Results from the Solar Neutrino Experiment BOREXINO

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Abstract.
We report about recent results from the solar neutrino experiment BOREXINO. With BOREXINO solar neutrino spectroscopy in the sub-MeV range became possible. In particular we demonstrate the measured counting rate of solar ^{7}Be neutrinos. Additionally we show data on solar ^{8}B neutrinos with an energy threshold of 2.8 MeV and discuss the implications for solar and neutrino physics. Finally further prospects of BOREXINO are discussed.

1. Experimental set-up and background suppression

Solar neutrinos are detected in BOREXINO via elastic scattering off electrons: $\nu + e \rightarrow \nu + e$. As a target around 300t of a liquid scintillator (solvent pseudocumene with PPO as wavelength shifter) is used. The scintillator is contained in a spherical nylon vessel. Outside a non-scintillating buffer liquid acts as passive shielding. The scintillation light is registered by more than 2200 photomultipliers (PMs) mounted on the inner surface of a stainless steel sphere. Most of the PMs are equipped with light concentrators. The steel sphere is placed inside a steel dome with a height of about 18m and a diameter with 18m, too. The volume between stell dome and sphere is filled with very pure water. Additional 205 PMs on the outside surface of the sphere and at the floor of the dome are mounted. Hence, the water volume acts as shielding against external gamma and neutron radiation and as an active muon veto. The detector is located in hall C of the deep underground laboratory at Gran Sasso, Italy.

Due to the high light yield of the detector system BOREXINO achieves a hardware energy threshold of well below 100 keV and an energy resolution of about 5% at 1 MeV energy deposition. Recoil electrons of solar ^{7}Be neutrinos deposit a maximal energy of 660 keV. Hence sub-MeV solar neutrino spectroscopy is possible with BOREXINO. However, special care has to be taken concerning background reactions. The muon veto of BOREXINO has a leak rate below 0.5%. Pulse shape techniques applied on the signal of the inner detector, when the muon traverses the steel sphere, allows to suppress this parameter below 0.01%. Hence, muon background in the energy window ($\approx$ 250 keV to $\approx$ 800 keV) of solar ^{7}Be neutrinos is negligible. However, muon induced radioactive nuclei can be a serious background for solar neutrino detection at higher energies.

Very high levels of the purity of the liquid scintillator have to be achieved. In BOREXINO several purification processes before and during the filling procedure have been applied. Degassing with ultra pure N_2, water extraction for the PPO solution as well as distillation of the solvent was used. The contamination level of radon in the scintillator was measured online during the whole filling period. So the development of air leaks in the filling system could be observed and cured immediately. Hence, dangerous contamination due to radioactive gaseous ^{85}Kr atoms could be avoided.

The measured delayed coincidence signals in the corresponding Bi-Po decays allow an online monitoring of the background due to decays in the Uranium and Thorium chains. Assuming radioactive equilibrium we obtain mass concentration levels of $1.6 \cdot 10^{-17}$ for Uranium and $6.9 \cdot 10^{-18}$ for Thorium, respectively. At the low energy side we observe the beta decays of ^{14}C at a level of $2 \cdot 10^{-18}$. This defines the lower analysis threshold for solar ^{7}Be neutrinos to be around 0.2 MeV. We do observe a peak in the ^{7}Be energy window due to alpha decays of ^{210}Po. However, pulse shape discrimination and/or the good energy resolution allows to separate this background from the solar ^{7}Be signal. Fortunately the ^{210}Bi beta background is clearly not in equilibrium with ^{210}Po, but much smaller. A detailed description of the experimental set-up of BOREXINO can be found in[1].

2. Data reduction and results on solar ^{7}Be neutrinos

Here we report on the results obtained in 192 live days of data taking. In order to reject muon events the signal must be in anti-coincidence to the veto. The position of each single event is reconstructed. In this way we can apply a fiducial volume (ca. 100t) cut for rejecting external gamma background. The delayed coincidence method described above is used to reject background from radon daughters. Finally pulse shape discrimination (PSD) may be applied to reject alpha events from ^{210}Po. Finally a common fit to the remaining spectrum is performed. The characteristic signature to solar ^{7}Be neutrinos is the Compton equivalent shoulder at 660 keV. Two analysis to the data, one with and one without PSD were done. The results of both techniques agree very well as it is shown in fig. 1 and 2. The final result on the counting rate is $R_{Be} = (49 \pm 3_{stat} \pm 4_{syst})\, d^{-1}$ in 100t fiducial mass[2].

