

# Solar neutrinos

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## Abstract

The Sun is a powerful neutrino source that can be used to study the physical properties of neutrinos and, at the same time, neutrinos are a unique tool to probe the interior of the Sun.

For these reasons, solar neutrino physics is both fundamental neutrino and solar physics. In this paper we summarize shortly the main results of the last three decades and then focus on the new results produced by running experiments. We also give a short look at already funded or proposed new projects and at their scientific perspectives.

## 1. Introduction

Solar neutrinos have been for long a formidable tool to study both the fundamental properties of neutrinos and to probe the interior of the Sun core.

Historically, the main interest of the first generation experiments (Homestake in particular, [1]) was the experimental verification of the Standard Solar Model (SSM) developed by J. Bahcall and co-workers, and particularly the search of a definite proof that the Sun is fueled by the pp fusion chain.

Since the early 70's, a clear discrepancy between theory and experiment was found by Homestake and later confirmed with different techniques and different energies by Kamiokande [2], Gallex/GNO [3] [4] and Sage [5]. This discrepancy used to be known as the solar neutrino problem (SNP).

It was early understood that a possible explanation (among others) of the SNP was the existence of neutrino flavour oscillations, which may occur if neutrinos have a non-zero mass and if the family lepton numbers are violated (global lepton number may still be conserved).

In the simplest case, neutrino oscillate through a mixing matrix that is the equivalent of the CKM matrix in the quark sector, although other scenarios that include additional sterile neutrinos are possible as well. Oscillations reduce the observed counting rate either because the experiment can see only electron neutrinos (this is the case of radiochemical experiments like Homestake, Gallex/GNO and Sage) or because the elastic cross section on electrons is lower for muon and tau neutrinos (Kamiokande, Borexino).

A convincing proof that the oscillations are indeed the right explanation of the SNP came in year 2001, when the SNO experiment [6] proved that the total neutrino flux is indeed in fair agreement with SSM, while the electron neutrino component is depleted by flavor oscillations. SNO could obtain this beautiful result thanks to the use of heavy water (D<sub>2</sub>O) as a target. Carefully designed neutron detectors allowed to disentangle charged current interactions (possible for electron neutrinos only at the solar neutrino energies of a few MeV) and neutral current interactions (possible for all neutrino types), allowing the independent measurement of the electron neutrino flux and the total neutrino flux. The latter agrees with the SSM while the former is depleted. This

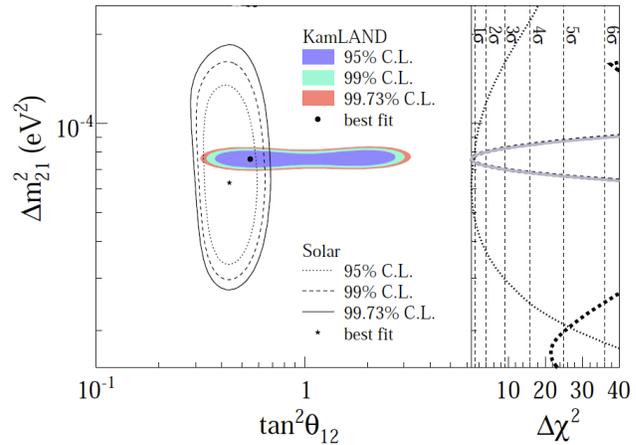


Fig. 1. Current knowledge of solar oscillation parameters  $\Delta m^2_{21}$  and  $\tan^2\theta_{12}$  as given in Ref. [7]. The result is obtained by combining solar neutrino results and reactor data.

is a clear proof of neutrino oscillations. Besides, with the use of the very precise elastic scattering measurement given by SuperKamiokande, SNO has been able to provide the first precise measurement of the oscillation parameters. This measurement was later confirmed and refined by the KamLand experiment [7], that could observe anti-neutrino oscillation in disappearance mode from nuclear reactors and constraint more precisely the  $\Delta m^2$ . The best result so far obtained for the oscillation parameters is shown in Fig. 1.

With the conclusion of SNO, the first generation of solar neutrino experiments was over and the existence of neutrino oscillations was established. However, several important issues related to neutrino physics and solar physics still require an answer and a new generation of experiment, either brand new or upgrading existing one, is in progress.

