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# Observation of neutrinos from sun and earth with the BOREXINO detector

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BOREXINO is a large organic liquid scintillation experiment located in the Italian Gran Sasso underground laboratory. The extremely high radio-purity of the interior of the detector allows the real-time detection of rare neutrino fluxes at low energies. For the solar $^7$Be-neutrino flux an event rate of $(49 \pm 3_{stat} \pm 4_{syst})$ counts/(d·100 t) was found. The $^8$B-flux could be measured with the lowest ever achieved threshold of 3 MeV. The result is $(0.22 \pm 0.04_{stat} \pm 0.01_{syst})$ counts/(d·100 t). BOREXINO has also detected anti-neutrino from European nuclear reactors and from the earth. For geo neutrinos a clear observation with 4.2 $\sigma$ evidence was accomplished. The experiment is now preparing for precision measurements and for the detection of yet unobserved lower intensity neutrino fluxes.

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## 1. Introduction

BOREXINO is a large volume liquid scintillator detector which is located deep underground ($\approx 3500$ meters of water equivalent, m w.e.) in hall C of the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. The main goal of the experiment is the study of nuclear fusion reactions in the sun by the observation of low energy solar neutrinos, in particular $^{7}$Be-neutrinos [1]. Neutrinos are detected by means of their elastic scattering off electrons in the liquid scintillator. The recoil energy is converted into scintillation light which is then collected by 2212 photomultiplier tubes (PMTs). The unprecedented characteristics of the BOREXINO detector make it also very competitive in the detection of anti-neutrinos from geophysical origin and from nuclear reactors as well as in the search for rare nuclear phenomena.

The standard solar model predicts interaction rates of a few tens of counts per day for solar $^{7}$Be-neutrinos for about 100 tons of target material. This corresponds to an equivalent radioactivity of nBq/kg. Therefore, the core of BOREXINO must be extremely radio-pure. To achieve this goal the design of the detector (see Figure 1) is made following a graded shield concept such that the interior is best shielded from environmental radioactivity. Moreover, a careful selection of construction materials by means of low background screening techniques was accomplished [2]. Finally, dedicated purification plants for gases and liquids were designed and installed next to the BOREXINO detector. To prove that the demanding radio-purity requirements can be met, a 4 tons prototype of BOREXINO, the Counting Test Facility (CTF) [3], was built and operated since 1995. The CTF played a key role in the demonstration of the feasibility of BOREXINO.

## 2. Detector performance

The effective light yield of the BOREXINO scintillator (pseudocumene (PC) with a small admixture of the fluor PPO) is about 500 photoelectrons (pe's) per MeV deposited energy which is consistent with the expectations [4]. An event is recorded when a certain number of PMTs (usually 25) detect at least one pe in a 60 ns time window. The readout sequence is also activated when at least 6 of the 208 PMTs of the outer Cherenkov detector detect light in a 150 ns time window. The typical trigger rate is $\approx 30$ Hz, largely dominated by low energy $^{14}$C events.

BOREXINO is designed such that external background is shielded by ultra-pure water in the outer detector and by pseudocumene (PC) doped with the light quencher DMP in the buffer. However, there are still external background events in the outer region of the inner vessel mostly due to radio-impurities in the PMTs. To suppress these events a fiducial volume cut is applied. The position of an event is reconstructed using a photon time of flight method. The spatial resolution was found to be $(13 \pm 2)$ cm in x and y coordinates and $(14 \pm 2)$ cm in z direction at the relatively high energies of the $^{222}$Rn progenies $^{214}$Bi and $^{214}$Po. For the $^{7}$Be analysis it is required that reconstructed events are contained in a spherical volume corresponding to approximately 1/3 of the total inner vessel volume. Moreover, a cut in z direction is performed to remove events from background sources near the poles of the vessel. The fiducial mass obtained in this way is 78.5 t [5]. Further cuts are applied to the raw data: i) Muon cut: If the outer detector trigger fires (indicating a muon) the event is not used. ii) After a muon crosses the detector all events within a 2 ms time window (after-pulses and spurious events) are rejected. The rate of such events is measured

