FUTURE SOLAR NEUTRINO EXPERIMENTS

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ABSTRACT

Upcoming solar neutrino experiments and some future projects are described. Here I will concentrate on low energy experiments able to measure in real time and with energy resolution. Borexino, which is going to be build up at the Gran Sasso underground laboratory, will measure low energy solar neutrinos with charged as well as neutral current mode. Lens, a proposed project, will be operating in the charged current mode. Results from both experiments can give proof to neutrino oscillations unambigeously.

1. Introduction: the ^7Be neutrino problem

The solar neutrino problem originates from the discrepancy between the ν_e expectations of the solar neutrino flux, as calculated by the Solar Standard Model [1], and the experimental results. In table 0.1 the experimental results are compared with the expected values of the standard model.

Table 0.1:

Experiment	Measured flux S.M. expectation	Threshold (MeV)
Homestake	0.27±0.06	0.814
Kamiokande	0.44±0.06	7.5
SuperKamiokande	0.358±0.009±0.014	6.5
Gallium (Gallex, Sage)	0.6 ± 0.06	0.235

Information from helioseismology confirm the solar standard model to an accuracy within <1%. In addition, experimental results from the LUNA experiment at low energies in the $^3He+^4He$-channel exclude explanations based on discrepancies in this nuclear cross section. At last, the overall performance of both gallium experiments has been tested by terrestial neutrino sources, and no discrepancy from the expected values has been found [2].

Data analysis of the existing experiments leads to the assumption of severe suppression of the solar ^7Be-branch. In fig. 0.1 the signal strength (1 SNU = 1 capture in 10^{36} target atoms per second) of any gallium experiment is depicted as function of the ^7Be neutrino flux, which acts as a free parameter and is shown as the abscissae of the plot. The only inputs in the calculation are the integral flux of the SuperKamiokande experiment, which is taken as the value for the $^8B-$neutrinos, and the known lu-

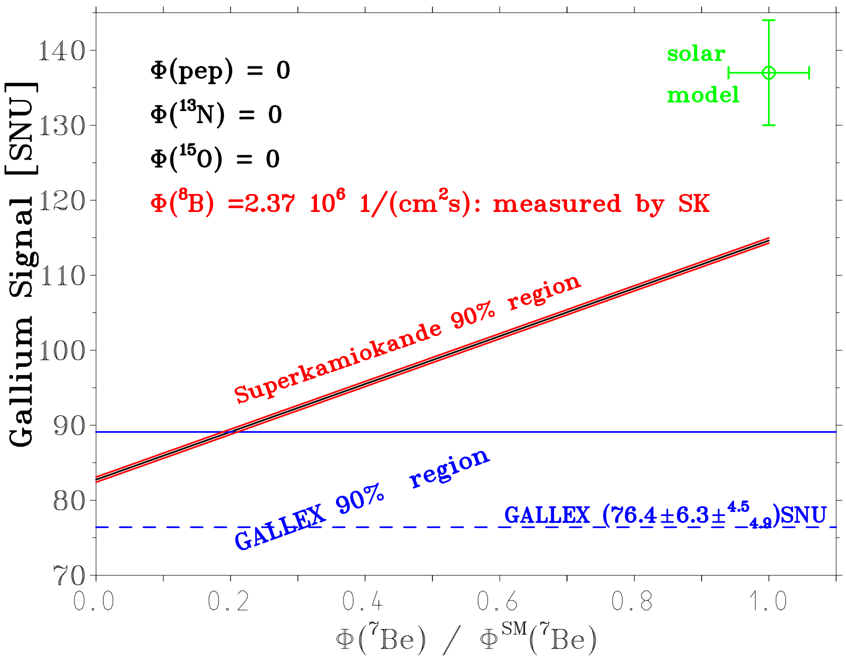

Figure 0.1: *Model independent constraint on the charged current solar 7-Be neutrino flux derived by the experimental results from SuperKamiokande, Gallex, and the value of the solar luminosity. The signal strength (1 SNU = 1 capture in* 10^{36} *target atoms per second) of a gallium experiment is depicted as function of the 7-Be neutrino flux, resulting in the black line. The width of the line represents the experimental uncertainty of SuperKamiokande. Within 90% CL only about 20% of the expected 7-Be neutrino flux is compatible with experimental results.*

