Solar Neutrino Spectroscopy

F. v. Feilitzsch
Technische Universität München, Physik Department E15, D-85747 Garching, Germany,
and Sonderforschungsbereich SFB-375 "Research in Particle-Astrophysics"

Since the pioneering experiment of R. Davis et al., which started neutrino astronomy by measuring the solar neutrinos via the inverse beta decay reaction on ^{37}Cl, all solar neutrino experiments find a considerably lower flux than expected by standard solar models. This finding is generally called the solar neutrino problem. Many attempts have been made to explain this result by altering the solar models, or assuming different nuclear cross sections for fusion processes assumed to be the energy sources in the sun.

There have been performed numerous experiments recently to investigate the different possibilities to explain the solar neutrino problem. These experiments covered solar physics with helioseismology, nuclear cross section measurements, and solar neutrino experiments.

Up to now no convincing explanation based on "standard" physics was suggested. However, assuming non-standard neutrino properties, i.e. neutrino masses and mixing as expected in most extensions of the standard theory of elementary particle physics, natural solutions for the solar neutrino problem can be found.

It appears that with this newly invented neutrino astronomy fundamental information on astrophysics as well as elementary particle physics are tested uniquely. In this contribution an attempt is made to review the situation of the neutrino astronomy for solar neutrino spectroscopy and discuss the future prospects in this field.

1. Introduction

The longstanding *Solar Neutrino Problem* consists of the discrepancy between the detected solar neutrino fluxes and the theoretical predictions. Here it generally is assumed that the sun is in thermal equilibrium, and the luminosity is given by proton nuclear fusion processes to ^{4}He.

There are presently experimental data available from the inverse beta decay reaction on ^{71}Ga (Gallex and Sage) and ^{37}Cl (Homestake), and on ν-e scattering (Kamiokande and Superkamiokande) at energies above 6.5 MeV. With these experiments we can already investigate the solar neutrino spectrum using the spectral information from ν-e scattering at energies above 6.5 MeV, and the different threshold energies for the inverse beta decay experiments. It is this spectral information which provides the most powerful arguments for the understanding of the solar neutrino problem.

Within the standard solar models it is assumed that the sun is in hydrostatic equilibrium, the energy is generated by nuclear fusion processes in the center of the sun, and the energy transport from the center to the surface is provided by photon diffusion or convection [5], [6], [7], [8].

The assumption of hydrostatic equilibrium was recently justified impressively by new measurements on helioseismology giving information on the propagation of density waves (p modes) throughout the interior of the sun. In these experiments the radial velocities are measured over the surface of the sun with high accuracy.

Starting from hydrogen fusion we can calculate the element abundances in the sun for an assumed age of $\approx 4.5 \cdot 10^9$ years. With these element abundances the solar fusion reaction rates can be calculated using the fusion reaction cross sections derived from nuclear experimental and theoretical investigations. In Fig.1 the dominating pp fusion chain to ^{4}He is shown. There are essentially three neutrino emitting reactions involved leading to an estimated solar neutrino flux on earth of

1.) $p + p \rightarrow {}^2\mathrm{H} + e + \nu_e$ ($E_\nu < 420\,\mathrm{keV}$):
$6 \cdot 10^{10}\,\nu/\mathrm{cm}^2/\mathrm{s}$

2.) $^7\mathrm{Be} + e \rightarrow {}^7\mathrm{Li} + \gamma + \nu$ ($E_\nu = 862\,\mathrm{keV}$ 90%):
$0.47 \cdot 10^{10}\,\nu/\mathrm{cm}^2/\mathrm{s}$

3.) $^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e + \nu$ ($E_\nu < 14.6\,\mathrm{MeV}$):
$5.8 \cdot 10^6\,\nu/\mathrm{cm}^2/\mathrm{s}$