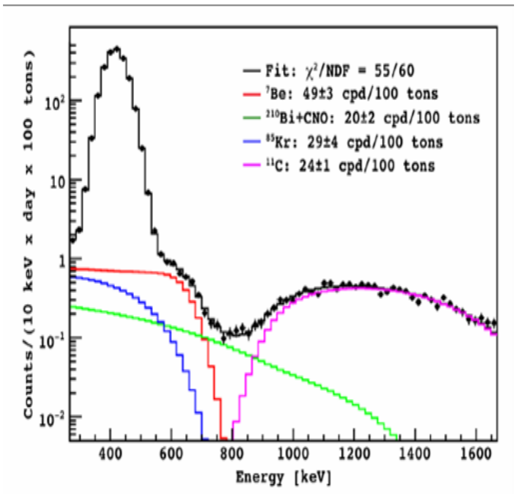

Figure 1. Energy spectrum including solar ^{7}Be neutrino recoil electrons after cuts without PSD

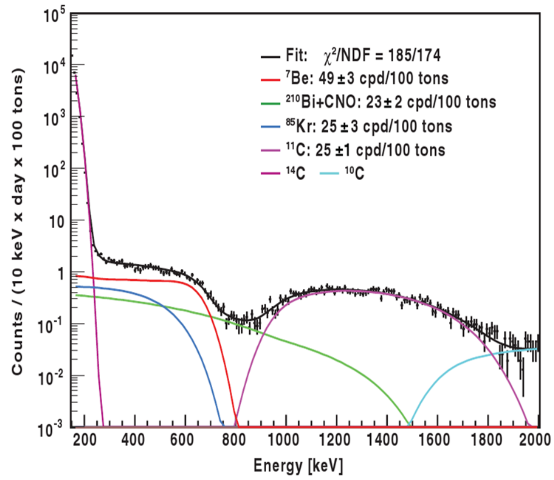

Figure 2. Energy spectrum including solar ^{7}Be neutrino recoil electrons after cuts with PSD

Without neutrino masses and neutrino mixing the expected rate would be $(74 \pm 4)\, d^{-1}$ in the same volume. Our result clearly excludes this scenario. However, taking the actual neutrino mass splitting $\Delta m^2_{12} \approx 8 \cdot 10^{-5}\, eV^2$ and mixing parameter $\theta_{12} \approx 32^0$ including solar matter effects our result is fully compatible with the predictions. For a low inner solar metallicity we expect $44 \pm 4\, d^{-1}$ and for high metallicity a value of $48 \pm 4\, d^{-1}$ in 100t for BOREXINO is expected.

A search for a day/night effect was performed. Our signal is stable in time and no significant difference in the counting rate during day and night was observed. We can report a preliminary limit on the parameter $a = (n-d)/(n+d) = 0.02 \pm 0.04_{stat}$, where n and d denote the averaged rates during night and day, respectively.

With our result new constraints on astrophysical parameters can be obtained. Taking the solar luminosity, the data of all solar neutrino experiments and the actual uncertainties on the neutrino mixing parameters we achieve a ratio f between measured and expected flux on pp-neutrinos of $f = 1.004^{+0.008}_{-0.020}$. Another analysis limits the contribution of the CNO-cycle to the solar energy generation to an amount of 5.4% (90% cl).

The systematic uncertainty is still dominated by the detector response function and the fiducial volume determination. However, due to a calibration campaign in 2009 with radioactive sources at dedicated locations inside the scintillator sphere these uncertainties will be much reduced and we aim to reach a ca. 3% precision on our solar ^{7}Be neutrino measurement.