minosity of the sun. The width of the line represents the experimental uncertainty of SuperKamiokande after roughly 1 year of data taking. Contributions from other branches of the pp-cycle and the CNO-cycle in a Gallium experiment are neglected. By comparing this dependence on the ^7Be neutrino flux with the actual result in the Gallex experiment only 20% of the expected *charged current* ^7Be neutrino flux is allowed within 90% CL. This fact is a strong hint for physics beyond the standard model since it cannot be explained by modifications of the standard astrophysical model of the sun: by decreasing the central solar temperature one always depletes the ^8B flux stronger than the ^7Be flux, because former is hindered by a Coulomb barrier.

Fig. 0.1 also illustrates the importance of an experiment which improves statistics as well as systematic uncertainties in the Gallium data. This is the aim of the GNO (Gallium Neutrino Observatory) project which follows Gallex at the Gran Sasso underground laboratory. If GNO is successful a constraint on the charged current ^7Be neutrino flux with high reliability can be claimed. Since Borexino will provide information about the charged and the neutral current contribution at low energies (see text below) the limit from GNO could become very important when discussing the strength of evidence for neutrino oscillations.

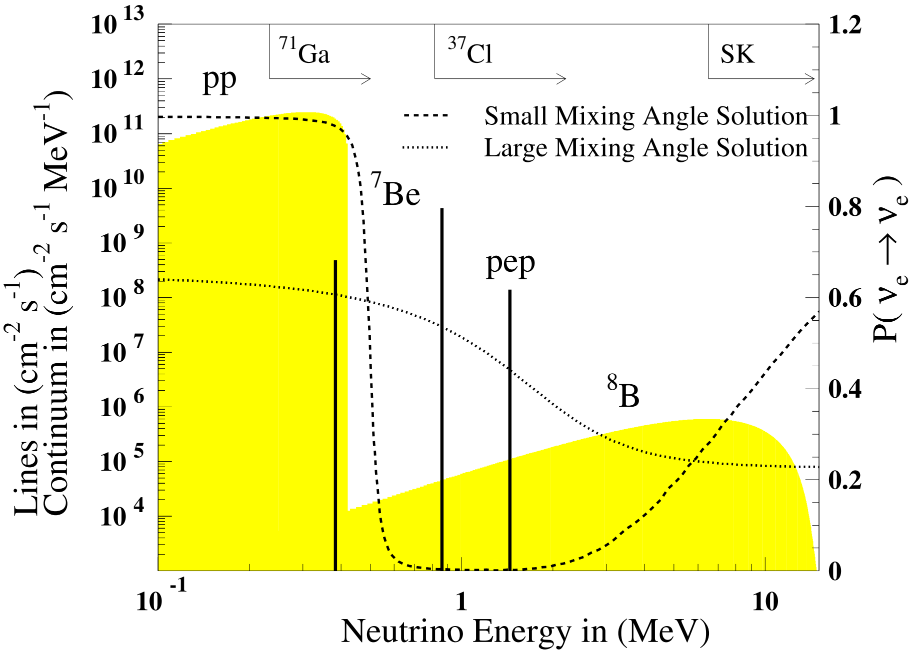

Figure 0.2: *The solar neutrino spectrum as calculated in the standard model and the electron neutrino survival curve due to resonant neutrino flavour transversion with typical values for the small (i.e.* $\Delta m^2 = 8 \cdot 10^{-6}\ eV^2$ *and* $sin^2 2\Theta = 5 \cdot 10^{-3}$*) and large mixing angle solution (i.e.* $\Delta m^2 = 2 \cdot 10^{-5}\ eV^2$ *and* $sin^2 2\Theta = 0.6$*). The 7-Be neutrino line at 861 keV is almost completely suppressed in the small mixing angle solution, as it is indicated by experimental data. The spectral shape of the high energy 8-B neutrino branch should be deformed. The measurement of this shape is aim of SuperKamiokande and SNO, Borexino will deliver information about the 7-Be neutrino flux.*