The main goal that is related to neutrino physics is the precise experimental test of the electron neutrino survival probability that is computed including neutrino oscillations in vacuum and in matter. The current solution of the SNP is based on the so called LMA-MSW model, where matter effects in the Sun play a crucial role in explaining why the neutrino deficit depends on neutrino energy. Although the model is in fair agreement with the existing data, the only precise measurement are the one done by Superkamiokande and SNO, all obtained so far with water Cherenkov detectors with energy threshold of 5 MeV or more (see Fig. 2). Low energy data before Borexino are limited to those provided by radiochemical experiments, which lack precision and integrate the flux in the whole energy range above detection threshold.

A precise test of the  $P_{ee}$  as a function of energy is mostly important to validate the current scenario and

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search for new physics. To do so, more measurements of the solar neutrino spectrum, and particularly those in the vacuum region (below 1 MeV) and in the transition region (1-3 MeV) are crucial.

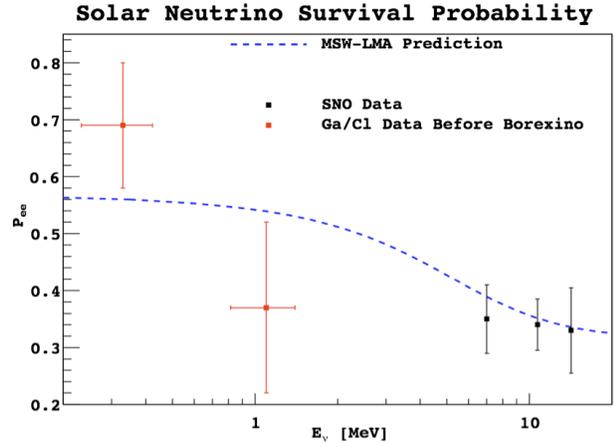
As already mentioned, besides a precise verification of the expected  $P_{ee}$ , precise solar neutrino measurement could be sensitive to new physics, like anomalous neutrino magnetic moments, non-standard interactions, or even probe  $\theta_{13}$ .

Precision measurement of solar neutrino fluxes are very important also for solar physics, particularly to understand what is the metallicity content of the core and what is the role of the CNO cycle in the Sun. In main sequence stars like the Sun the CNO contribution to the energy production is expected to be of the order of 1%, but the precise value is unknown. Besides, the measurement of the metal content in the core is of course not possible, and the models that are required to infer this value from metallicity measurements in the solar corona are difficult, and their result is still debated. This is the so called metallicity controversy. Old calculations done with 1D numerical models were in fair agreement both heliosimulogy measurements (very accurate) and with the available neutrino data (rather poor on this matter). New improved calculations with 3D models have spoiled this nice agreement and the situation is now unclear. A precise measurement of  ${}^7\text{Be}$  flux could help to clarify this matter, as it is shown in Table 1. A direct measurement of the CNO neutrino flux, even with moderate precision, would be decisive to clarify the role of CNO cycle in the Sun [17].

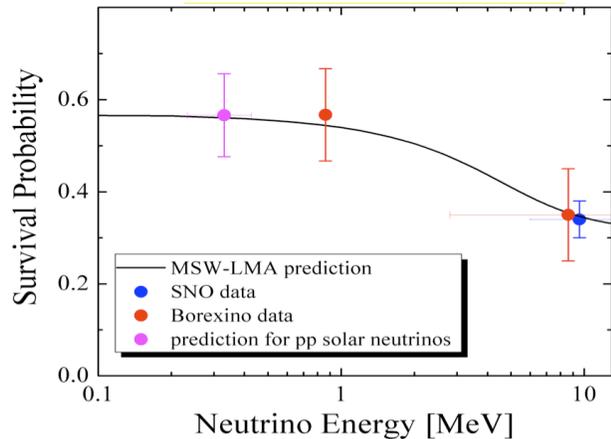
At the time of writing, the running solar neutrino experiments are Borexino, Sage, Superkamiokande and KamLand. The SNO collaboration is upgrading the detector to start a new solar neutrino phase with liquid scintillator instead of heavy water (SNO+). Other experiments that are under discussion include solar neutrino programs. In the following we review the main results of the running experiments and outline the future perspectives of some of the others.