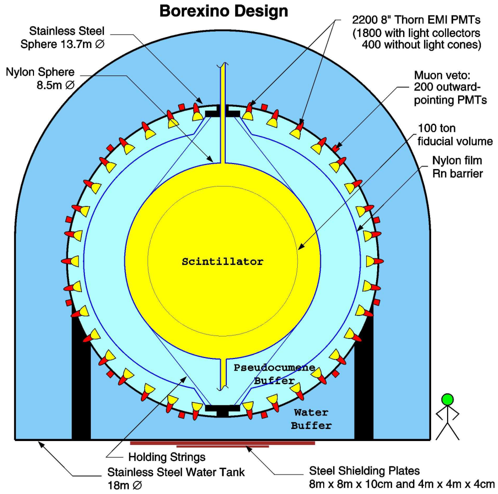

**Figure 1:** Sketch of the BOREXINO detector.

to be $(0.055 \pm 0.002)\ \mathrm{s}^{-1}$, thus, the introduced dead time is negligible. iii) After a $^{214}$Bi-$^{214}$Po coincidence event all events which have occurred in the preceding three hours in a sphere of 85 cm radius around the $^{214}$Bi-$^{214}$Po event are eliminated to remove the other $^{222}$Rn progenies. Another important feature for background reduction is the alpha/beta-discrimination which was extensively studied with the CTF [6]. The scintillation signal created by an alpha decay in the BOREXINO scintillator mixture has a longer tail than the signal from a beta decay. This can be exploited by discrimination procedures like e.g. the Gatti optimum filter [6].

## 3. Backgrounds

Backgrounds in BOREXINO are estimated by exploiting unique signatures in the respective decays or by a spectral fit. Figure 2 shows the raw data spectrum (black line), the spectrum after the cuts explained above (blue line) and after the statistical alpha/beta subtraction (red line).

The low energy part of the spectrum is dominated by the continuous $^{14}$C beta spectrum (endpoint: 156 keV). Due to the limited energy resolution and pile-up events the spectrum reaches to energies slightly above 200 keV. The fit yields a $^{14}$C/$^{12}$C-ratio of $2.7 \cdot 10^{-18}$ which is very similar to what was measured earlier with the CTF in different PC samples. The second prominent peak is the alpha peak at $\approx 200$ photoelectrons, which is due to $^{210}$Po. $^{210}$Po is an alpha emitter with an energy of 5.4 MeV, however, due to the light quenching effect of alpha-particles in the scintillator the apparent energy is roughly 400 keV. It is evident that $^{210}$Po is not in equilibrium with its progenitors $^{210}$Bi and $^{210}$Pb, as one does not see the $^{210}$Bi beta spectrum (endpoint: 1.2 MeV) in Figure 2. The rate of $^{210}$Po (half-life 138 days) at the beginning of data taking was $\approx 60$ counts/d/t.

At higher energies (above $\approx 400$ photoelectrons) the $^{11}$C positron spectrum is visible. $^{11}$C is produced in situ by nuclear reactions induced by residual cosmic ray muons crossing the detector. The rate obtained by the fit is $(25 \pm 1_{stat} \pm 2_{syst})$ counts/(d$\cdot$100 t) [5]. This is higher than what was measured with a smaller amount of scintillator ($\approx 4$ tons) in the CTF $(13.0 \pm 2.6_{stat} \pm 1.4_{syst})$ counts/(d$\cdot$100 t) [7] and higher than derived from a dedicated beam experiment [8].

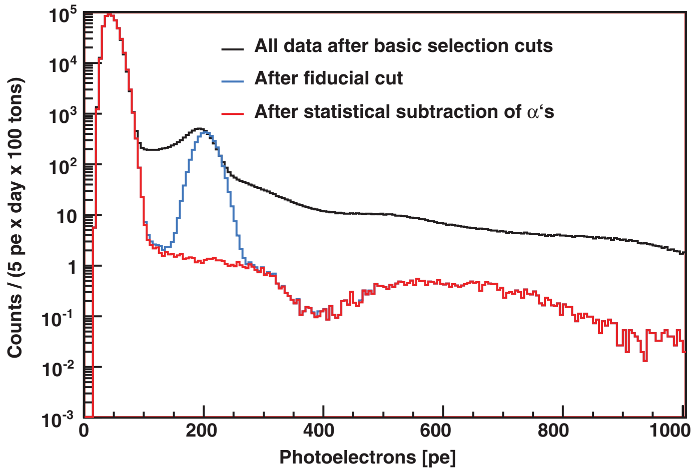

**Figure 2:** Raw data spectrum (black line) and the spectrum after the fiducial cuts with (red line) and without (blue line) alpha/beta discrimination.

The background due to $^{222}$Rn is evaluated using the characteristic $^{214}$Bi-$^{214}$Po-coincidence signature. If secular equilibrium was established the measured rate would corresponds to an uranium concentration of $(1.6 \pm 0.1) \cdot 10^{-17}$ g/g in the scintillator. Also the $^{232}$Th decay chain features a fast coincidence ($^{212}$Bi-$^{212}$Po) which can be used for tagging. Here the thorium concentration (again assuming secular equilibrium) is even lower. The measured number is $(6.8 \pm 1.5) \cdot 10^{-18}$ g/g.