1.1. Neutrino Oscillations as Solutions to the Solar Neutrino Problem

If neutrinos have non-zero masses and if they mix in analogy to the quark sector, neutrino oscillations arise. It can be shown (e. g. see fig. ??) that certain parameter on neutrino masses and mixing angles provide a solution to all observed results. There exist three parameter areas: the MSW[a]small mixing angle solution with values

[a]Mikhejev, Smirnov, Wolfenstein effect: resonant flavour conversion inside the sun, e.g. ref [3]

typically for neutrino mass differences $\Delta m^2 \approx 10^{-6} \rightarrow 10^{-5}\ eV^2$ and mixing strength in the region $10^{-6} < sin^2 2\theta < 2 \cdot 10^{-5}$, the MSW large mixing angle solution for the same mass region but almost full mixing strength, and the vacuum oscillation solution with strong mixing at $\Delta m^2 \approx 10^{-10}$ eV^2.

Fig. 0.2 shows the deformation of the solar neutrino spectrum as expected in case of the MSW solution. The ^7Be neutrino line at 861 keV is almost fully suppressed in the small mixing angle solution as it is indicated by experimental data. The spectral shape of the high energy ^8B neutrino branch should be deformed. The measurement of this shape is aim of SuperKamiokande and SNO, whereas Borexino will deliver information about the ^7Be neutrino flux.

In case of the large mixing angle solution the ^7Be neutrino line at 861 keV is not fully suppressed and the deformation of the shape of the high energy 8-B neutrino branch is different as compared to the small mixing angle solution.

2. Borexino

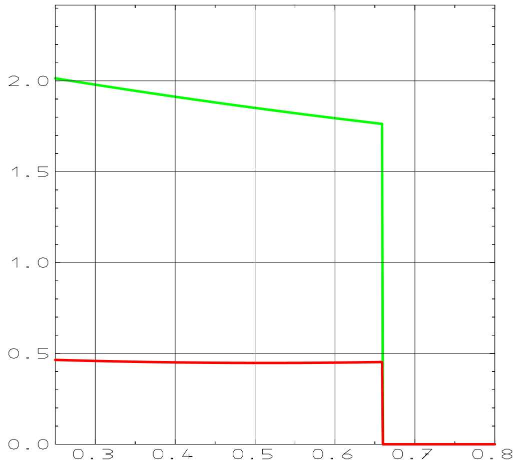

Figure 0.3: *Ideal recoil spectrum in the Borexino experiment for 7-Be neutrino electron scattering. Units of the abscissae, the recoil energy, is in MeV, the ordinate is given in arbitrary units. The maximal energy of the scattered electron is 660 keV. The upper curve corresponds to electron neutrinos. In this case for 100t of target mass a counting rate of 55 events per day is expected. In case of total flavour conversion only the neutral current contribution of muon or tau neutrinos contribute (lower curve). The corresponding integral counting rate in Borexino would reduce to ca. 12 events per day.*

The aim of Borexino is to measure in real time the solar neutrino flux with low energy threshold at high statistics, and energy resolving via pure leptonic neutrino electron scattering $\nu + e \rightarrow \nu + e$. Liquid scintillator (300t total mass) will be target and detector material. Monoenergetic ^7Be-neutrinos give rise to a compton like recoil spectrum in Borexino with a edge at 660 keV (see fig. 0.3). Assuming validity of the standard model a counting rate for ^7Be-neutrinos, which would consist in this case purely as ν_e, of roughly 55/day in Borexino is expected. Here charged current as well as neutral current interaction in the neutrino electron scattering takes place.

