SOLAR NEUTRINO SPECTROSCOPY WITH THE BOREXINO DETECTOR AND PRELIMINARY RESULTS FROM THE CTF EXPERIMENT

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Abstract

The objective of the BOREXINO project is to measure the solar ^{7}Be neutrino flux. The current status of the experiment is reviewed and recent results achieved with the Counting Test Facility (CTF) at Gran Sasso are presented.

1. Introduction

At present there are four operating solar neutrino experiments which all measure a lower solar neutrino flux than predicted by Standard Solar Models. The discrepancy between theoretical predictions and experimental observations ranges from about 30% to 60% and this is in general referred to as the Solar Neutrino Problem[2]. Table 1 lists the experimental results and the predictions derived from Standard Solar Models (SSM). Both Non–Standard Solar Models as well as physics beyond the Standard Model of Electroweak Interaction have been proposed in order to reconcile the disagreement between prediction and observation. The goal of the BOREXINO project is to measure directly in real time the mono energetic solar ^{7}Be neutrino flux, the only approved experiment with this objective.

Figure 1. The hydrogen burning nuclear fusion cycle (pp-cycle) with its different terminations and the corresponding solar neutrino spectrum (solid) is illustrated.

2. The ^{7}Be Neutrino Problem

The impact of the Solar Neutrino Puzzle has evolved over the last decade. The first problem arose from the inconsistency between theoretical prediction and experimental observations of the high energetic branch of ^{8}B neutrinos, a subdominant termination of the pp-cycle (cf. Figure 1). The comparison of the results of the Homestake and the Kamiokande experiment which operate with different energy thresholds, indicated already at an early stage a substantial suppression of the ^{7}Be neutrino line at 862 keV. This has been confirmed by the recent results obtained by the gallium experiments. By taking the luminosity of the sun and the ^{8}B neutrino flux as measured by the Kamiokande experiment, one can conclude[3] that the ^{7}Be neutrino flux is lower than 20% (90% CL) of its predicted value in SSM.

Astrophysical models have difficulties to explain a suppression of the ^{7}Be flux. This can be inferred from a simple argument: In the pp-cycle ^{7}Be is created prior to ^{8}B (cf. Figure 1). A competing channel to the termination of the cycle via ^{8}B production ($^7\mathrm{Be} + \mathrm{p} \rightarrow {}^8\mathrm{B} + \gamma$) is to terminate via electron capture in ^{7}Be ($^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu$) which is the dominant process. In the latter process monoenergetic ^{7}Be neutrinos are emitted. No mechanism to date has been proposed which will sustain the ^{8}B creation process and at the same time suppress the ^{7}Be electron capture process. This is a necessary precondition *assuming standard neutrino properties*, to accomodate the experimental observations.

Experiment	Detection	Threshold [MeV]	Data units cf. below	SSM Prediction[4] units cf. below
Homestake[5]	$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$	0.814	2.55 ± 0.25 [a]	9.3 ± 3.1 [a]
Kamioka[6]	$\nu + e^- \rightarrow \nu' + e'^-$	7.5	$\Phi_B = 2.8 \pm 0.4$ [b]	$\Phi_B = 5.7 \pm 0.8$ [b]
GALLEX[3]	$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$	0.233	77 ± 10 [a]	132 ± 7 [a]
Sage[7]	$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$	0.233	69 ± 12 [a]	132 ± 7 [a]

Table 1
Experimental results and theoretical predictions of solar neutrino experiments. The interaction rate in radio chemical experiments is given in units of SNU (a). For the neutrino electron scattering experiment Kamiokande, the ^{8}B flux (Φ_B) is given in units of $10^6\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (b).

Scenarios which adopt *non-standard neutrino properties* can provide a substantial flux suppression at intermediate energies. The magnitude of this suppression factor, however, depends strongly on the assumed particle physics solution. It consequently is desirable to undertake a high precision spectroscopic real–time measurement of *solar neutrinos at intermediate energies*, especially of the ^{7}Be neutrino flux. This is the objective of the BOREXINO experiment. Together with the statistically improving results of the Gallium experiments and the forthcoming experiments Super-Kamiokande and SNO which will measure the ^{8}B neutrino spectrum above about 5 MeV, the complete solar neutrino spectrum will be accessible.