Another fast coincidence tag is present in the $^{85}$Kr decay scheme, however, only with a small branching ratio of 0.43 %. Currently, the best estimate for the initial $^{85}$Kr decay rate is $(29 \pm 14)$ counts/(d·100 t). A better estimate is obtained from the fit of the $^{85}$Kr beta spectrum to the data. Although the spectrum covers a similar energy range as the $^{7}$Be-neutrino recoil spectrum, it can be disentangled due to the different shape. We got a result of $(25 \pm 3_{stat} \pm 2_{syst})$ counts/(d·100 t).

The extremely low radioactive background in BOREXINO, which was never achieved before, allows a broadening of the scientific scope of the experiment. Its solar neutrino physics program covers now also the observation of $^{8}$B-neutrinos and aims for the study of pep-, CNO- and, possibly, pp-neutrinos.

## 4. Results

The BOREXINO collaboration has published two articles about the observation of solar $^{7}$Be-neutrinos. The first real time detection was reported few months after the start of data taking [4]. At that time a result of $(47 \pm 7_{stat} \pm 12_{syst})$ counts/(d·100 t) was measured. In the second publication [5] after 192 days of live time, both, the statistical and the systematic uncertainties could be reduced. Figure 3 shows the spectrum after all cuts and the best fit. The Compton-like edge of the $^{7}$Be-neutrino recoil spectrum is clearly visible around 650 keV. It corresponds to an interaction rate of $(49 \pm 3_{stat} \pm 4_{syst})$ counts/(d·100 t). The systematic uncertainty is dominated by two effects: The fiducial mass and the detector response which can both be significantly improved by a detector calibration with radioactive sources (see section 5).

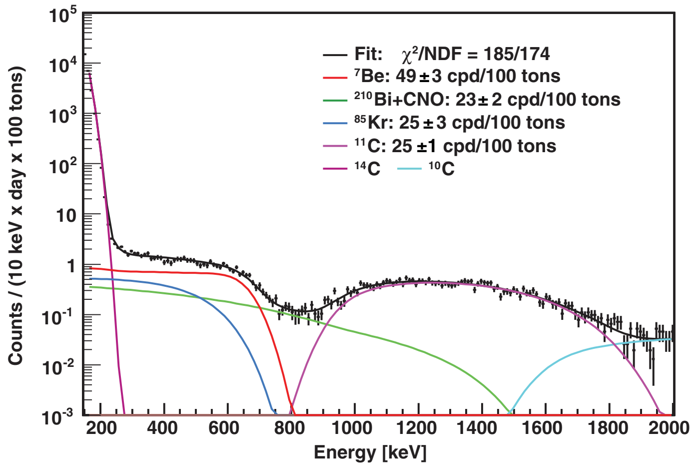

**Figure 3:** Measured energy spectrum (192 days of live time) after fiducial cut and alpha/beta-discrimination and the best fit with its individual contributions.

The data obtained until now are well in agreement with the theoretical expectations by the standard solar model and neutrino flavor conversion in vacuum and matter. The no oscillation hypothesis can be rejected by BOREXINO at a 4 $\sigma$ level [5]. Our results can be combined with results of other solar neutrino experiments, which have measured at different energies, to determine the pp-neutrino flux. As illustrated in [5] the ratio $f_{pp}$ between the measured and the predicted pp-neutrino flux is $f_{pp} = 1.04^{+0.13}_{-0.19}$. Moreover, if the well known solar luminosity is constrained, one gets $f_{pp} = 1.005^{+0.008}_{-0.020}$ which is the most precise result obtained so far. Similar investigations for the CNO-flux show that the CNO-cycle contributes with less than 3.3 % to the solar neutrino luminosity.

Meanwhile, a preliminary analysis of the day-night asymmetry of the solar neutrino flux was performed. The asymmetry parameter between the rate at day D and at night N was found to be $A_{DN}$=2·(N-D)/(N+D)=$-0.007 \pm 0.073$. The absence of a day-night asymmetry allows BOREXINO alone to exclude the so-called LOW solution of the MSW effect at a 3 $\sigma$ level.