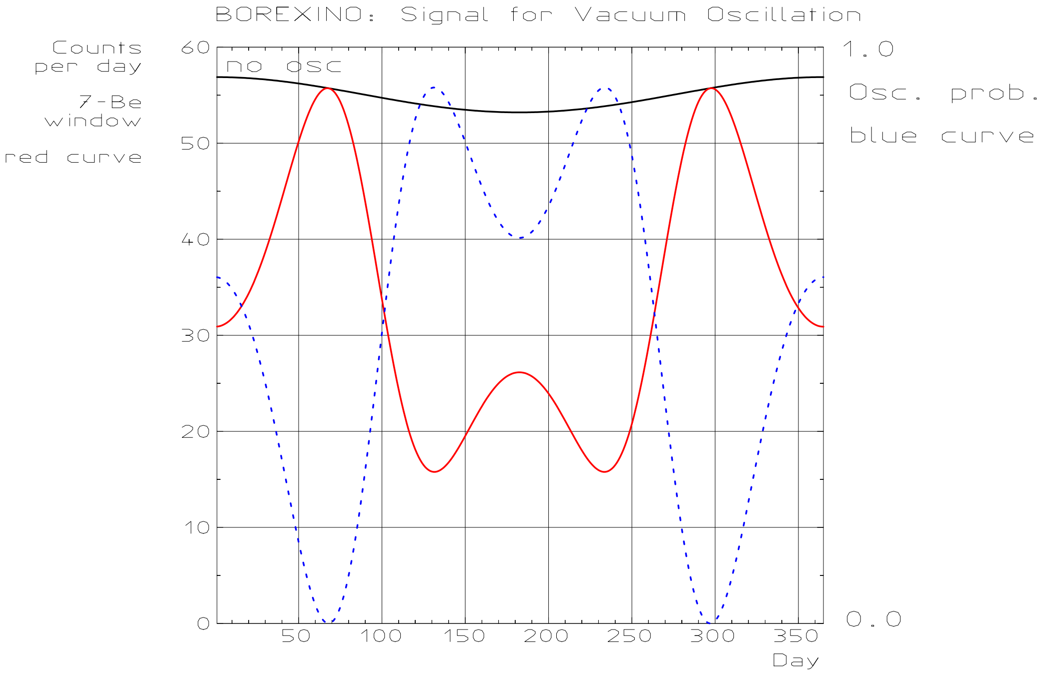

Figure 0.4: *Counting rate of the 7-Be solar neutrino flux in Borexino in case of vacuum oscillations for parameters favoured by the recent SuperKamiokande results. A very distinct seasonal dependence should be observed. As a dashed line the oscillation probability is indicated with the scale on the right side.*

In scenarios of total neutrino flavour conversion, i.e. for neutrino mass differences $\Delta m^2 \approx 10^{-6} \rightarrow 10^{-5}\ eV^2$, a reduced flux of approximately 12/day would be measured due to the lower cross section of $\nu_{\mu,\tau}$ scattering, which occurs only via neutral current interaction.

Fig. 0.3 shows the theoretical recoil spectrum of electrons scattered off by ^7Be-neutrinos. The upper curve corresponds to ν_e- while the lower curve belongs to ν_μ or ν_τ-scattering where only neutral current interaction can occure.

In case of vacuum oscillations, i.e. for neutrino mass differences $\Delta m^2 \approx 10^{-10}\ eV^2$, Borexino would see a distinct time dependent periodical neutrino signal due to the seasonal eccentricity of the earths orbit around the sun. In fig. 0.4 the counting rate of the 7-Be solar neutrino flux in Borexino is depicted in case of vacuum oscillations for parameters favoured by the recent SuperKamiokande results. A very distinct seasonal dependence should be observed. As a dashed line the oscillation probability is indicated with the scale on the right side. But also for other parameters in the range of $\Delta m^2 \approx 10^{-10}\ eV^2$ a very clear seasonal fluctuation should be expected.

For neutrino mass differences in the range of $\Delta m^2 \approx 10^{-7}\ eV^2$ and for large mixing Borexino should see a 'day/night' effect due to electron neutrino recovery during the path through the earth.

