SOLAR NEUTRINO SPECTROSCOPY WITH BOREXINO AND RECENT RESULTS FROM THE CTF EXPERIMENT

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The main objective of the BOREXINO detector is to measure the monoenergetic ^{7}Be-solar neutrino flux ($E_\nu = 862\,\mathrm{keV}$) by neutrino-electron scattering in a liquid scintillator target. To study the radiopurity of the detector components, and to check the feasibility of BOREXINO a small scale prototype detector, the Counting Test Facility (CTF), has been installed in the Gran Sasso Underground Laboratory in Italy. In this article the current status of the experiment and recent results from the CTF are reported.

1 Introduction

The longstanding *Solar Neutrino Problem* consists of the discrepancy between the detected solar neutrino fluxes and the theoretical predictions. At present, all operating solar neutrino experiments measure a ν-flux which is 30% to 60% lower than predicted by Standard Solar Models. To explain this significant suppression, both Non-Standard Solar Models as well as physics beyond the Standard Model of Elektroweak Interaction have been proposed.

Comparing the results of the Homestake ($^{37}Cl + \nu_e \rightarrow\ ^{37}Ar + e^-$; $\langle\Phi_\nu\rangle = 2.55 \pm 0.25\,\mathrm{SNU}$) and the Kamiokande [4] ($\nu e \rightarrow \nu e$; $\langle\Phi_{\nu_B}\rangle = (2.8 \pm 0.4)\cdot 10^6 cm^{-2}s^{-1}$) experiments, which operate with different energy thresholds the data indicate a substancial suppression of the ^{7}Be neutrino line at $E_\nu = 862\,\mathrm{keV}$. Here, 1 SNU is defined to 1 ν reaction per 10^{36} target atoms and sec. Recent results obtained by the GALLEX experiment [1] and the SAGE experiment using the reaction $^{71}Ga + \nu_e \rightarrow\ ^{71}Ge + e^-$, observe a neutrino flux $\langle\Phi_\nu\rangle = 69.7 \pm {}^{7.8}_{8.1}$ SNU and $\langle\Phi_\nu\rangle = 69 \pm 10 \pm {}^{5}_{7}$ SNU respectively, whereas 132 SNU are expected from standard solar model calculations.

Fig.1 shows the calculated GALLEX ν-signal as a function of the rate $\Phi_\nu(^7Be) : \Phi_\nu(^7Be)_{SSM}$ assuming the two cases that (1) no pep-, CNO-, and ^{8}B-neutrinos are generated, and (2) that only ^{8}B neutrinos with a flux as measured by Kamiokande are present [1],[3].

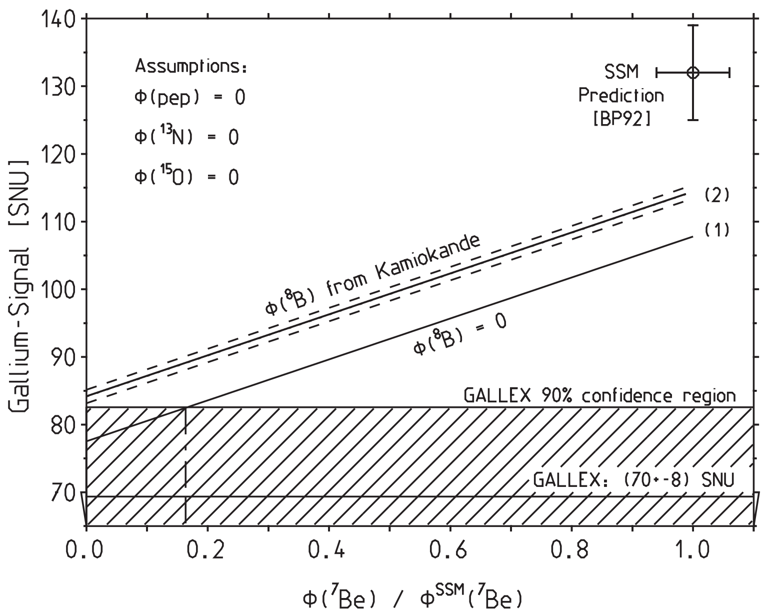

Figure 1: Expected GALLEX-signal as a function of the ^{7}Be neutrino flux [1].