The solar $^8$B-neutrino flux was intensively studied above $\approx$ 5 MeV by water Cherenkov detectors. BOREXINO was able to push down the threshold to 3 MeV [9]. Background sources in that region are $^{214}$Bi and $^{208}$Tl contaminations, high energy gamma rays from neutron capture, decay of cosmogenic isotopes and residual cosmic muons. The contribution of all these backgrounds and possible discrimination techniques were studied in [9]. Finally, a count rate of $(0.22 \pm 0.04_{stat} \pm 0.01_{syst})$ counts/(d·100 t) from $^8$B-neutrino interactions could be derived for an energy threshold of 3 MeV. This is again in agreement with the theoretical predictions. If the high-Z abundance standard solar model [10] is chosen, the result can be converted in an averaged electron neutrino survival probability for $^8$B-neutrinos. At their mean energy of 8.9 MeV the result is $\bar{P}_{ee}$=$(0.29 \pm 0.10)$. The same can be done for the mono-energetic $^7$Be-neutrino flux, for which one obtains $P_{ee}$=$(0.56 \pm 0.10)$ [4]. BOREXINO is thus the only experiment so far which sees at the same time vacuum-dominated neutrino oscillations (at low energies) and the matter-induced suppression (at high energies). The results are plotted in Figure 4. Considering that the systematic error due to the fiducial mass determination affects the two data points in the same way, their ratio differs from unity by 1.9 $\sigma$.

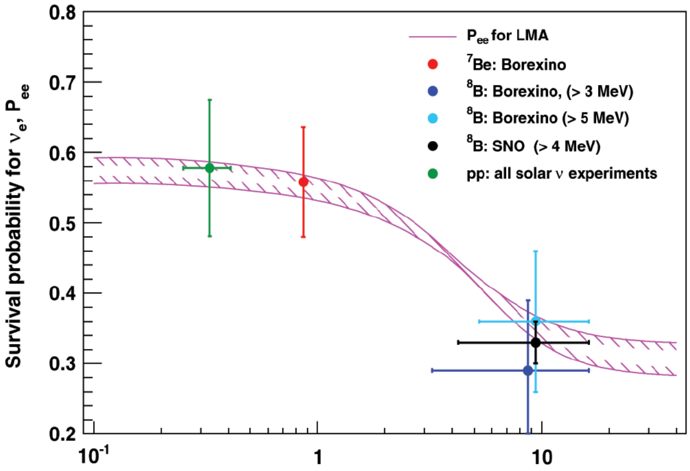

**Figure 4:** The survival probability for solar electron neutrinos measured by BOREXINO simultaneously at low energies and high energies.

In BOREXINO electron anti-neutrinos can be detected via the inverse beta decay $\bar{\nu}_e + p \rightarrow n + e^+$ with an energy threshold of 1.8 MeV. The positron is stopped and annihilates emitting two 511 keV gamma quanta yielding a prompt event with a visible energy $E_{prompt}$=$E_{\bar{\nu}_e} - 0.782$ MeV. Subsequently, the free neutron is captured on a proton after a mean time of approximately 256 $\mu$s resulting in the emission of a 2.2 MeV gamma ray. The characteristic time and spatial event pattern offers a clean signature for $\bar{\nu}_e$ events. Due to the unprecedented low background of BOREXINO the accidental coincidence rate is sufficiently small to detect few anti-neutrino events per year with an excellent signal to noise ratio. Residual muon-induced background can be suppressed to a similarly low level by dedicated cuts [11].

Terrestrial electron anti-neutrino are emitted from nuclear power plants (reactor neutrinos) and from the decay of long-lived radioisotopes in the earth (geo neutrinos). The absence of nuclear power plants in Italy offers a unique possibility for geo neutrino detection with BOREXINO. With an exposure of 252.6 ton year the prompt positron event spectrum shown in Figure 5 was obtained [11]. The best estimate for the number of reactor neutrino events is $10.7^{+4.3}_{-3.4}$ and for geo neutrino events $9.9^{+4.1}_{-3.4}$, while the background is negligible. The results imply an observation of geo neutrinos at 4.2 $\sigma$ and a geo neutrino reaction rate of $3.9^{+1.6}_{-1.3}$ events/(100 ton·year) which is compatible with geochemical BSE models [11]. The reactor neutrino rate is in agreement with the expectation if the suppression due to neutrino oscillations is included.

The BOREXINO collaboration has also performed a search for anti-neutrinos from the sun and from hypothetical other sources [12]. Compared to the larger KamLAND experiment BOREXINO benefits from its much lower reactor anti-neutrino background. Best limits were obtained for unknown anti-neutrino sources in the energy region between 1.8 MeV and 17.8 MeV. For the special case of the solar $^8$B-neutrino flux the fraction of $\bar{\nu}_e$ in that flux could be limited to $< 1.3 \cdot 10^{-4}$ (90 % C.L.) assuming an undistorted $^8$B-neutrino spectrum. Finally, BOREXINO has performed a search for decays which would violate the Pauli exclusion principle. New limits could be set for various hypothetical decay modes of $^{12}$C nuclei [13].

