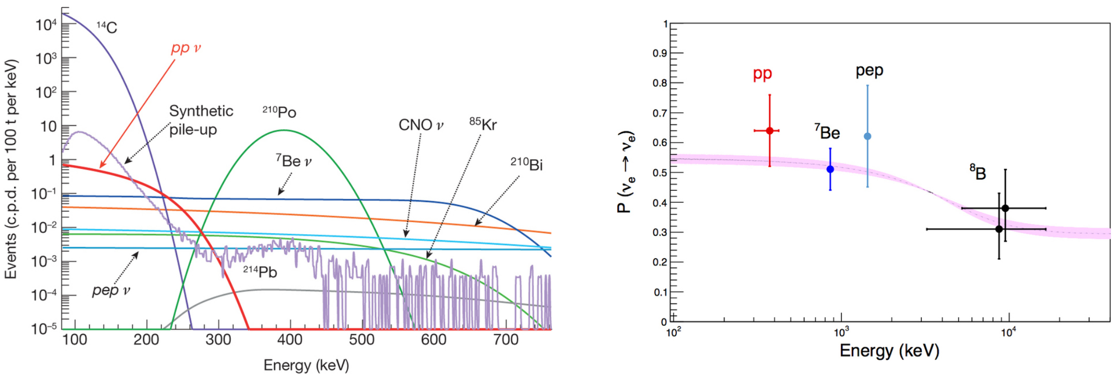

Figure 1: (*left*) Energy spectra for both solar neutrino and radioactive background components, from [4]. At low energy, ^{14}C and pile-up events represent the main contamination when looking for *pp* neutrinos. (*right*) Survival probability of electron neutrinos produced by different processes, from [4]. The violet band corresponds to the ± 1 σ prediction of the MSW-LMA oscillation solution.

2. ... to the Earth

The extremely low contamination allowed also to look for neutrinos produced in the Earth, the so-called geo-neutrinos [5, 6]. Geo-neutrinos are electron antineutrinos which are produced by the decay of radioactive isotopes present in the crust and the mantle of our planet. The interdisciplinar field of neutrino geoscience aims to take advantage of the neutrino experiments to study the Earth interior with these direct messengers. Due to its low background level as well as its position in Italy, a nuclear free country, Borexino is leading this interdisciplinary field.

The detection of geo-neutrinos in Borexino relies on the signature of the inverse β decay (IBD) reaction $\bar{\nu}_e + p \to e^+ + n$ where the positron, the "prompt" signal, is followed by the neutron capture on hydrogen, the "delayed" signal. The prompt and the delayed signals are correlated in space and time, allowing to accurately identify electron antineutrino signal. With an IBD threshold of 1.806 MeV, only geo-neutrinos coming from the decays of ^{238}U and ^{232}Th chains can be detected.

Despite being in a nuclear free country, the dominant background remains electron antineutrinos emitted by nuclear reactors, mostly those present in the countries close to Italy. It is nonetheless possible to estimate the expected number of nuclear reactors events, N_{react}, as follows:

$$N_{\mathrm{react}} = \sum_{r=1}^{R}\sum_{m=1}^{M}\frac{\eta_m}{4\pi L_r^2}P_{rm} \times \int \mathrm{d}E_{\bar{\nu}_e}\sum_{i=1}^{4}\frac{f_i}{E_i}\phi_i(E_{\bar{\nu}_e})\sigma(E_{\bar{\nu}_e})P_{ee}(E_{\bar{\nu}_e}, L_r), \tag{2.1}$$

where r runs over the number of nuclear reactors R considered, m runs over the number of months M considered, η_m stands for the exposure in month m and includes detector efficiency, L_r is the detector-reactor distance, P_{rm} is the effective thermal power of reactor r in month m, i runs over the spectral components of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu, f_i is the power fraction of component i, E_i the average energy released per fission of component i, $\phi_i(E_{\bar{\nu}_e})$ the antineutrino energy spectrum per fission of component i, $\sigma(E_{\bar{\nu}_e})$ the IBD cross section and $P_{ee}(E_{\bar{\nu}_e}, L_r)$ the survival probability of the emitted antineutrinos of energy $E_{\bar{\nu}_e}$ created at distance L_r.

Other backgrounds can mimick an IBD reaction in Borexino, such as accidental coincidences, (α,n) background which depends on the ^{210}Po rate or cosmogenic background such as ^{9}Li and ^{8}He. All these backgrounds together appear to be of the order of 100 less abundant than antineutrino candidates, making Borexino an almost background-free experiment for antineutrinos search.

Between December 2007 and August 2012, Borexino observed 46 antineutrino candidates. Figure 2 shows the prompt energy spectrum of these candidates. Since antineutrinos from nuclear reactors and geo-neutrinos can not be distinguished by the selection cuts, we performed an unbinned maximal likelihood fit of the prompt energy spectrum of the 46 antineutrino candidates. The best fit values have been found to be $N_{\mathrm{geo}} = 14.3 \pm 4.4$ events and $N_{\mathrm{react}} = 31.2^{+7.0}_{-6.1}$ events. This results allowed to exclude the null geo-neutrino signal at 4.4 σ.

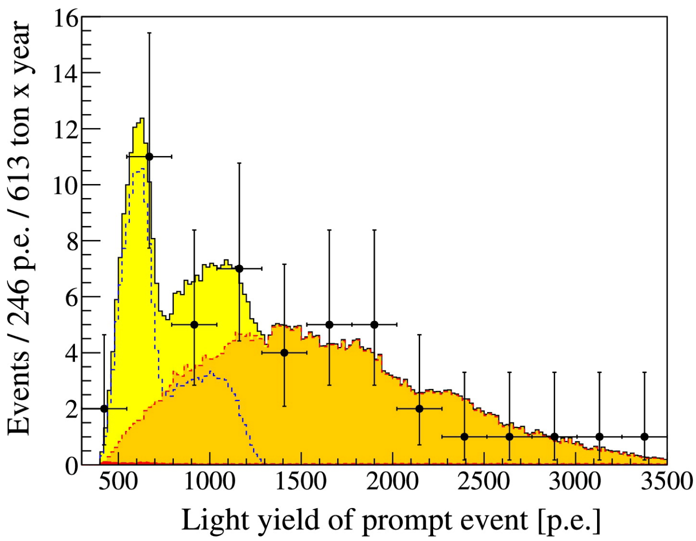

Figure 2: Prompt energy spectrum of the 46 antineutrino candidates, from [6]. The dashed blue line (dashed red line) corresponds to the geo-neutrino signal (antineutrino from nuclear reactors signal) from the fit.

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