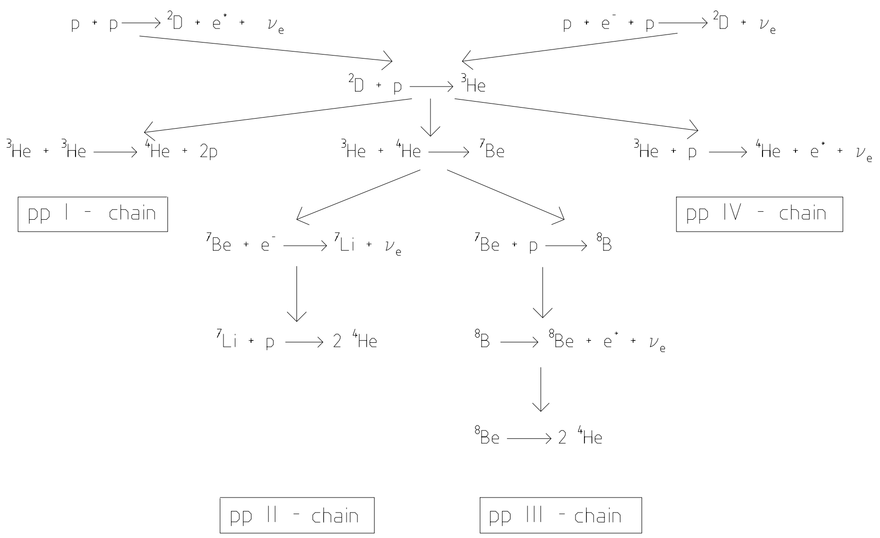

Figure 1. The four reaction chains of the pp fusion to ^{4}He.

A solar neutrino spectrum, as calculated on these standard solar model assumptions by J. Bahcall [5], is shown in Fig.2.

2. Status of present experiments

At present, all operating solar neutrino experiments measure a ν-flux which is 30% to 60% of the flux predicted by Standard Solar Models. To explain this significant suppression, both Non-Standard Solar Models as well as physics beyond the Standard Model of Electroweak Interaction have been proposed.

Comparing the results of the Homestake [1] ($^{37}\mathrm{Cl}+\nu_e \rightarrow {}^{37}\mathrm{Ar}+e^-$; $\langle N_\nu \rangle = 2.55 \pm 0.25\,\mathrm{SNU}$) and the Superkamiokande [10] ($\nu e \rightarrow \nu e$; $\Phi_{\nu_B} = (2.44 \pm 0.4), \pm^{0.25}_{0.09} \cdot 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) experiments, which operate with different energy thresholds, the data indicate a substantial suppression of the ^{7}Be neutrino line at $\mathrm{E}_\nu = 862\,\mathrm{keV}$. Here, 1 SNU is defined to 1 ν reaction per 10^{36} target atoms and sec. Recent results obtained by the GALLEX experiment [2] and the SAGE experiment [3] using the reaction $^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$, show a neutrino flux $\langle \Phi_\nu \rangle = 76.4 \pm 6.3 \pm {}^{4.5}_{4.9}$ SNU and $\langle \Phi_\nu \rangle = 74 \pm {}^{11}_{10} \pm {}^{5}_{7}$ SNU respectively, whereas 115-137 SNU are expected from different standard solar model calculations [5], [6], [7], [8].

Fig.3 shows the calculated GALLEX ν-signal as a function of the rate $\Phi_\nu(^7\mathrm{Be}) : \Phi_\nu(^7\mathrm{Be})_{\mathrm{SSM}}$, assuming that only ^{8}B neutrinos with a flux as measured by Superkamiokande are present [2], [4].

From this picture we derive a stringent upper constraint on the ^{7}Be neutrino flux by only taking the actual GALLEX (or SAGE) with the Superkamiokande data and the solar luminosity constraint into account. Within the GALLEX and Superkamiokande 90% confidence levels, the beryllium flux is about $\Phi_\nu(^7\mathrm{Be}) : \Phi_\nu(^7\mathrm{Be})_{\mathrm{SSM}} \leq$ 20% i.e. $\Phi_\nu(^7\mathrm{Be}) \leq 1 \cdot 10^9\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. As the gallium data are obtained from an inverse beta decay reaction, these limits apply to the ν_e flux essentially.

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

There is up to now no solution based on stan-

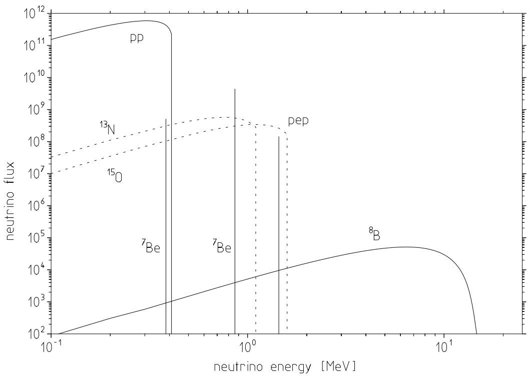

Figure 2. The solar neutrino spectrum as calculated by J. Bahcall [5]. The neutrino flux of the continuous spectra is given in $MeV^{-1}cm^2s^{-1}$ and the neutrino flux of the line spectra in $cm^{-2}s^{-1}$. The hep-neutrinos and the neutrinos from the CNO-cycle are neglected.