Borexino also can serve for additional projects in neutrino physics. Search for a magnetic moment can be performed by means of terrestial neutrino sources by investigating the electron recoil shape at low momentum transfer. Via the inverse beta-decay $\bar{\nu}_e + p \rightarrow e^+ + n$ Borexino can look for signals from geophysical neutrinos [5] as well as for neutrinos emitted by european nuclear power plants [6]. The latter would serve as a long baseline neutrino oscillation experiment probing the large mixing angle solution for the solar neutrino problem.

2.1. The Borexino Detector

The detector is shielded successively from outer radioactivity by means of an onion-like structure. Here the adjacent inner layer serves as shielding and has to provide an increased purity in terms of internal radioactivity. Fig. 0.5 shows the experimental setup.

Borexino is placed in hall C of the underground laboratory at Gran Sasso, Italy. An overburden of ca. 3500 m.w.e. suppresses the cosmic muon flux to 1.1 $/h\,m^2$ and shifts the mean energy of the muons to 280 GeV. The outer part of the detector consists of a steel tank with 18m in height and diameter. Inside this 'external' tank a stainless steel sphere will support 2240 phototubes on the inside and 208 tubes at the outside. The steel is treated via an electropolishing procedure in such a way that the reflection of photons is suppressed. Most of the tubes inside the sphere will be equipped with light guides in order to increase the geometrical coverage and hence the energy resolution. Between external tank and sphere high purity water will serve as shielding against external gamma rays and as an active Cherenkov counter tagging penetrating cosmic muons. The steel sphere will be filled with a transparent, high purity buffer liquid which itself holds a nylon sphere, filled with organic scintillator. Between the steel sphere and the scintillator region an additional nylon shroud hinders radon convection from the outer area towards the critical region.

The active scintillator mass will be around 300t. By means of time of flight measurements the event position can be reconstructed and a fiducial volume for solar neutrino interaction defined. Latter should be about 100t, establishing a counting rate of 55 neutrinos per day according to the standard solar model. The outer part of the scintillator sphere serves as active shielding.

The demands on purity in terms of radioactivity in Borexino, especially for the scintillator itself, are challenging. In order to be able to extract a clear signal from background events also in case of total flavour conversion, an intrinsic concentration in Uranium and Thorium of ca. 10^{-16} should not be exceeded significantly. The amount

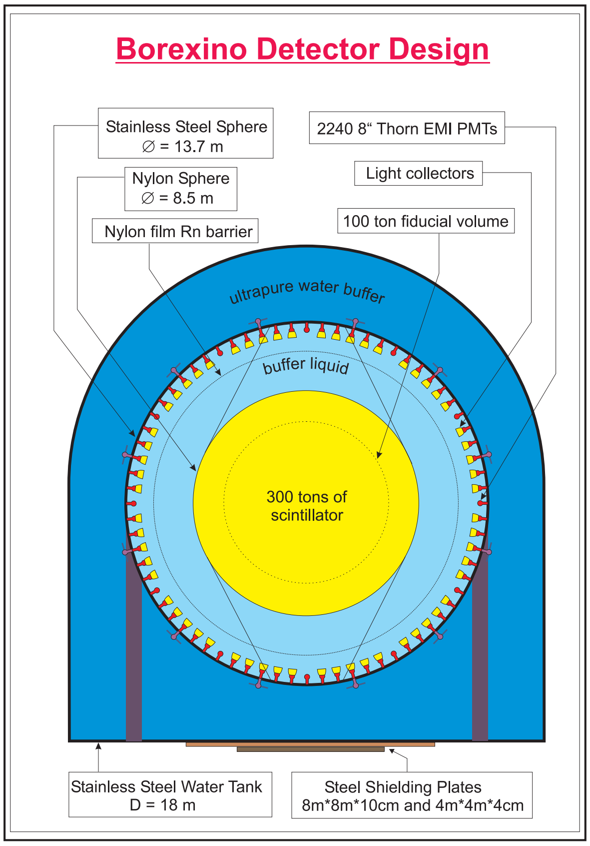

Figure 0.5: *Schematic view of Borexino. The ultrapure scintillator (300t) inside a nylon vessel is shielded differentially by means of a liquid buffer (1040t), a steel sphere on which the tubes are mounted, and the outer water buffer which is contained in an external steel tank (diameter and height ca. 18m). A transparent nylon shroud hinders radon convection in the liquid buffer region. Additional tubes mounted on the outer surface of the steel sphere allow detection of penetrating muons via the Cherenkov effect. Each 6th of the inner tubes has no light guide, which enhances the acceptance of Cherenkov photons arising from muons intersecting the liquid buffer. This allows further muon identification. For explanation see text.*