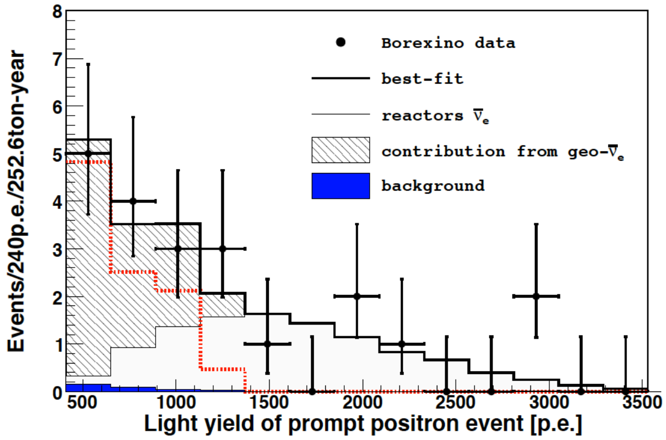

**Figure 5:** Results of the BOREXINO anti-neutrino search after an exposure of 252.6 ton·year.

## 5. Recent activities and outlook

The next goal of BOREXINO is a precise measurement of the $^7$Be-flux. This is achieved by collecting more statistics and by a thorough detector calibration with light sources and radioactive sources. In 2008 the calibration campaigns started with an on-axis calibration and were followed in 2009 by a series of comprehensive off-axis calibrations in which different alpha-, beta-, gamma- and neutron-sources were placed at more than 200 various positions inside the inner vessel. The obtained data is used to reduce remaining systematic uncertainties, in particular the energy response function of the detector and the determination of the fiducial volume. Together with the accumulated statistics a 5 % precision measurement of the $^7$Be neutrino flux seems possible.

Another ambitious goal of BOREXINO is the direct detection of the solar pep and CNO neutrinos with an endpoint energy of 1.44 MeV and 1.73 MeV, respectively. Although the expected event rate is in the order of 1 count/d in 100 tons it may be detectable due to the ultra-low radioactive background in the detector. However, the muon-induced positron emitter $^{11}$C (half-life 20.38 min) is a remaining source of background in the region of interest. Since a neutron is emitted in most cases in which a $^{11}$C is produced [14], the latter may be tagged by a threefold coincidence technique between the primary muon, the subsequent neutron capture (releasing a 2.2 MeV gamma ray) and the decay of $^{11}$C itself. The main challenge is the optimization of the applied cuts in order to minimize the mass-time fraction loss. The inclusion of the reconstructed muon track in the analysis helps to further minimize the mass-time fraction loss. It leads to the definition of a cylindrical volume around the track intersecting with the spherical one centered on the 2.2 MeV gamma rays. The applied techniques can efficiently remove $^{11}$C events (up to 90%) while minimizing the fraction of lost data.

Another potential background component are external gamma rays (mostly from PMTs and light concentrators) penetrating into the fiducial volume. The spectral shape of that background was studied by a non-invasive external calibration, in which a MBq $^{228}$Th source is placed from the outside in close neighborhood to the PMTs. For this purpose a custom-made $\sim$ 5 MBq $^{228}$Th source was developed. By replacing the ceramics in the source with gold the neutron emission rate due to ($\alpha$, n)-reactions could be reduced to about 7 neutrons per second minimizing the risk of activation reactions in the detector.

The detection of low intensity solar neutrino like the pep- and CNO-fluxes requires ultimate radio-purity inside the detector. Therefore, after the phase of detector calibration a series of scintillator purification campaigns was started. The main goal is to reduce $^{85}$Kr, $^{210}$Po and an unspecific flat component which might be $^{210}$Bi. The applied techniques include water extraction, sparging with ultra-pure nitrogen and distillation. The first full purification loops were carried out in 2010 and the purification effort is continued in 2011.

## 6. Summary

BOREXINO has achieved an unprecedented low radioactive background on a large (100 tons) scale. It is the only experiment able to study low energetic solar neutrinos in real time. The results obtained so far include the measurement of solar $^{7}$Be- and $^{8}$B-neutrinos as well as the observation of anti-neutrinos from nuclear reactors and from the earth. Moreover, best limits for various hypothetical rare processes were obtained. The near-future goals include a precision $^{7}$Be-neutrino flux measurement as well as the detection of lower intensity solar neutrino fluxes. Therefore, dedicated detector calibration and scintillator purification campaigns are carried out and elaborated tagging techniques to remove remaining background sources are worked out.

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