3. Data reduction and results on solar ^{8}B neutrinos

Again the muon veto and the fiducial volume cut and are applied to the raw data. Radon daughter signals are rejected also. However the long lived background contributions due to radioactive nuclei of ^{10}C and ^{11}Be, created in spallation processes of cosmic muons on Carbon in the scintillator are very important. A 5 second long veto after each muon event in the inner detector rejects short lived cosmogenic background very efficiently. The production of the cosmogenic nuclei often is connected to the production of a neutron which can be detected with high efficiency after it has slowed down in the liquid scintillator. In order to reject the long lived nuclei a three fold coincidence using the muon signal, the neutron event and the cosmogenic generated nucleus is applied. The data from one year were used for this analysis which translates into a a live time period of 246 days. With an energy threshold of 2.8 MeV we measure a counting rate of 0.33 per day in 100t fiducial mass[3]. A spectral fit to the remaining data after cuts is performed.

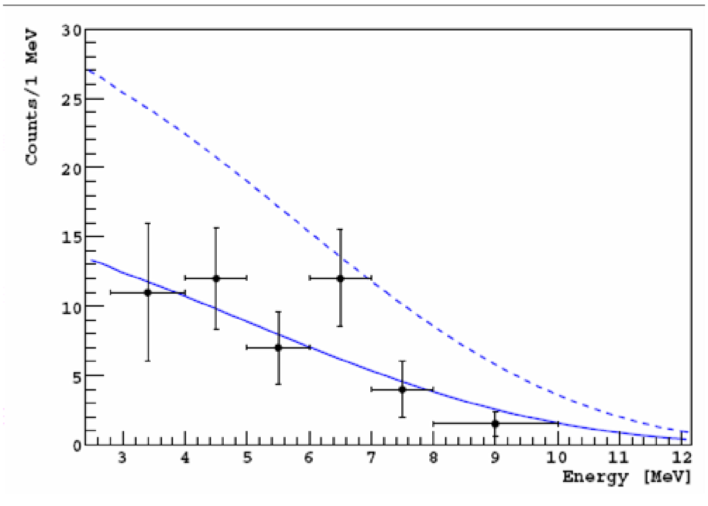

Figure 3. Spectral fit to solar ^{8}B neutrino candidates after cuts. The dashed line shows the expected spectrum in case of no neutrino masses and mixing, the solid line the expected MSW-curve.

In fig. 3 this spectrum of neutrino candidates after all cuts in comparison with the expected curve for the case of no neutrino mixing (dashed line) and in case of the MSW large angle solution is shown. Again our data are in very good agreement with the standard scenario of neutrino masses and mixing. Note, that for the first time data of solar ^{8}B neutrinos below 5 MeV are available.

Combining all available data on solar neutrino experiments it is possible to show the survival probability for solar electron neutrinos to stay in this state as function of the neutrino energy. The precision of the data points in the low energy region have been improved significantly after BOREXINO. In fig. 4[4] the good agreement between experimental values and the MSW prediction is demonstrated.

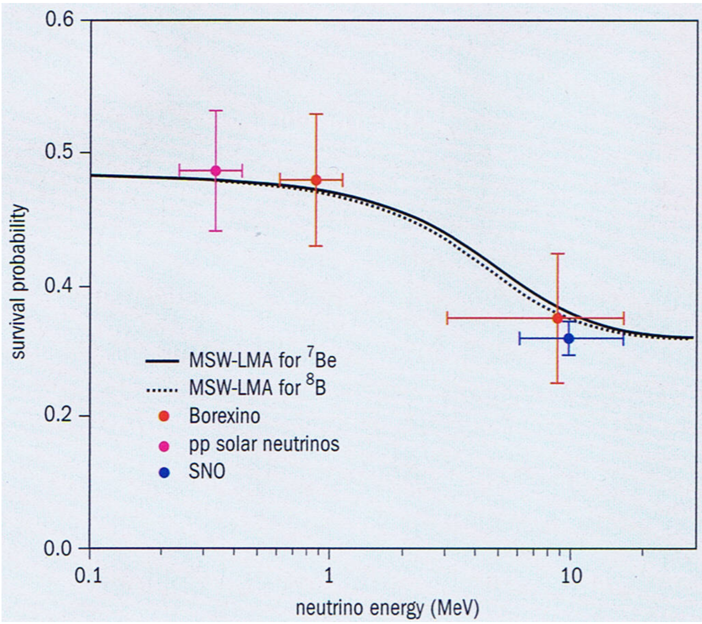

Figure 4. Survival probability of solar ν_e as function of its energy. Data points from solar neutrino experiments are compared with the MSW expected curve.