source	BPS08 (GS)	BPS08 (AGS)	Difference (%)
pp	$5.97 \pm 0.006$	$6.04 \pm 0.005$	1.2%
pep	$1.41 \pm 0.011$	$1.45 \pm 0.010$	2.8%
hep	$7.9 \pm 0.15$	$8.22 \pm 0.15$	4.1 %
${}^7\text{Be}$	$5.07 \pm 0.06$	$4.55 \pm 0.06$	10%
${}^8\text{B}$	$5.94 \pm 0.11$	$4.72 \pm 0.11$	21%
${}^{13}\text{N}$	$2.88 \pm 0.15$	$1.89 \pm 0.14$	34 %
${}^{15}\text{O}$	$2.15 \pm 0.17$	$1.34 \pm 0.16$	31%
${}^{17}\text{F}$	$5.82 \pm 0.16$	$3.25 \pm 0.15$	44%

**Table 1.** Expected neutrino flux as in ref. [17] assuming a high metallicity content (old, GS model) or the lower value indicated by improved 3D calculations (new, AGS model). Large differences between the two models are clear in  ${}^7\text{Be}$ ,  ${}^8\text{B}$ , and CNO fluxes. A measurement of  ${}^7\text{Be}$  with 5% precision or better would be very useful to clarify the metallicity controversy. A measurement of CNO neutrinos would be probably conclusive. The table presents the predicted fluxes, in units of  $10^{10}$  (pp),  $10^9$  ( ${}^7\text{Be}$ ),  $10^8$  (pep,  ${}^{13}\text{N}$ ,  ${}^{15}\text{O}$ ),  $10^6$  ( ${}^8\text{B}$ ,  ${}^{17}\text{F}$ ), and  $10^3$  (hep)  $\text{cm}^{-22} \text{s}^{-21}$ .



**Fig. 2.** The electron neutrino survival probability  $P_{ee}$  predicted by the LMA-MSW solution compared to available data before Borexino. Precision measurement were available only above 5 MeV.



**Fig. 3.** The same curve as in Fig. 1. after first Borexino results. The flux of  ${}^7\text{Be}$  neutrinos is now known at 12% level, and a precision determination of pp flux is possible by means of luminosity constraint to solar model.

## 2. Borexino

The main solar neutrino experiment that is running at the time of writing is Borexino [8, 9, 10], a large volume liquid scintillator detector whose primary purpose is the real-time measurement of low energy solar neutrinos. It is located deep underground ( $\simeq 3800$  meters of water equivalent, m w.e.) in the Hall C of the Laboratori Nazionali del Gran Sasso (Italy).

The original main goal of the experiment was the detection of the monochromatic neutrinos that are emitted in the electron capture decay of  ${}^7\text{Be}$  in the Sun [8]. However, the observed radioactive background is much lower than expected, which results in a potential broadening of the scientific scope of the experiment. Particularly, Borexino now also aims at the spectral study of other solar neutrino components, such as low energy  ${}^8\text{B}$  neutrinos, and possibly pep, pp and CNO neutrinos [14]. Besides solar physics, the unprecedented characteristics of its apparatus make Borexino very competitive in the detection of anti-neutrinos ( $\bar{\nu}$ ), particularly those of geophysical origin. The physics goals of the experiment also include the detection of a nearby supernova, the measurement of the neutrino magnetic moment by means of

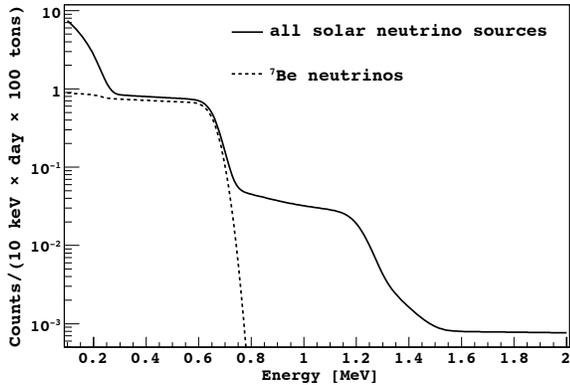


Fig. 4. The expected solar neutrino spectrum in a liquid scintillator with 100 t of active target. The two shoulders around 0.7 MeV and 1.3 MeV are due to monochromatic  ${}^7\text{Be}$  and pep neutrinos and are the main features that can be used to extract these signals. The  ${}^7\text{Be}$  component is also shown separately as dotted curve.