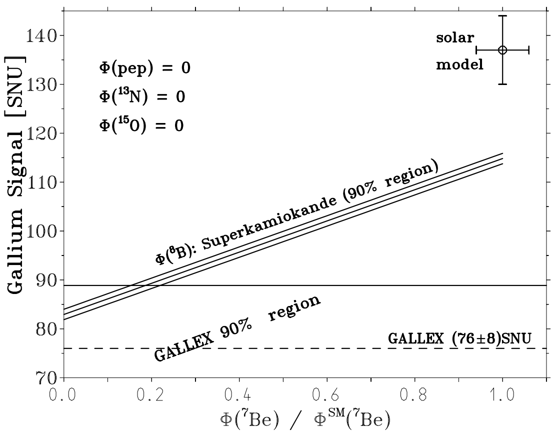

Figure 3. Expected GALLEX-signal as a function of the ^{7}Be neutrino flux .

dard physics proposed to explain these experimental findings. However, if we assume neutrino oscillations i.e. neutrino masses and mixing as suggested in most extensions of the standard model of elementary particle physics, the data can be readily explained. Neutrino oscillation in vacuum as well as in matter can be a solution to the data (see Fig.4).

For a model independent determination of the origin of the present experimental situation, a detailed solar neutrino spectroscopy is required. This can be provided to a large extent with the forthcoming second-generation solar neutrino experiments and with those being under investigation for the third generation even in the charged and neutral current channels separately.

3. Forthcoming solar neutrino experiments

The HOMESTAKE experiment detects solar neutrinos with the inverse beta decay reaction

$$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e$$

being purely sensitive to electron neutrinos. The experiment has been continuously running for 30 years (with a small technical interruption).

It is planned to continue taking data for the next future to provide the ν_e flux with an energy threshold of 814 keV during data taking of the forthcoming second generation solar neutrino experiments. Particular emphasis is put on for an investigation of possible correlations between the solar neutrino flux and solar flair activities.

For this purpose there is in addition a second experiment being set up using a similar radiochemical technique, but which uses ^{127}I as a solar neutrino target. The threshold energy for inverse beta decay at this isotope is 789 keV with a nuclear crossection about one order of magnitude larger than in ^{37}Cl allowing for a higher statistical accuracy of the measurement. This experiment is constructed in a modular technique allowing for a subsequent extension of the target mass [16].

The GALLEX Collaboration has stopped taking data in January 97. Since then extensive tests have been performed to improve further the understanding of systematic uncertainties. In particular, efficiency tests have been performed for the extraction of radiochemically introduced ^{71}Ge by the β-decay of ^{71}As within the target solution. This test has convincingly confirmed the efficiency of Ge extraction out of the $GaCl_4$ target solution.

There is a new collaboration formed to continue data taking with the present Ga target. For this purpose the Ga, which was on loan up to now, has

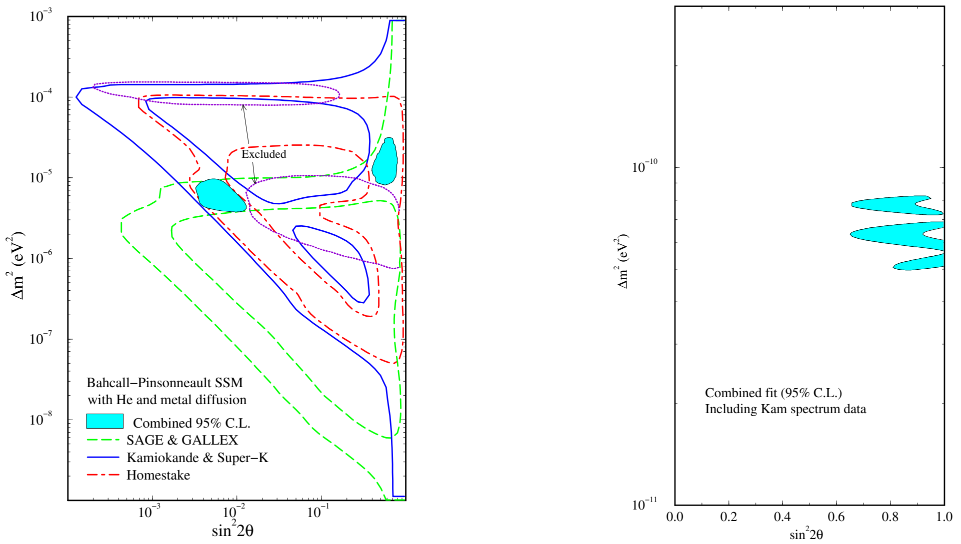

Figure 4. The small and large mixing angle solutions for neutrino oscillations in matter (on the left) and the vacuum oscillation solutions (on the right) as calculated by Hata and Langacker [9]