of $^{14}C/^{12}C$ must not be higher than $\approx 10^{-18}$. In order to test scintillating materials a large Counting Test Facility (CTF) has been built up in hall C of the underground laboratory at Gran Sasso, which resembles a small prototype (ca. 5t of scintillator) of Borexino. From beginning of 1995 until summer 1997 several tests about the feasibility of Borexino including procedures to maintain the purity of the scintillator have been performed, which showed encouraging results: $^{14}C/^{12}C = 1.94 \cdot 10^{-18}$, $^{238}U = (3.5 \pm 1.3) \cdot 10^{-16}\ g/g$, $^{232}Th = (4.4 \pm 1.5) \cdot 10^{-16}\ g/g$. A complete discussion of the CTF results including experimental techniques for further background suppression are given in ref. [7] and ref. [8]. Details about the experimental setup of the CTF can be found in ref. [9].

Highly developed neutron activation analysis (NAA) of scintillation samples performed in Munich was sensitive in the same regime, providing an independent test on the radiopurity and allowing tests on the secular equilibrium of the decay chains. With NAA an upper limit for uranium of $^{238}U < 2 \cdot 10^{-16}$ g/g (90% CL) has been obtained. In addition concentration values or limits have been measured by this method for various isotopes, including man-made nuclei for different detector materials. For details, see ref. [10].

In Garching a new low background laboratory with shielding against the cosmic hadronic and soft electromagnetic component has been built up and completed in 1998. First measurements with neutron activation at the research reactor FRMI in Garching, chemical extraction in the laboratory of the radiochemistry, and final data taking in the low background laboratory show, that sensitivities in Uranium far below the 10^{-16} limit can be reached now. For Thorium the improvement is at one order of magnitude as it is for most of the other relevant radionucleides. It should be emphasized, that this laboratory can provide very useful analysis for any experiment which has to rely on low background levels.

3. Lens

Direct, electron flavour specific ν_e detection is possible only by the inverse beta reaction on nuclei: $\nu_e + {}_ZA \rightarrow e^- + {}_{Z+1}A$. The electron signal realizes neutrino spectroscopy, because the energy deposited in a detector $E_e = E_\nu - Q$ is given by the neutrino energy and the energy threshold Q. Low Q-values are required to allow for detection of ^{7}-Be neutrinos and for pp-neutrinos.

In order to achieve a neutrino reaction signature it is suggestive to search for allowed transitions to daughter nuclei which relax to the ground state via a delayed coincidence. In this case correlation in space and time of the prompt electron and the delayed signal can be used to suppress background events. Hence transitions from the initial state I not to the ground state but to an excited final state $F^* =_{Z+1} A^*$ are important. Low energy threshold demands nuclear masses such that M_I is close to M_{F^*}. This however results normally to beta decay of $I \rightarrow F$ which can impose severe background problems. If candidates for such transitions can be found "Low Energy Neutrino Spectroscopy" (Lens) in the charged current channel could become feasible.

Recently R. Raghavan [4] proposed the use of $\beta\beta$-decay nucleides to overcome this problem. Isobaric triplets (with A even, Z even) were chosen for a search for the very rare process of $\beta\beta$-decay specifically with $M_I \approx M_F$. The initial nucleus is therefore practically stable even at low energy thresholds for the inverse beta decay. Three candidates for use in doped liquid scintillators have been proposed: ^{176}Yb, ^{160}Gd, and ^{82}Se. The energy thresholds are 301 keV, 244 keV , and 173 keV respectively. Therefore even solar pp-neutrino detection is possible. Lifetimes of the delayed coincidences range from 10ns (^{82}Se), 50 ns (^{176}Yb), to 94.5 ns (^{160}Gd). Therefore, from a practical view Yb and Gd seem to be more favourable as Se.

