Spectroscopy of solar Neutrinos with the BOREXINO Detector

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ABSTRACT

The BOREXINO detector will detect solar neutrinos by neutrino electron scattering in a liquid scintillator target. In particular the monoenergetic solar neutrino flux at 861 keV from electron capture in ^{7}Be will be determined directly. In this article we report the status of the experiment and first results from a counting test facility (CTF) to study the radio purity of the detector components and to check the feasibility of BOREXINO.

1. Introduction

Presently four solar neutrino experiments have been performed, all of them showing a significant suppression of neutrino rates with respect to the expectations from the present understanding of the solar fusion processes being the source of these neutrinos. The most striking deviation from expectations is the low relative rate between the ^{7}Be-neutrinos, emitted after electron capture in ^{7}Be, and the ^{8}B-neutrinos, originating from the fusion of ^{7}Be with protons. The combination of solar neutrino data, experimentally obtained from ^{71}Ga-, ^{37}Cl-, and water cerencov-detectors, indicate a much stronger suppression of the ^{7}Be-neutrinos than of the ^{8}B-neutrinos [1–4]. Within standard solar models these results can hardly be understood [5] which may indicate non-standard properties of neutrinos like neutrino mass and mixing. From present experiments the ^{8}B-neutrino flux is known, but there are no directly measured data available for the flux of the monoenergetic ^{7}Be-neutrinos. The determination of the ^{7}Be-neutrino flux is therefore a key to the question whether the solar neutrino puzzle is caused by neutrino mass and mixing or not.
The direct real time measurement of the ^{7}Be-neutrino flux is the goal of the BOREXINO experiment. The neutrinos are detected via elastic neutrino electron scattering in 100 tons of liquid scintillator. Due to the high light yield of scintillator, the required low energy threshold can be achieved. On the basis of the standard solar model the neutrino scattering event rate from the solar ^{7}Be-neutrino flux is expected to be 50 counts per day [6, 7].
The sensitivity of the detector to low energy neutrinos is predominantly limited by background events originating from spurious radioactive contamination inside the detector. Therefore, a counting test facility (CTF) has been installed in the Gran

Sasso Underground Laboratory to study the radio purity levels of the scintillator and other critical detector components and to check the feasibility of the BOREXINO experiment.

2. The BOREXINO detector[8]

The BOREXINO detector consists of 300 tons of scintillator contained in a spherical vessel with a radius of 4.25m fabricated of a thin film of highly transparent nylon. This sphere is immersed in 3300 m^3 high purity buffer liquid serving as a shield against external radioactive background. The scintillator is viewed by 1700 phototubes equipped with light cones for a more efficient collection of scintillation light. By means of the measurement of time differences between the light detected in different phototubes, position sensitivity is obtained for events taking place in the scintillator. A fiducial mass of 100 tons is selected for solar neutrino induced signals, while the external part of the scintillator serves as an active shielding against radioactivity from the nylon sphere, the buffer liquid, the phototubes, and the environment.
The whole detector is installed in the Gran Sasso Underground Laboratory for sufficient shielding against cosmic ray background. The underground depth of the laboratory corresponds to 3500 m H_2O equivalent. Against the remaining cosmic muon flux of approximately $1\mu/m^2h$, muon detection is planned, in order to identify muon correlated background.
Materials used for the construction of the BOREXINO detector have to reach increasing radio purity the closer to the scintillator they are placed. The highest purity is required for the scintillator itself. The most crucial contamination in the scintillator is the β-decaying ^{14}C with its beta endpoint energy of 156 keV. Together with the energy resolution this limits the threshold energy of BOREXINO. The maximum acceptable concentration in the scintillator is within in the range of $^{14}C/^{12}C \approx 10^{-18}$g/g. Specifications for U, Th and K are given in table 1. The signal to background ratio

Table 1. Goals for radio purity.