been bought to allow for a long term use in a Gallium Neutrino Observatory (GNO). The goal of this collaboration is similar to that of the Cl and I experiments but covering with the low energy threshold of 233 keV all solar neutrino sources, in particular the dominating pp neutrinos.

After a revision of the experimental set up, data taking will continue with the present target in 98. It is planned to further develop the technique for the registration of the ^{71}Ge decay to achieve a still higher detection efficiency, and in particular a reduction of systematic uncertainties. In addition an increase of the target mass up to 100 t is considered to allow for a high statistics measurement.

The second Ga neutrino collaboration SAGE plans also to continue data taking in the Baksan neutrino laboratory.

The SUPERKAMIOKANDE experiment is a second-generation version of the Kamioka experiment in Japan. It consists of a 50000 t H_2O Cerenkov detector out of which 22000 t of H_2O are used as a solar neutrino target. The detector is surrounded by a veto Cerenkov detector to suppress cosmic ray induced background. On the basis of standard solar models a rate of ≈ 60 solar induced events per day are expected. The detected rate is $0.368^{+0.06}_{-0.009}(\mathrm{stat})^{+0.025}_{-0.09}(\mathrm{syst})$ of the standard solar model rate. The uncertainties are dominated by systematic uncertainties of the energy calibration which will be improved in the near future. The total data taken since April 96 (4395 solar neutrino events per 306 days of data taking) is close to be a factor of ten more than all data from Kamiokande. The energy threshold for solar neutrino detection is presently 6.5 MeV and is expected to be lowered to 6 MeV.

It will be of particular interest to compare the measured ^{8}B neutrino spectral shape with the shape expected from nuclear beta decay. This will provide a model-independent test for the energy-dependent neutrino oscillation. More detailed information on this experiment is found in a special contribution to these proceedings.

The Sudbury Neutrino Observatory (SNO) is a further experiment being presently completed, aiming for the ^{8}B solar neutrino spectroscopy. This experiment consists of a 1000 t D_2O Cerenkov detector installed in the Sudbury mine in Canada. Solar neutrinos can be detected in this case via neutral current (NC) and charged current (CC) induced reactions. The detection reactions are

- $\nu_e + d \rightarrow p + p + e$ (CC with $E_\nu > 5$ MeV)
- $\nu_x + d \rightarrow p + n + \nu_x$ (NC with $E_{th} = 2.2$ MeV)
- $\nu_x + e \rightarrow \nu_x + e$ (CC+NC with $E_e > 5$ MeV)

The comparison of the NC to CC reaction rates will be in this case a further model-independent test of the ν_e/ν_x flux ratio in the ^{8}B neutrino spectrum.

The CC induced reaction rate on d will provide a particularly sensitive test of the spectral shape as the emitted electron carries the neutrino energy minus the reaction threshold energy of 1.44 MeV.

The experimental installations will be completed in early 98 when the filling of the detector will start. The first data significant for the solar neutrino problem are expected within 1 or 2 years.

The ICARUS experiment uses a large volume liquid Ar time projection chamber with very high granularity in spacial and energy event reconstruction. With this detector it will be possible to detect solar neutrinos with energies above 7 MeV. The electron trace reconstruction will allow for a high accuracy directional information, and therefore provide the spectral shape. The detector is constructed in a modular system, each containing 600 t of liquid Ar as a solar neutrino target. The detector will in addition be used for a search for proton decay and a long baseline neutrino oscillation experiment with a high energy neutrino beam from CERN.

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

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 using neutrino-electron scattering in an organic liquid scintillator. This reaction includes charged and neutral current interactions, and is therefore sensitive to the ν_e and $\nu_{\mu,\tau}$ flux. Together with the forthcoming high-accuracy Ga-experiment GNO, and the other second-generation solar neutrino experiments, it may therefore be possible to obtain information on the charged and neutral current contributions separately.