Neutrino capture strengths measurements on Gd and Yb nucleides have been initiated recently. This can be done by using (p,n) reactions on the neutrino target. First measurements seem to confirm estimations performed by Raghavan [4]. The ν_e cross sections have to be directly calibrated by a MCi ^{51}Cr source as it was demonstrated in the Gallium experiments Gallex and Sage. A ^{51}Cr source is particularly useful for low energy solar neutrino spectroscopy, because it emits two neutrino lines close in energy to the *pp* and ^7Be solar neutrino branches. Assuming Logft-values in the range between 3.7 and 5 for several Gamov-Teller transitions, which have to be confirmed by experimental data, different reactions rate can be expected as it is listed in table 0.2.

Table 0.2: *Event rate in experiments for charged current solar neutrino experiments at low energies. The rates are given for pp- and ^{7}-Be-neutrinos in units of counts per year for 10t target material.*

Target	Q (keV)	pp	^{7}-Be
^{176}-Yb	301	19	183
^{160}-Gd	245	134	68
^{82}-Se	173	125	30

Obviously Yb is the best candidate for measuring the ^7Be line when regarding the counting rate only, as Gd and Se are favourable for determing the solar *pp* flux. However, the background scenarios have also to be considered carefully.

3.1. Possible detector configurations

It should be stressed, that Lens is at a starting point. At the time the talk to this proceedings have been given no collaboration was existing. However, many physicists working in this field showed large interest. For possible detector configurations I only want to make general remarks, for more details see ref. [4].

The quite small value of the lifetime of the isomeric states (in the order of 100ns) requires fast detector systems. Possible solutions are liquid scintillators, loaded with target atoms. The metal loading procedure is a very critical step since quite high loading in the range 5% to 10% should be reached. Raghavan reports [4] about promising results on a laboratory scale for Yb doted scintillators. The Chooz collaboration, which used Gd-loaded scintillator (at a much lower concentration) for a long baseline reactor experiment, reported about stability problems of their scintillator. It is clear that further investigations in this point has to be done.

The detector concept could be homogeneous like in Borexino or can be considered as an aggregate of long cells with lateral dimensions of $\approx$20cm. The former configuration in general allows a higher light yield, the latter shows better position resolution in two dimensions even for low energy signals.

The experience of Borexino encourages the development of such an experiment in general. Analysis of spurious radioactive elements will be crucial also for Lens. Information about the ^{14}C content is now available via the CTF of Borexino. Latter is especially important for *pp*-neutrino detection. It should be also mentioned that experience in the handling of ultrapure organic liquids is required as it is for Borexino. Cosmogenic background reactions have been studied at the SPS beam at CERN by the Borexino group of the TU Munich and in this context also Gd- and Yb-samples have been measured.

4. Conclusions

- Solar neutrino experiments up to now measure significantly a lower flux as it is calculated and confirmed by helioseismology. Therefore these experiments in terms of neutrino oscillations can be considered as disappearance experiments.
- SuperKamiokande and SNO perform spectroscopy on high energy solar neutrinos. Spectral deformation of the ^8B-neutrino branch and the measurement of the charged and neutral flux may show a clear signal of neutrino oscillations.
- The low energy experiments Borexino and Lens together deliver information about the charged and neutral current flux of low energy ^7Be solar neutrinos. Since the MSW-effect should be maximal here, as it is indicated by the results of Gallium experiments and SuperKamiokande, they could be considerd *together* as neutrino oscillation appearance experiments.
- Borexino is an excellent experiment for detecting vacuum oscillations. In addition a rich program in neutrino physics like probing the large mixing angle solution with reactor neutrinos can be accomplished.

5. Acknowledgements

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