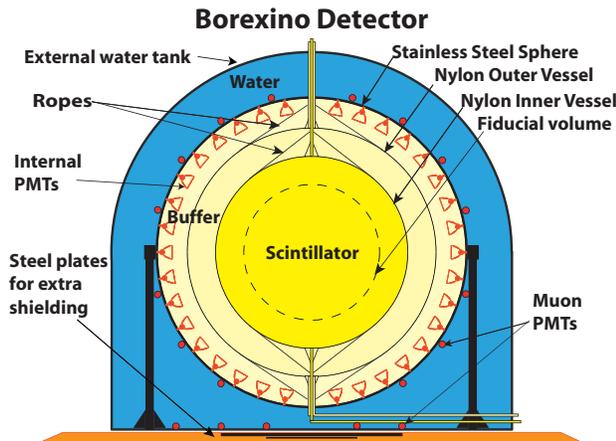


Fig. 5. Schematic structure of the Borexino detector.

a powerful neutrino source, and the search for very rare events like the electron decay [15] or the nucleon decay into invisible channels [16].

In Borexino low energy neutrinos ( $\nu$ ) of all flavors are detected by means of their elastic scattering of electrons or, in the case of electron anti-neutrinos, by means of their inverse beta decay on protons or carbon nuclei. Fig. 4 show the distribution of the electron recoil energy for all solar neutrino components in liquid scintillator, normalized to 100 t of target.

The electron (positron) recoil energy is converted into scintillation light which is then collected by a set of photomultipliers. A sketch of Borexino apparatus is shown in Fig. 5 For more details about the detector see [10].

This technique has several advantages over both the water Cherenkov detectors and the radiochemical detectors used so far in solar neutrino experiments. Water Cherenkov detectors, in fact, can not effectively detect solar neutrinos whose energy is below several MeV, both because the Cherenkov light yield is low and because the intrinsic radioactive background cannot be pushed down to sufficiently low levels. On the other hand, radiochemical experiments cannot intrinsically perform spec-

tral measurements and do not detect events in real time.

An organic liquid scintillator solves the aforementioned problems: the low energy neutrino detection is possible because of the high light yield, that in principle allows the energy threshold to be set down to a level of a few tens of keV\*; the organic nature of the scintillator, and its liquid form at ambient temperature, provide very low solubility of ions and metal impurities, and yield the technical possibility to purify the material as required. However, no measurement of the direction of the incoming neutrino is possible and, even more importantly, the neutrino induced events are intrinsically indistinguishable from  $\beta$  and  $\gamma$  radioactivity, posing formidable requirements in terms of radiopurity of the scintillator and of the detector materials.

As shown in [11] and [13] these requirements have been all met, and sometimes also exceeded, yielding the first measurement of  ${}^7\text{Be}$  solar neutrino flux and of the  ${}^8\text{B}$  neutrinos with a electron energy threshold of 2.8 MeV [12]. Fig. 6. shows the spectrum measured by Borexino with 192 days of live time in the energy region between 300 and 1700 keV of electron recoil energy. The characteristic "Compton edge" of the monochromatic  ${}^7\text{Be}$  neutrinos is clearly visible in the spectrum. Fit results yield a rate of  $49 \pm 3 \pm 4$  cpd/100 ton where the first error is statistical and the second error is systematic. See [13] for more details.

In the high energy region of Fig. 6. a large bump between above 900 keV is visible. This is largely due to the  $\beta^+$  decay of cosmogenically produced  ${}^{11}\text{C}$  and is the main source of background for a possible future measurement of pep and CNO neutrinos. This background is un-avoidable in liquid scintillator detectors and its size depends on the depth of the laboratory in which the detector is located. All running and future experiments will have to deal with it. The Borexino collaboration has developed a technique ([14]) to tag this events by exploiting the fact that the production of  ${}^{11}\text{C}$  is accompanied in 95% of the case with at least one emitted neutron. The triple coincidence among the neutron, the captured neutron and the  ${}^{11}\text{C}$  decay can be used to tag and remove these events. This technique has been already validated in the Counting Test Facility.

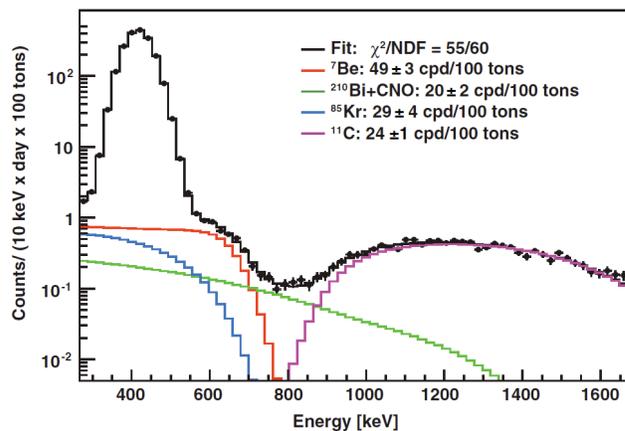


Fig. 6. The spectrum in the energy region between 300 keV and 1700 keV observed by Borexino with 192 days of live time. See [13] for details.