4. Neutrino magnetic moment and rare event search

With the 192 days sample of data a search for a non zero neutrino magnetic moment was performed. In case of a non vanishing neutrino magnetic moment, the electroweak cross section for neutrino electron scattering is modified by the addition of an electromagnetic term proportional to 1/T, where T is electron recoil kinetic energy. The best limit of $\mu_\nu < 1.1 \cdot 10^{-10}\,\mu_B$ obtained so far using solar neutrino data comes from the SuperKamiokaNDE detector above 5 MeV. As BOREXINO is achieving a significant lower energy threshold we obtain better constraints by investigating the recoil shape of our ^{7}Be signal. An upper limit of $\mu_\nu < 5.4 \cdot 10^{-11}\,\mu_B$ at 90% cl is reached[2]. This result is independent from parameters which usually contribute dominantly to the systematic uncertainty, like fiducial volume or the solar neutrino flux. The currently best limit on the neutrino magnetic moment $\mu_\nu < 3.2 \cdot 10^{-11}\,\mu_B$ was reported recently from an experiment at a nuclear power reactor[5].

Shortly we want to mention the possibility of rare event search in BOREXINO. It is based on the very high level of radiopurity in the liquid scintillator. For example the Pauli exclusion principle is going to be tested with unprecedented precision by searching for the emission of gamma-, neutron-, proton-, and electron/positron radiation emitted in a Pauli blocked transition from the $1P_{3/2}$ to the filled $1S_{1/2}$ state.

5. Prospects

Is it possible to measure solar neutrinos from the pep-reaction and from the sub-dominant CNO cycle? The pep-neutrino flux is predicted in solar models very accurately, as it is strongly connected to the luminosity of the Sun. Of course this is based on the assumption, that its luminosity hasn't change since the last couple of 10^5 years. But if this is the case a pep-neutrino measurement would be very interesting, as these monoenergetic neutrinos with $E_\nu = 1.44MeV$ are inside the transition region between vacuum and matter dominated flavor transitions (compare with fig. 4). Deviations of the measured survival probability from the MSW expectation could reveal non-standard features like flavor changing neutral current interactions. A measurement of the CNO-neutrino flux at Earth would reveal the solar metallicity in the solar center, which is of astrophysical relevance. Recent data from helioseismology show a discrepancy to existing solar models and deliver hints, that the metallicity in the Sun could be higher as assumed. Common for both solar branches is the difficulty to measure them. Besides ultra high levels in radiopurity of the scintillator (here especially for ^{210}Bi and ^{40}K) the rejection of cosmogenic produced ^{11}C background is necessary. Work is in progress to separate these muon induced events by means of a muon tracking routine and search for coincidences with neutron signals. Probably the CNO-neutrinos are even more difficult to detect as the sum of their recoil spectra is not as distinct as that from the monoenergetic pep-neutrinos, where a distinct Compton like edge should be observed.

Low energy electron anti-neutrinos can be detected in BOREXINO by the inverse beta decay on free protons $\bar{\nu}_e + p \rightarrow e^+ + n$. The strong correlation in space and time of the prompt e^+- and the delayed n-signal delivers a tool to separate these events from background with very high efficiency. Sources for $\bar{\nu}_e$ are European nuclear power reactors and neutrinos from the Earth, both emitted in beta decays. As the energy spectra from the two sources are different it is possible to separate them. Only few events per year in the detector are expected. A measurement of terrestrial neutrinos could be used to probe geophysical models, the measurement of reactor neutrinos could be used as a test of the KamLAND result on neutrino oscillation, however at lower statistics. Background can origin from external fast neutrons or from beta-neutron cascade decays, like from ^{9}Li. The former should be identified by our muon veto, the latter can be discriminated by a veto of a few seconds duration after a muon traversed the inner detector.

References

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