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 neutrino detection reaction relies on 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 neutral 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 is

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

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.6). The conceptual design of BOREXINO is shown in Fig.5 [11].

The BOREXINO detector consists of 300 t of ultrapure liquid scintillator contained in a vessel ('Inner Vessel', radius = 4.25 m) made of a thin, UV-transparent nylon film. This vessel is immersed in 1100 m^3 buffer liquid contained in a stainless steel sphere of radius 6.75 m. 2200 photomultipliers are fixed on the inner side of the steel sphere to view the scintillation light and Cerenkov light from the buffer liquid. 1800

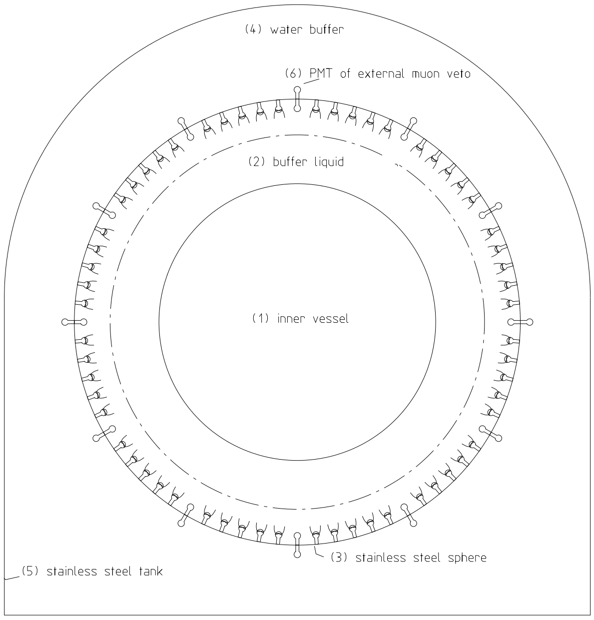

Figure 5. Conceptual design of the BOREXINO detector: (1) Inner Vessel, containing 300 t of liquid scintillator (d=8.5 m; (2) ultrapure buffer liquid; (3) stainless steel sphere (d=13.5 m) with 2400 PMT's; (4) water buffer: 1100 t of high purity, deionized water; (5) stainless steel tank; (6) external Muon Veto .

of the photomultipliers are equipped with light-cones for an efficient collection of scintillation light from the inner vessel. The remaining 400 photomultipliers without light-cones collect in addition Cerenkov light from the buffer liquid for an efficient identification of muon-induced signals.

The three-dimensional arrangement of the phototubes provides the possibility of position reconstruction of signals within the detector volume. Therefore, a fiducial volume of 100 t 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 an ultra pure buffer liquid (possibly pseudocumene), which serves in addition as an active shielding against radioactive background from the outer detector parts. Finally, the whole detector is located in a steel tank with 16 m of height and 17 m of diameter, filled with about 1100 t of high purity, deionized water to shield against external radiation. Furthermore, an external Cerenkov muon veto will be installed. This will surround the inner detector and consist of additional 200 phototubes mounted outside the stainless steel sphere to detect muon-induced Cerenkov light in the external water shield. The internal and external detection of Cerenkov light in the shielding liquids will provide a highly efficient identification of muon-induced background.

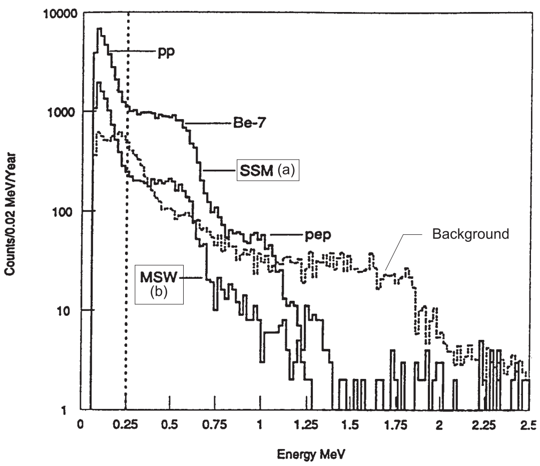

Figure 6. Simulated spectra for solar neutrino events in BOREXINO (100 t FV) for (a) SSM prediction, and (b) MSW-solution, including background. The background spectrum, due to radioactive impurities given in Table 1, is shown as dotted line.

The identification of solar neutrinos in this detector essentially relies on a very low radioactive background of all detector components.