\*However, the unavoidable contamination of  ${}^{14}\text{C}$  that is present in any organic liquid practically limits the "neutrino window" above  $\approx 200$  keV

The current precision in the  ${}^7\text{Be}$  neutrino measurement is limited by lack of energy calibration and by the still incomplete knowledge of the detector response function. Borexino has undertaken in 2009 several calibration campaigns with  $\alpha$ ,  $\beta$ ,  $\gamma$  and neutron sources located in different positions of the detector volume, within and outside the neutrino fiducial volume used for flux measurements. After a complete analysis of the calibration data, a 5% (or better) measurement of  ${}^7\text{Be}$  flux is anticipated. This result will be a strong check of the LMA-MSW scenario and may give important hints on the Sun metallicity problem.

Finally, the Borexino collaboration is getting ready for a purification campaign in early 2010. The goal of this effort is to reduce  ${}^{85}\text{Kr}$  content in the scintillator (the main source of statistical error in the  ${}^7\text{Be}$  region and a severe background for a possible future measurement of pp neutrinos) and to reduce the  ${}^{210}\text{Bi}$  background. If this effort will be successful, Borexino will try to measure pep and possibly CNO neutrinos, and may also search for a pp neutrino signal.

### 3. Superkamiokande, SNO and KamLand

The Superkamiokande experiment is a large water Cherenkov detector located in the Kamioka mine, in Japan. The importance of this experiment in solar, atmospheric and supernova neutrino physics is so significant that does not need to be reviewed here. We just focus on the future perspectives in solar physics [18] [19] [20].

The main current goal of the experiment in solar neutrino physics is the reduction of the energy threshold. So far, SK has observed solar neutrinos with an electron recoil energy threshold of about 5 MeV (changed slightly in the different phases of the experiment). In order to probe the transition region of the  $P_{ee}$  a lower threshold is necessary. SK has recently upgraded the electronics and has installed a new purification system of the water. With better triggering, better electronics and lower radioactive background from U and Th daughters dissolved in water, the experiment aims to push the threshold below 4 MeV and an analysis is in progress with a threshold of 4.5 MeV. If this will be successful, the experiment should be sensitive to the raise of the  $P_{ee}$  at lower energy, the so called "energy upturn". This would yield a very nice check of the LMA-MSW and probe new physics.

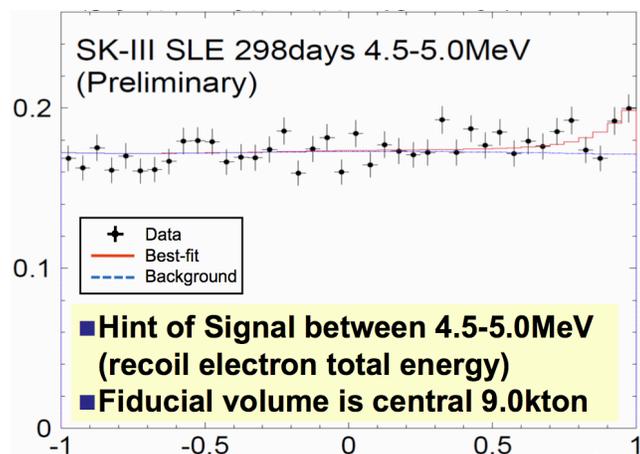


Fig. 7. The SK-III preliminary hint of evidence of solar neutrino signal for events in the energy region between 4.5 and 5 MeV in electron recoil energy [21].