From this picture we derive a stringent upper constraint on the ^{7}Be neutrino flux by only taking the actual GALLEX (or SAGE) data and the solar luminosity constraint into account. Within a GALLEX 90% confidence level, the beryllium flux is required to be less than about $\Phi_\nu(^7Be) : \Phi_\nu(^7Be)_{SSM} \leq 17\%$ i.e. $\Phi_\nu(^7Be) \leq 8\cdot 10^8 cm^{-2}s^{-1}$ for case (1), or for the more realistic case including the ^{8}B neutrinos (2) equal to zero, or even negative within 1 σ uncertainty of the Kamiokande data and the 90% confidence level of GALLEX. As the Ga data are obtained from an inverse beta decay reaction, these limits apply to the ν_e flux essentially. Recent results from the new experiment Superkamiokande confirm the results of Kamioka.

The deficit of beryllium neutrinos, together with the ^{7}Be/^{8}B neutrino discrepancy, appears now as the essence of the solar neutrino problem.

Up to now, there is no directly measured data available for the flux of monoenergetic ^{7}Be neutrinos at 862 keV, which as well will not be detectable by the forthcoming solar neutrino experiments SNO and Superkamiokande.

Therefore, the objective of the BOREXINO experiment is the *direct real time measurement* of the solar ν-spectrum for $E_\nu \geq 450$ keV and, in particular, the measurement of the ^{7}Be neutrino flux by neutrino-electron scattering in an organic liquid scintillator. This reaction includes charged and neutral current interaction and is therefore sensitive to the ν_e and $\nu_{\mu,\tau}$ flux. With the forthcoming high- accuracy Ga-experiment GNO, it may therefore be possible to obtain information on the charged and neutral current contribution separately.

2 The conceptual Design of the BOREXINO Detector

The BOREXINO detector is being built up in Hall C of the Italian National Laboratory at Gran Sasso (LNGS) in order to shield against cosmic ray induced background. The shielding by the Gran Sasso massif corresponds to 3600 meter of water equivalent, which reduces the muon flux to an amount of 1 μ/m^2h.

The neutrino detection reaction relies on the pure leptonic process of elastic neutrino-electron scattering

$$\nu + e^- \rightarrow \nu + e^- \,,$$

which is sensitive to all neutrino flavors. While the ν_e can interact via charged current as well as nutral current, the $\nu_{\mu,\tau}$ can only interact via neutral current, which results in different cross sections for ν_e and $\nu_{\mu,\tau}$. At an energy of 660 keV the cross section ratio

$$\sigma(\nu_e) : \sigma(\nu_{\mu,\tau}) \approx 4 \,.$$

With the BOREXINO detector neutrino energies above 450 keV can be detected according to a software threshold of 250 keV for the deposited energy of the recoil electron. For ^{7}Be neutrinos with an energy of E_ν=862 keV, the 'compton'-like edge of the recoil energy spectrum lies at E_e=660 keV (see also Fig.3.) [6]. The conceptual design of BOREXINO is shown in Fig.2.

Figure 2: (1) Inner Vessel, containing 300 tons of liquid scintillator (d=8.5 m; (2) ultrapure buffer liquid; (3) stainless steel sphere (d=14 m) with 2000 PMT's; (4) water buffer: 3000 tons of high purity, deionized water; (5) stainless steel tank; (6) Muon Veto (400 PMT's).

The BOREXINO detector consists of 300 tons of ultrapure liquid scintillator contained in a thin, UV-transparent nylon vessel ('Inner Vessel', radius = 4.25m). This vessel is enclosed by a spherical stainless steel sphere of radius 7 m, on which 2000 photomultipliers are fixed on the inner side to view the scintillator. The photomultipliers are equipped with light-cones for an efficient collection of scintillation light. In addition, the three-dimensional arrangement of the phototubes provides a position reconstruction of the neutrino interaction within the detector volume. Therefore, a fiducial volume of 100 tons of scintillator can be determined by software cuts to reduce the external background rate to a minimum. The volume between the inner vessel and the stainless steel sphere is filled with 3300 m^3 of an ultra pure buffer liquid (possibly pseudocumen), which serves as an active shielding against radioactive background from the outer detector parts. Finally, the whole detector is located in a steel tank with 18 m of height and 18 m of diameter filled with about 3000 tons of high purity, deionized water to shield against external γ-radiation. Furthermore, a Cherenkov muon veto will be installed. This will surround the detector and consist of additional 600 phototubes mounted outside and inside the stainless steel sphere to identify the muon correlated background.