The simulated spectra for the solar neutrino signals under the assumption of the background levels given in Table 1 are shown in Fig.6. The upper solid line shows the recoil electron spectrum

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)	$4 \cdot 10^{-11}$	10^{-10}	$6 \cdot 10^{-6}$	
Buffer liquid	10^{-13}	10^{-13}	10^{-10}	
Photomultiplier	$3 \cdot 10^{-8}$	10^{-8}	$2 \cdot 10^{-5}$	
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.

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 ($250\,\mathrm{keV} < E_e < 800\,\mathrm{keV}$) is about 50 counts/d (SSM), or about 10 counts/d (MSW effect) respectively.

The radio purities are controlled by ultra-low background gamma spectroscopy, mass spectroscopy, and Neutron Activation Analysis (NAA), 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 cleaning procedures for BOREXINO.

The CTF consists of 4.6 t of liquid scintillator contained in a 0.5 mm thick nylon vessel ('Inner Vessel', radius 1.1 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 t of ultrapure, deionized water.

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 the ^{14}C/^{12}C level.

Furthermore, a variety of purification methods to remove impurities have been tested [12], [13], [14].

In addition, a very sensitive Neutron Activation Analysis (NAA) technique has been developed during the past years to determine the uranium, thorium, and potassium content of 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.

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 [15].

These NAA techniques meet the requirements for BOREXINO in many cases. Further work is in progress to yet improve the sensitivity, in particular for K and Th.

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 near to completion. A fluid handling system to allow for test measurements of the scintillator in the CTF before filling in the BOREXINO detector is installed. A scintillator storage capacity of 400 m^3 is under preparation. BOREXINO is expected to be operational by the year 2000. The experiment is presently funded by the Italian and German collaborations and expected to be funded by the US collaboration as well.

4. Future developments

There are further solar neutrino experiments under investigation. These aim in particular for more information on the low energy part of the solar neutrino spectrum.

Two groups (SUPERMUNU [17] and HELLAZ [18]) investigate large volume gas time projetion chambers with high granularity to measure the low energy part of the solar neutrino spectrum with the neutrino electron scattering reaction. For this development the chambers have to be built in a very low radioactive background version. If this development would be successful, and if the directionality of the incoming neutrinos could be sufficiently well determined, a sensitve spectroscopy at low energies could give even more detailed information on the solar neutrino spectrum.

For a seperate charged current information, in particular for the ^{7}Be solar neutrinos with 862 keV, a real time detector using an inverse beta decay reaction with simultaneous energy information would be desirable.

There were the isotopes ^{115}In and ^{176}Yb, among others suggested by R. Raghavan [19], to be used in large volume scintillation detectors. Both isotopes allow for delayed β-γ coincidence measurements to improve the signature for neutrino induced events.

^{115}In with an inverse beta decay threshold energy of 119 keV decays with a half life of $4 \cdot 10^{14}$ years. This natural decay constitutes a severe background for solar neutrino detection and makes it very difficult for pp neutrino detection, as the beta decay end point energy is 485 keV. The detection of ^{7}Be neutrinos at 862 keV should however be possible.

^{176}Yb, however, is a stable element and should therefore constitute less problems in terms of internal background in the detector. The inverse beta decay threshold energy in this case is 445 keV allowing for the detection of electron neutrinos from ^{7}Be at 862 keV. The coincident measurement of the emitted electron with subsequent γ-rays from the populated 339 keV 1^+ state in ^{176}Lu may provide a good signature for the reaction.

In both cases, however, a development of a scintillator with sufficient light transparency and stability would still be required. There is an evidence that this can be achieved at least for In loaded scintillators [20].

5. Conclusions

With the experiments presently operating and under preparation it will be possible to provide detailed information on the whole solar neutrino spectrum. It will be possible, in particular to compare the high energy part of the solar neutrino spectrum with the nuclear beta decay spectral shape and obtain information on the electron neutrino flux with respect to the total neutrino flux. From a comparison of the data taken with Ga experiments, and the flux measured with BOREXINO and SNO or/and Superkamiokande, the pp neutrino flux between 233 keV and 420 keV can be derived.

With these results we can expect to get sufficient information to prove neutrino oscillations if they are the origin of the solar neutrino problem.

If there would be an additional experiment available, which could measure the ^{7}Be neutrino flux by a pure charged current reaction, the whole solar neutrino spectrum could be model-independently derived in terms of electron or muon and tau neutrino fluxes.

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