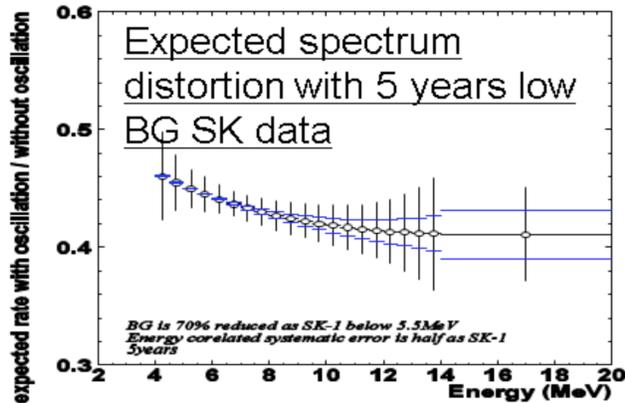


Fig. 8. The expected sensitivity to the energy upturn for 5 years of data taking in SK-IV with low energy threshold and low background.

The SNO experiment has finished data taking in 2008 after a very successful program where neutrino oscillations have been established. The current effort, besides the detector upgrade program that we will cover in the next section, is to re-analyze the available data with a lower energy threshold. A new code has been developed for this task and the goal is to study the neutrino signal down to 3.5 MeV. Even for SNO, the scientific reason for this is to study the energy upturn and probe  $P_{ee}$  in the transition region.

KamLand experiment has begun in 2007 a strong effort to purify the scintillator and reach the background levels required for solar neutrino physics. Purification campaigns have been done in 2007 (Apr. - Aug. ) and from June 2008 until Feb. 2009, reducing the backgrounds of 4-5 orders of magnitude.

According to [22], the second purification campaign was very successful, and after a few months needed to get a stable background ( ${}^{210}\text{Bi}$  decay), the solar neutrino run has begun.

The collaboration plans to measure the  ${}^8\text{B}$  neutrino flux with an error of 10 % and with an energy threshold of 3 MeV, and the  ${}^7\text{Be}$  flux with an error of 13 %. Both measurements will be completed in two years of data taking.

### 4. Future projects

Several ambitious experiments are under construction or are being considered by the scientific community. For lack of space it is not possible to give a comprehensive review of all proposed projects. I will limit the discussion for those who are already approved or very mature for approval.

The most important future project in solar neutrino physics, besides of course those already running, is SNO+ [23].

The SNO+ collaboration aims at the construction of a liquid scintillator experiment re-using the vessel and the photomultipliers of the SNO experiment. The scintillator is linear alkylbenzene (LAB) doped of PPO, which is safe (high flash point), low cost and compatible with the existing acrylic vessel. A holding net will be installed to counterbalance the buoyancy force that will develop as soon as the scintillator will be put in the vessel (the external shielding is still done with water, which is denser than LAB+PPO).

The project aims at the measurement of pep and CNO neutrinos with high precision. The higher depth of the Sudbury mine compared to Gran Sasso and Kamioka

yields a much lower cosmogenic background from  $^{11}\text{C}$  (700 times less than Kamioka, 100 times less than LNGS). According to the simulations, SNO+ may be able to measure the CNO neutrino flux with 6% error. This precision is sufficient to measure the metal content of the solar core in a model independent way and possibly solve the solar metallicity problem. Besides, the project aims at the measurement of pep neutrinos. These are very important to probe  $P_{ee}$  in the transition region. They are monochromatic neutrinos, and their production rate in the Sun is very well known because its value is strongly correlated to solar luminosity. Therefore, a precision measurement of the pep flux at Earth yields a precise measurement of  $P_{ee}$  with small uncertainties. The expected signal in SNO+ for pep and CNO neutrinos is shown in Fig. 9.

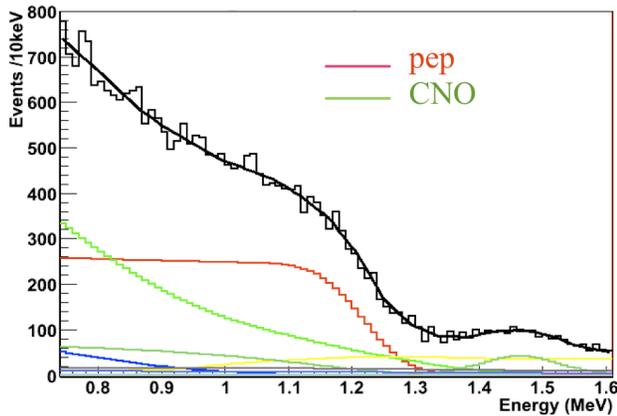


Fig. 9. The signal expected in SNO+ in three years of data taking for CNO and pep neutrinos. The low cosmogenic  $^{11}\text{C}$  background and the high mass make SNO+ may allow a 6% measurement of CNO neutrinos in three years of data.