material	$^{238}U(g/g)$	$^{232}Th(g/g)$	$^{nat}K(g/g)$
scintillator	$10^{-15}/10^{-16}$	$10^{-15}/10^{-16}$	10^{-14}
nylon for scintillator vessel	10^{-12}	10^{-11}	10^{-8}
H_2O	10^{-14}	10^{-13}	10^{-10}

in the range of the ^{7}Be-neutrino signal is approximately 5 to 10. It strongly depends on the radio purity achieved in the scintillator and in the detector components. The radio purities are controlled by ultra low background gamma spectroscopy, mass spectroscopy and neutron activation analysis, as well as high sensitivity measurements of radon emanation. It was shown that for the water and the nylon vessel the range of purity as given in table 1 can be achieved. However, these techniques do not attain sufficient sensitivity for the scintillator, in particular for the test of the U, Th, and ^{14}C contamination. Information on the impurities ought to be obtained by the counting test facility. There may as well be other spurious radioactive impurities, as for example ^{85}Kr or fission products. Further radioactive background may originate from decay products of Radon such as ^{210}Pb and ^{210}Bi.

3. The counting test facility (CTF)

The CTF is installed in hall C of the INFN Gran Sasso Underground Laboratory in Italy where the Borexino detector is planned to be operated. It is constructed following the concept of BOREXINO. 1000 tons of high purity water serve as a shielding against radioactive background originating from the environment of the laboratory and the water tank. 4.5 m^3 of scintillator, contained in a spherical nylon vessel, are placed in the center of the water tank. The scintillator is observed by 100 phototubes spherically distributed in a distance of 3.3 m from the center of the scintillator. Each phototube is equipped with a light cone to increase the effective coverage up to 30% of 4π.

The scintillator tested presently for BOREXINO is based on pseudocumene as a solvent with 0.15% PPO which is used as a wavelength shifter. To reduce the cosmic ray produced ^7Be in the scintillator, the pseudocumene was transported to the Gran Sasso Laboratory immediately after its last distillation of the production process. The exposure to cosmic rays was therefore limited to less than 2 days. With this scintillator and the present geometry of the CTF about 290 photoelectrons are registered per MeV in the phototubes. The primary light yield of the scintillator is estimated to be 12000 photons per MeV. The absorption length is measured to be more than 5m. At 500keV the energy resolution is about 10% and the position resolution about 16cm. The hardware threshold of the CTF is set to 25 keV using a trigger of a 6 fold coincidence of photomultiplier signals. Each photomultiplier (8 inch EMI) is operated with single photoelectron sensitivity.

By using pulse shape discrimination and time measurement, delayed $\alpha - \beta$ - coincidences are identified. This leads to a high sensitivity for the detection of natural decay chains of U and Th. Due to the low energy threshold, a high sensitivity for the detection of ^{14}C β-decays is achieved.

4. First results on radio purity

The main goal of the CTF was to demonstrate that the purity from U, Th and ^{14}C can be achieved as required for the feasibility of BOREXINO. For this, the most crucial prerequisite is a low level of ^{14}C contamination, because ^{14}C by no means could be removed from the scintillator. The β activity of ^{14}C with an endpoint energy of 150 keV can be directly measured at low energies. From the spectral intensity an upper limit of

$$^{14}\mathrm{C}/^{12}\mathrm{C} < (1.45 \pm 0.008) * 10^{-18} g/g$$

for the ^{14}C concentration in the scintillator can be derived. At this low concentration the ^{14}C activity will contribute to the background in BOREXINO in the energy window for ^{7}Be-neutrino detection (250keV $< E <$ 800keV) less than 0.1 event per day. The concentrations of ^{232}Th and ^{238}U in the scintillator are indirectly measured by using $\beta - \alpha$ delayed coincidences of their decay products Bi and Po. This strictly speaking yields only the concentrations of the last predecessor nucleus in the decay chain with a half life long compared to the time scale of the experiment. If there were chemical processes during the scintillator production, causing disequilibrium of the decay chains, the ^{232}Th and ^{238}U concentrations could be different from the values deduced under the assumption of equilibrium with their decay products. Even if neutron activation analysis (NAA) is not so sensitive as the CTF, it therefore still has to be used for the Th and U analysis, in order to confirm independently the values resulting from the CTF.
From the delayed $\beta - \alpha$ (^{212}Bi, ^{212}Po) coincidence and under the assumption of equilibrium we obtain a value for the ^{232}Th concentration within 90% CL of

$$(2.5^{+1.3}_{-1.0}) * 10^{-16}\ \mathrm{g}\ ^{232}\mathrm{Th}\ /\mathrm{g}\ \mathrm{scintillator}.$$