2.1 Main Sources of Background in BOREXINO

The strategy for BOREXINO is to reduce the background as far as possible by using highest purity materials, and by absorption of external radiations. The sources of background can be devided into three main sections as follows:

- **Natural Radioactivity:**
  The most dangerous source of background is contamination of the scintillator and of the detector components with ^{238}U and ^{232}Th, and their chain of decay products. In these decay chains several α- and β decays occur occasionally, accompanied by γ-rays. In addition, ^{40}K with 90% of its decays proceeding by emission of β's, and 10% by electron capture with secondary emission of a 1.46 MeV γ-ray is a dangerous background source. The background requirements of the BOREXINO detector components for the radioimpurities mentioned above were calculated to obtain a signal/background-ratio of about 10 in the so-called ^{7}Be neutrino energy window of 250 keV - 800 keV, and are shown in table 1.

- **Cosmogenic Radioactivity**
  Another important source of background are cosmic ray-induced radionuclides, above all ^{14}C and ^{7}Be, which are critical for BOREXINO because of their long half-lifes and their decay energies.

Material	^{238}U [g/g]	^{232}Th [g/g]	K [g/g]	^{14}C/^{12}C
Scintillator	10^{-16}	10^{-16}	10^{-14}	10^{-18}
Inner Vessel (Nylon)	10^{-10}	10^{-10}	10^{-7}	
Buffer liquid	10^{-13}	10^{-13}	10^{-10}	
Photomultiplier	10^{-7}	10^{-7}	10^{-4}	
Stainless steel tank	10^{-8}	10^{-8}	10^{-5}	

Table 1: *Background requirements for* BOREXINO *detector components concerning contamination with U, Th, K and ^{14}C in grams per gram of the given materials.*

^{14}C decays with a half-life of 5730 years by β ray emission with a maximum energy of 156 keV. Even if this energy is below the neutrino energy window (250 - 800 keV), pile-up effects, together with the finite energy resolution of the detector, can lead to contributions to the signal above 250 keV. Because there are no chemical methods to extract the ^{14}C content of the scintillator, the concentration of ^{14}C determines the attainable energy-threshold above which neutrino interaction can be observed. An upper limit for the required ^{14}C-concentration in the scintillator is $^{14}C/^{12}C \approx 10^{-18}$ ($\Rightarrow$ ^{14}C-activity in 300 t of scintillator $\approx$ 100 Bq).

A further source of internal background which potentially could jeopardize the experiment is ^{7}Be, which can be produced via the reactions ^{12}C(n, α n n) and ^{12}C(p, α n p). It decays by electron-capture with a half-life of 53 days, with 10% of the decays emitting a 478 keV γ-quant.

- **Anthropogene ('man-made') Radionuclides**
  Man-made isotopes, such as ^{137}Cs, ^{60}Co, and ^{85}Kr can also contribute to a contamination of detector components. Examples are:

  ^{85}Kr has a half-life of 10.7 y and decays with a branching ratio of 0.43% via β^{-} emission (endpoint energy at 173 keV), followed by a γ-quant with 514 keV. If the scintillator gets in contact with air, this noble gas may desolve into the scintillator. There, it can create a signal which is close to the maximum recoil energy of electrons after a scattering with ^{7}Be-Neutrinos (665 keV).

  The β-decay of ^{137}Cs ($T_{1/2}$ = 30.2 a, Q_{β^-} = 1.173 MeV) has a branching fraction of 95% for the decay of a 661.7 keV γ-quant.