3. The BOREXINO Detector[8]

Neutrino detection relies on the leptonic process of neutrino–electron scattering within an unsegmented, spherical liquid scintillator target with mass of about 300 tons. A transparent nylon sphere (inner vessel) is planned to contain the scintillator target and this is to be enclosed by a spherical stainless steel sphere of radius 7.5 m. The volume in between the stainless steel sphere and the inner vessel is filled by an ultra clean buffer liquid.

A water buffer with mass of about 3000 tons surrounds the stainless steel sphere and shields the neutrino target against ambient radioactivity. Approximately 2000 photo multipliers will collect the scintillation light which provides both the energy and the position in space of the neutrino interaction within the detector volume.

According to the prediction of the Solar Standard Model there will be 50 ^{7}Be neutrino interactions per day and per 100 tons of target mass depositing an energy above 250 keV. The neutrino signal of the ^{7}Be neutrino line (862 keV) will be observable as a distinct step in the electron recoil spectrum at 660 keV.

The BOREXINO detector will be located in hall C of the underground facilities of the National Laboratory of Gran Sasso (LNGS) in order to shield against cosmic ray induced background. The shielding by the Gran Sasso massif corresponds to 3500 meter of water equivalent. The residual muon flux amounts to one muon per hour and square meter. A muon identification system will be installed in order to recognize the background events which are related to muon interactions.

4. Radiopurity Requirements

Interactions of decay products of radio-isotopes within the scintillator target can be difficult to distinguish from neutrino interactions. Consequently, it is imperative for the success of the experiment to control the amount of radio-isotopes in all detector components. The closer the detector components are located to the scintillator target, the more restrictive are the required radiopurities. Table 2 lists some of the detector components and the corresponding tolerable contamination levels. The neutrino signal acquired after one year of data taking is depicted in Figure 2 under the assumption of a Standard Solar Model neutrino flux and of a background level according to Table 2.

The concentration of ^{14}C (max. β energy: 150 keV) in the scintillator together with the energy resolution of the detector determine the attainable energy threshold above which neutrino interaction can be observed. Fission products (especially radioactive noble gases) or cosmogenically produced isotopes such as ^{7}Be could potentially jeopardize the experiment.

Radiopurities are controlled by ultra low background γ spectroscopy, mass spectroscopy and neutron activation analysis as well as radon emanation measurements. However, the contamination levels which are required for the scintillator (^{14}C,U,Th) are beyond the sensitivity of state of the art laboratory detection techniques. To overcome this limitation a Counting Test Facility (CTF) was built.

Detector Component	^{238}U (g/g)	^{232}Th (g/g)	nat K (g/g)	^{14}C/^{12}C
Scintillator	10^{-16}	10^{-16}	10^{-14}	10^{-18}
Nylon (Inner Vessel)	10^{-12}	10^{-11}	10^{-8}	
H_2O - Buffer	10^{-14}	10^{-13}	10^{-10}	

Table 2
Radiopurity requirements for the main detector component in units gramme impurity per gramme detector material.

5. The Counting Test Facility

In the frame of the BOREXINO project, a small scale prototype detector (Counting Test Facility – CTF), similar to the BOREXINO detector design, was developed in order to investigate the attainable radiopurity levels. The spectrometer part of the CTF consists essentially of

Figure 2. Simulated spectrum for solar neutrino events in the BOREXINO detector and background spectrum according to the contamination levels of table 1. The energy transfer from the mono energetic ^{7}Be neutrinos to the target electrons via neutrino–electron scattering becomes visible in a distinct step like spectral shape.

4.6 tons of liquid scintillator which is contained in a nylon sphere with radius of one meter and this is shielded by 1000 tons of ultrapure water. One hundred photo multipliers (Thorn EMI 8") are positioned concentrically around the inner vessel at a distance of 330 cm from its centre. Light concentrators (length 57 cm, aperture 50 cm) are mounted on the photo multipliers to provide a geometrical coverage of 30% of 4 π steradians. The scintillator which is currently under investigation consists of two components: pseudocumene (PC) as solvent and of PPO (1.5 g/l) as fluor. A yield of 260 photo electrons per MeV is obtained and an energy resolution σ of 8% at 825 keV observed. Events are reconstructed in space with an uncertainty σ of 15 cm at this energy. The trigger is defined by a sixfold coincidence of photo multiplier signals which corresponds to an energy threshold of about 20 keV.