Another more ambitious project for solar neutrino physics is LENS, Low Energy Neutrino Spectroscopy. This experiment aims at the precise measurement of all solar neutrino components by detecting neutrinos via charged current interactions (inverse beta decay) with  $^{115}\text{In}$ .

The experimental tool used in the LENS detector for the detection of solar neutrinos is the tagged capture of  $\nu_e$ s on  $^{115}\text{In}$  via charged current inverse beta decay. The tagged technique has two outstanding advantages over competing scattering experiments: First, there is a one-to-one correspondence between the incoming neutrino energy and the measurable electron energy  $E_\nu = E_e + Q_d$  ( $Q_d$ : capture threshold), and second, the  $\gamma$ -cascade allows the application of time/space coincidence techniques to suppress ubiquitous radioactive backgrounds as well as the inherent background from the beta decay of  $^{115}\text{In}$ . A modular detector is required. The LENS detector is a novel Scintillation Lattice Chamber, an optically segmented, three dimensional array of 0.5 l cells of liquid scintillator loaded with 8-10 wt% Indium. The scintillation signal from each cell will be always viewed by the same set of 3-6 phototubes. Thus, the full scale LENS of 125 tons InLS, though large in size, is in essence, a large array of small detectors capable of bench-top precision nuclear spectroscopy. It will provide extraordinary spatial resolution in a large mass of liquid scintillator through segmentation rather than time of flight information, which allows adequate background rejection using the time/space coincidence tag even for

low energy (100 keV) events.

The LENS collaboration is funded by NSF for a complete R&D of a detector based on Indium immersed in liquid scintillator modules, as shown in Fig. 10. If successful, this experiment might really represent the future of solar neutrino physics because of the superbe energy resolution possible for all neutrino energies. A spectrum of the expected signal in LENS is shown in Fig. 11.

Finally, several new projects include solar neutrino in their scientific program. Among those, we briefly mention Clean [25] and Xmass [26]. We refer to the references for more details. All these programs want to use the nice features of cryogenic liquid as active targets for solar neutrinos and search for neutrinoless double beta decay and dark matter. Particularly, liquid noble gases have a good light yield, high density and can be purified thoroughly, yielding good signals and low background. Large mass detectors of this type maybe a crucial tool for next generation solar neutrino experiments.



Fig. 10. Lens conceptual design. Isotropically emitted scintillation light is channeled to the outside of the detector along the main axes via total internal reflection, providing direct information about the location of the event.

## 5. Conclusions

Solar neutrino physics is still a very exciting field of reasearch. After the end of the first generation of experiments, and the establishment of neutrino flavour oscillations, several important topics in neutrino physics and solar physics can be probed via a careful and precise measurement of solar neutrino components. Borexino is currently running at Gran Sasso and is giving fundamental results in low energy neutrino physics, particularly on  $^7\text{Be}$  and  $^8\text{B}$  neutrinos. Other experiments like KamLand and Kamiokande will soon be able to probe the low energy region as well, and test the LMA-MSW solution. Future projects like SNO+ and possibly LENS will make another big step forward, and open the era of high precision solar neutrino spectroscopy. Other more ambitious projects like Clean, Deap and Xmass may join in the near future.

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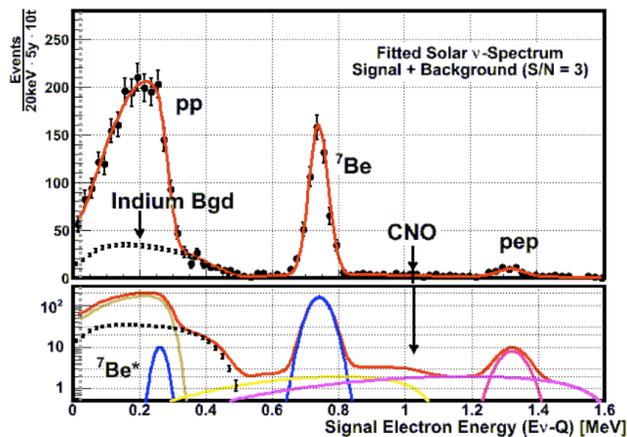


Fig. 11. Lens expected spectral resolution on solar neutrinos. If the detector will work as anticipated, LENS will give a beautiful spectral measurement of all solar neutrino components separately, with very high precision and low background.

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