  A contamination of ^{60}Co in the steel used for the construction of the detector may contribute to the external background by emitting high energy γ's with 1.17 MeV and 1.33 MeV.

The simulated spectra for the solar neutrino signals under the assumption of background levels given in table 1. are shown in Fig.3. The upper solid line shows the recoil electron spectrum due to the SSM neutrino fluxes, while the solid line below corresponds to a full conversion of ν_e into $\nu_{\mu,\tau}$ (via MSW effect). The expected number of ν-events in the ^{7}Be-neutrino energy window (250 keV $< E_e <$ 800 keV) is about 50 counts/d (SSM), or about 10 counts/d (MSW effect) respectively.

The ^{7}Be-neutrino signal to background ratio is approximately 5 to 10 for SSM neutrino fluxes. It strongly depends on the radio purity achieved in the scintillator and the detector components. The radio purities are controlled by ultra-low background gamma spectroscopy, mass spectroscopy, and Neutron Activation Analysis (NAA $\rightarrow$ see sec.4), as well as high sensitivity measurements of radon emanation. However, in general, these techniques do not reach sufficient sensitivity for the scintillator, in particular for the test of the ultra-low U, Th and ^{14}C contamination. Therefore a prototype detector, the *Counting Test Facility (CTF)*, has been installed in Hall C of the INFN Gran Sasso Underground Laboratory to measure radioimpurities, to test the stability of scintillator properties, and to test material and cleansing procedures for BOREXINO.

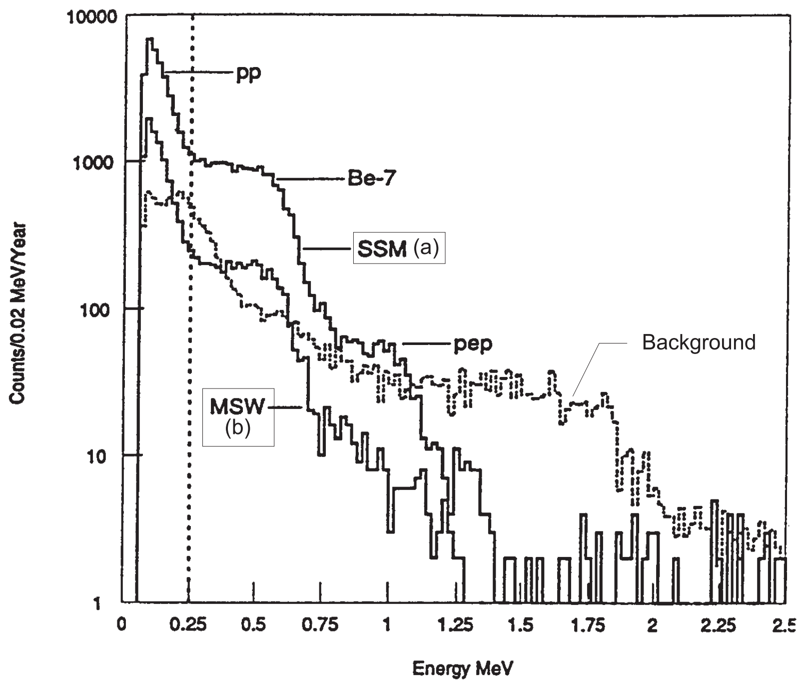

Figure 3: Simulated spectra for solar neutrino events in Borexino (100 tons FV) for (a) SSM prediction, and (b) MSW-solution, including background. The background spectrum due to radioactive impurities given in table 1 is shown as dotted line.

3 The Counting Test Facility (CTF)

The assembly of the CTF detector was finished in autumn 1994; in January 1995 the data acquisition has been started. Even if the design of the CTF is very similar to the BOREXINO detector design, it should be emphasized 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 CTF consists of 4.6 tons of liquid scintillator contained in a 0.5 mm thick nylon vessel ('inner vessel', radius 1 m). The scintillator vessel is viewed by 100 photomultipliers fixed on a spherical steel structure at a distance of 3.3 m (photo cathode) from the center of the vessel. Light concentrators (length 57 cm, aperture 50 cm) are mounted on the phototubes to increase the light collection, and to provide a geometrical coverage of 30% of 4π steradians. To shield this structure against background radiation originating from the environment of the laboratory, the whole detector is immersed in a large steel tank (11 m diameter, 10 m height) filled with 1000 tons of ultrapure, deionized water.