It is noteworthy that the CTF is not designed for solar neutrino detection. The detector size and its volume to surface ratio are too small to provide sufficient self shielding. The dominating counting rate in the ^{7}Be neutrino energy range is consequently related to the radiopurity of the water buffer and to the nylon sphere. A sensitivity similar to BOREXINO is not reachable in the CTF geometry.

6. Preliminary Results from the CTF

The primary objective of the CTF is to investigate the concentration of radio contaminants in organic liquids which are of interest as scintillator components for BOREXINO. Furthermore, a variety of purification methods to remove potential contaminants are being tested.

One of the most important issues was to evaluate the concentration of ^{14}C in the scintillator. ^{14}C is a pure β emitter with an endpoint energy of 150 keV. The energy spectrum at low energies measured in the CTF coincides with a shape expected from ^{14}C β decay. A value of 1.2×10^{-18} is deduced for the ratio ^{14}C/^{12}C. At this level it will not contribute significantly to the background in the energy range relevant for ^{7}Be neutrino detection. ^{14}C can be a constituent

Figure 3. Photo multipliers with mounted light concentrators and inner vessel are shown. The photo has been taken prior to the filling of the inner vessel and the water shield.

of the fluor (PPO) and/or of the solvent (PC). In this sense, the above mentioned number can be considered as an upper limit for a contamination of the solvent.

The counting rate in the CTF is dominated at low energies (40 keV - 180 keV) by the ^{14}C content. The major contribution for energies above the ^{14}C energy range originates from the residual radon contamination in the water buffer. The Rn activity is determined to be about 15–20 mBq/m^3 of water.

The question of how to measure the contamination levels of ^{238}U and ^{232}Th at the 10^{-16} g/g level was addressed by measuring delayed coincidences in the decay chains. The determined activities reflect the parent activities under the assumption of secular equilibrium.

A value of $(4.2 \pm 2.0) \times 10^{-16}$ g/g scintillator could be deduced for ^{238}U from the delayed $\beta - \alpha$ coincidence in the decay of $^{214}\mathrm{Bi} \rightarrow {}^{214}\mathrm{Po} \rightarrow {}^{210}\mathrm{Pb}$. A direct limit for ^{238}U of $< 3.5 \times 10^{-15}$ g/g is obtained from neutron activation analysis. This constrains a possible disturbance of the secular equilibrium to less than a factor 10.

From the delayed $\beta - \alpha$ coincidence of the consecutive decays of ^{212}Bi and ^{212}Po a value of $(2.5 \pm 1.2) \times 10^{-16}$ g/g is derived for ^{228}Th. Provided that the short lived isotope ^{228}Th is not differently removed in chemical treatments than the long lived isotope ^{232}Th, this limit is also applicable to the latter.

At present three different purification techniques are being tested. They consist of N_2 stripping in order to remove gaseous contaminations, of H_2O extraction to remove ionic contaminants and of distillation for contaminants bound to organic compounds. A considerable reduction of radio impurities has been observed. As the experiments and data evaluation are still ongoing, final numbers can not be quoted here.

Preliminary values for the counting rate in the neutrino energy window (*nw*) (250 keV - 800 keV) can be summarized as following: After the recent scintillator purification treatments, the counting rate in the *nw* was about 1900 per day. About 1400 events per day of this rate are related to the residual ^{222}Rn contamination in the water buffer. About 100 events per day originate from muon cerenkov interactions in the water buffer which are not discarded by the muon recognition criteria. There is indication that the events of the residual rate of about 400 per day in the *nw* are located at the surface of the inner vessel. The decay of long living Radon daughter isotopes could account for the observed data. The ongoing experimental efforts are being carried out in order to clarify this question unambiguously.

7. Conclusions

Important milestones for the preparation of the BOREXINO experiment have been achieved with the Counting Test Facility at Gran Sasso. One of of the most important results is the measured low concentration of ^{14}C in the scintillator. This is an imperative precondition for the feasibility of BOREXINO. Furthermore, the measured contamination levels of uranium and thorium show that the required high purity levels for BOREXINO are attainable in aromatic scintillation liquids.

A variety of purification techniques are currently under investigation and in the near future an alternative scintillator (PXE) with density of 0.99 g/cm^3 will be tested in the CTF. Construction work for BOREXINO will commence in spring 1996 while the final details of the design for the BOREXINO detector is under preparation.

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