The limit from NAA is

$$\text{less than } 1.2 * 10^{-14}\ \mathrm{g}\ ^{232}\mathrm{Th}\ /\mathrm{g}\ \mathrm{scintillator}.$$

It is planned to further improve the NAA technique in the next future, to increase its sensitivity. The values for the ^{238}U concentration are, from the delayed $\beta - \alpha$ (^{214}Bi, ^{214}Po) coincidence in the CTF

$$(4.2 \pm 2.0) * 10^{-16}\ \mathrm{g}\ ^{238}\mathrm{U}\ /\mathrm{g}\ \mathrm{scintillator}.$$

From the NAA the limit is [9]

$$\text{less than } 3.5 * 10^{-15}\ \mathrm{g}\ ^{238}\mathrm{U}\ /\mathrm{g}\ \mathrm{scintillator}.$$

The CTF was not designed to reach the sensitivity of BOREXINO due to its much

smaller size. For this reason it is difficult to give a limit on the K concentration from a measurement of the 1.46MeV γ-line of ^{40}K decay in the CTF. From the NAA we obtain a limit on the K concentration in the range of 10^{-12}g/g.
This purity levels are very important milestones for the preparation of BOREXINO and they are achieved without any further purification of the scintillator. Nevertheless, there is within the energy window for neutrino detection (250 keV $< E <$ 800 keV) a rate of about 1700 electron or γ like events detected per day. From position analysis, about 600 of them can be accounted to external background, caused by the phototubes, the nylon vessel, and the ^{222}Rn in the water. The remaining events are homogeneously distributed within the scintillator volume. From an introduction of some small amount of air, during the filling of the inner vessel, there is some ^{210}Pb from ^{222}Rn decay in the scintillator, which now causes about 400 β-events per day by subsequent ^{210}Bi decay. The rest of the background may be explained by various other sources which are presently investigated (^{85}Kr, ^{7}Be, ^{39}Ar, ...). In particular, a scintillator purification system is installed using gas purging, water extraction, and distillation to remove remnant radioactive impurities. From the air in the scintillator, there were also about 300 events per day from ^{85}Kr β-decay, which can be traced by a $(\beta-\gamma)$ coincidence with a branching ratio of 0.43%. As a result of a first gas purging, most of the ^{85}Kr could be removed and the related β count rate went down to less than 100 per day.
In addition, μ correlated background is investigated by use of a μ veto, installed on top of the tank. All μ's passing the tank, even if only through the water, cause signals in the detector. Most of them are rejected by pulse shape analysis and energy cuts. But about 80 per day remain as background in the neutrino energy window. For BOREXINO therefore a μ veto is planned.

5. Conclusion

Borexino will determine the ^{7}Be solar neutrino flux. The intensity of this flux strongly depends on whether neutrino mixing exists or not. With the sensitivity and the purity levels presently achieved in the CTF, and in particular with the purity of the scintillator, a very important milestone for the preparation of the BOREXINO detector has been reached. The most important result may be the very low level of ^{14}C in the scintillator, because a ^{14}C contamination was the only conceptual obstacle for BOREXINO. Also the purity from Th and U of the scintillator, of the nylon vessel, and of the shielding water as the main detector components, are in the range of the design goals. To our knowledge, the CTF is the detector with the lowest background activity. Certainly there are numerous questions for the construction of BOREXINO still to be answered and the possibilities of scintillator purification have to be investigated. Yet, we believe to be in a position to start the final design and first construction work for this experiment. On the basis of the results of the CTF, the advisory committee of the Gran Sasso Laboratory has recommended BOREXINO to the Italian INFN to be the next solar neutrino experiment.

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8. BOREXINO collaboration list

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