The scintillator used in the CTF consists of the solvent PC (pseudocumene, 1-2-4 trimethylbenzene $C_6H_3(CH_3)_3$), and the wavelength shifter PPO (diphenyl-oxazol, $C_{15}H_{11}NO$) at a concentration of 1.5 g/l. In view of BOREXINO, a test of an alternative liquid scintillator PXE (phenyl-ortho-xylylethene, $C_{16}H_{18}$) with PT (para-terphenyl, $C_{18}H_{14}$) as wavelength shifter has been performed. PXE may provide several advantages and will be further investigated, in case technical problems with PC should arise. To reduce the background of cosmic ray-produced

^{7}Be in the scintillator, the PC was immediately transported to the Gran Sasso Underground Laboratory after its production (last distillation) in Sardinia. The exposure to cosmic rays was therefore limited to less than 2 days. To remove other remaining impurities, a purification system has been installed to purify the scintillator in a recirculation loop, by water extraction, Rn stripping, and vacuum distillation.

3.1 Recent Results from the CTF

The main goal of the CTF is to investigate the concentration of radio contaminants in the organic liquid scintillator, in particular of U, Th, and of the $^{14}C/^{12}C$ level. Furthermore, a variety of purification methods to remove impurities are being tested.

By using pulse-shape analysis for $\alpha-\beta$ discrimination and the method of delayed $\alpha-\beta$ coincidences ($^{214}\mathrm{Bi} \rightarrow {}^{214}\mathrm{Po} \rightarrow {}^{210}\mathrm{Pb}$ and $^{212}\mathrm{Bi} \rightarrow {}^{212}\mathrm{Po} \rightarrow {}^{208}\mathrm{Pb}$), the CTF can provide information about the contamination of radioactive daughters from the decay chains of ^{238}U and ^{232}Th in the scintillator. This, strictly speaking, yields only the concentrations of the last predecessor nucleus in the decay chain with a half-life long as compared to the time scale of the experiment (^{226}Ra or ^{228}Th respectively). If there were chemical processes during the scintillator production, causing unequilibrium of the decay chains, the ^{238}U and ^{232}Th concentrations could be different from the values deduced under the assumption of equilibrium with their decay products.

- **Contamination due to the ^{232}Th family** :
  The contamination due to the ^{232}Th family in the CTF scintillator has been studied by measuring the delayed α-β-Bi-Po coincidence $^{212}\mathrm{Bi} \rightarrow {}^{212}\mathrm{Po}\,(\mathrm{T}_{1/2} = 300\,\mathrm{ns}) \rightarrow {}^{208}\mathrm{Pb}$. Under the assumption that the whole decay chain is in secular equilibrium, one obtains a ^{232}Th concentration in the CTF scintillator of

  $$(2.5 \pm 1.3) \cdot 10^{-16}\mathrm{g/g} \quad .$$

- **Contamination from the ^{238}U family**:
  To measure the contamination due to the ^{238}U family, the delayed α-β-Bi-Po coincidence $^{214}\mathrm{Bi} \rightarrow {}^{214}\mathrm{Po}\,(\mathrm{T}_{1/2} = 164\,\mu\mathrm{s}) \rightarrow {}^{210}\mathrm{Pb}$ has been used.
  Due to a short contact with air during the filling, Rn from the air in hall C could get into the scintillator which decays with a lifetime of 3.825 days. The Rn activity due to ^{238}U in the scintillator remains constant. The measured distribution of delayed Bi-Po-coincidences versus time has been fitted with an exponential (decay parameter: Rn lifetime) plus a constant. During 35 days of data-taking we obtained a constant counting rate which corresponds to a ^{238}U concentration of

  $$(4.9 \pm 1.5) \cdot 10^{-16}\mathrm{g/g} \quad .$$

- **Contamination due to ^{14}C**:
  To evaluate the concentration of ^{14}C in the scintillator, the energy spectrum at low energies measured in the CTF was superimposed to the corresponding simulated ^{14}C spectrum and normalized to the same area in the region 50 keV - 100 keV. The data are in very good agreement with the simulation, and one can deduce a level of

  $$\frac{^{14}\mathrm{C}}{^{12}\mathrm{C}} = (1.45 \pm 0.01) \cdot 10^{-18} \quad .$$

At this level, the ^{14}C contamination does not contribute significantly to the total background relevant for the ^{7}Be neutrino detection in BOREXINO.

- **Internal Background in the CTF**:
  By Rn insertion into the water buffer it could be demonstrated that the external background rate in the CTF was mostly dominated by Rn contamination in the external water shielding. A comparison of the radial distribution of CTF events prior to Rn insertion with the radial distribution of the determined external background gives an 1 σ upper limit for the internal background rate in the ^{7}Be neutrino energy window (250-800 keV) in 4.5 tons of scintillator:

  $$\text{internal background: } < 40 \text{ counts/day } (1\,\sigma).$$

  This limit is consistent with a vanishing counting rate due to possible contaminations of the scintillator.

4 Neutron Activation Analysis (NAA) for BOREXINO

A very sensitive Neutron Activation Analysis (NAA) technique has been developed at the Technical University of Munich in the past years to determine the uranium, thorium, and potassium content in organic liquid scintillators and plastics. This NAA analysis is of great importance because it provides complementary information to the CTF by a *direct* measurement of ^{238}U and ^{232}Th in the scintillator, which cannot be expected to be in secular equilibrium with long-lived daughters (see sec. 3.1).

Furthermore, NAA is sensitive to other natural radionuclides as ^{40}K, ^{87}Rb, ^{113}Cd, ^{115}In, ^{138}La, or ^{176}Lu, which may be background sources in the scintillator, and is an important tool to select and test other detector components as water and several plastics, as well as to test scintillator purification techniques.

To meet the high sensitivity required for BOREXINO, all important factors for sensitive NAA have to be optimized, high sample mass, long irradiation time, high neutron flux, radiochemical treatment of the irradiated sample, coincidence techniques, low background Ge-detectors with high efficiency.

A special facility at the research reactor in Garching (FRM) allows the irradiation of liquids with a volume of 250 ml, and an irradiation-time up to 100 h at a thermal neutron flux of $5 \cdot 10^{12} cm^{-2} s^{-1}$. After irradiation, radiochemical separation methods are applied. This allows the removal of main interfering nuclides, causing background during the measurement of the sample, and can be necessary, if the interesting nuclides have to be mixed with a scintillator for coincidence techniques with β's or conversion electrons. These coincidence techniques are a further step to improve the signal to background ratio. For the detection of ^{238}U, a special signature in the decay of ^{239}Np is used, and the present detection limit is about 10^{-16}g/g. The detection limit for potassium is presently 10^{-12}g/g, and for ^{232}Th about 10^{-15}g/g [7].

These NAA techniques meet the requirements for BOREXINO in many cases and may be useful for other low background experiments, too.

5 Conclusions

The high sensitivity and purity levels obtained with the CTF prototype detector located at the Gran Sasso Underground Laboratory in Italy show that the most important milestones for the preparation of the BOREXINO experiment have been reached. Above all, the measured low concentration of ^{14}C is of special interest for the feasibility of BOREXINO. Also the high purity levels of U and Th in the scintillator, of the nylon vessel, and the water shielding are within the range of the design goals given in table 1.

Due to the results achieved with the CTF, the construction of BOREXINO has been started. Presently, the external tank is close to be completed. A fluid handling system to allow for online test measurements of the scintillator for Borexino before filling is installed. A scintillator storage capacity for 400 m^3 is being in preparation. Borexino is expected to be operational by the end of 1999. The experiment is funded by the Italian Istituto Nazionale di Fisica Nucleare (INFN) and the Bundesministerium für Bildung, Forschung und Technologie (BMBF), as well as by the Sonderforschungsbereich SFB 375 for Astro-Particle Physics in Germany. Funding is also expected from the NSF in the USA.

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