

# Solar Neutrinos

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## Abstract

Solar neutrino investigation has represented one of the most active field of particle physics over the past decade, accumulating important and sometimes unexpected achievements. After reviewing some of the most recent impressive successes, the future perspectives of this exciting area of neutrino research will be discussed.

## 1 Introduction

Solar neutrino research is a mature field of investigation which over the recent years has accumulated a long series of outstanding achievements. Originally conceived as a powerful tool to deeply investigate the core of our star, solar neutrinos underwent a very successful detour to particle physics, crucially concurring to the experimental evidence of the neutrino oscillation phenomenon, according to the MSW mechanism [1][2].

The solar experiments were also paramount to determine with high accuracy the  $\Delta m_{12}^2$  and  $\sin^2\theta_{12}$  parameters of the PMNS mixing matrix governing the oscillation in the solar sector [3], with the recent fascinating prospect of a possible positive indication regarding the value of the subleading  $\theta_{13}$  angle [4], connecting the solar and atmospheric sectors of the PMNS matrix itself. Nevertheless the currently accepted oscillation model for solar neutrinos, MSW-LMA, has been validated until now only in matter, while only very recently investigations of the oscillation in vacuum in real time have been carried out [5]. The validation of the oscillation model in vacuum, in matter and in the transition region between these two regimes, the direct experimental measurements of the fluxes produced by the single nuclear reactions occurring in the Sun, the precision measurements of the neutrino oscillation parameters are the next goals of the solar neutrinos study. Furthermore, once completed the mission of unveiling the oscillating nature of neutrinos, solar experiments are and will be back to the original concept of testing the functioning mechanism of the Sun; in this context important insights are awaited from the running and future experiments, of special relevance to address the current issue regarding the metallic content of the Sun [6].

## 2 Insights on the neutrino oscillations parameters obtained so far by the solar experiments

It is now well known, after several decades of theoretical and experimental investigations, that neutrinos are abundantly produced in the core of the Sun. They originate from the nuclear reactions that power our star, producing the energy required to sustain it over the billions of years of its life. Two different chain reactions occur at the temperatures characteristic of the core of the Sun, the so called pp chain and CNO cycle, respectively. Actually for the Sun the vast majority of the energy (>98%) is coming from the pp chain, while the CNO contribution is estimated to be less than 1.6 %. On the other hand the reactions concurring to the CNO cycle are dominant in the massive stars.

The effort to develop a model able to reproduce fairly accurately the solar physical characteristics, as well as the spectra and fluxes of the several produced neutrino components, was led for more than forty years by John Bahcall [7]; this effort culminated in the synthesis of the so called Standard Solar Model (SSM), which represents a true triumph of the physics of XXth century, leading to extraordinary agreements between

predictions and observables. Such a beautiful concordance, however, has been somehow recently weakened as a consequence of the controversy regarding the metallic content of the Sun, stemming from a more accurate 3D modeling of the Sun photosphere. Therefore, there are now two versions of the SSM, according to the adoption of the old (high) or revised (low) metallicity [8].

From the experimental side, solar neutrino experiments also represent a successful 40 years long saga, commenced with the pioneering radiochemical experiments, i.e Homestake, Gallex/GNO and Sage, continued with the Cerenkov detectors Kamiokande/Super-Kamiokande in Japan and SNO in Canada, and with a last player which entered very recently the scene, Borexino at the Gran Sasso Laboratory, which introduced in this field the liquid scintillation detection approach and allows the study of the neutrino interactions below 2 MeV thanks to the developments of technologies on purpose.

For more than 30 years the persisting discrepancy between the experimental results and the theoretical predictions of the Solar Model formed the basis of the famous Solar Neutrino Problem, which in the end culminated with a crystal clear proof of the occurrence of the neutrino oscillation phenomenon, via the MSW effect. In particular, the joint evaluation of the results from the solar experiments and from the KamLAND antineutrino reactor experiment pin points the values of the oscillations parameter within the LMA (large mixing angle) region of the MSW solution. Specifically, the global solar + KamLAND analysis reported in [3] gives  $\Delta m_{12}^2 = 7.59_{-0.21}^{+0.19} \times 10^{-5} eV^2$ , and  $\theta_{12} = 34.4_{-1.2}^{+1.3}$  deg; it is interesting to underline that the precise determination of the mixing angle is driven essentially by the solar data, while the mass parameter is governed by the KamLAND data.

In addition to these solid and well established results, more recently an intriguing hint of a possible non zero value of the  $\theta_{13}$  angle has emerged while performing the solar+KamLAND analysis in a full 3 neutrino framework [4], suggesting in particular  $\sin^2\theta_{13}=0.016\pm 0.01$  (specifically it is the tension between the solar only fit and the KamLAND only fit that leads to this suggestion). Therefore this promising evidence is weak, but if true would be a striking result, suited to be early confirmed by the next generation of reactor and beam experiments devoted to the  $\theta_{13}$  search.

The task of the solar neutrino studies is far to be completed. The study of the by far dominant part of the solar neutrino spectrum ( before the Borexino experiment only less than 0.1% was explored), the refined validation of the MSW-LMA oscillation model, a more precise measurement of the oscillation parameters, checks of exotic interactions, are the next frontier of the research in this field. The experiments in R&D phase, as far as in prototypes construction, are a good demonstration of the scientific expectations of the neutrino physics from the solar sector.

In the following we will illustrate the main existing and planned solar experiments, underlining the future plans of each of them.

### 3 Results and future perspectives of the running, or just completed, experiments

#### 3.1 Borexino

We start this review with the most recent project, Borexino at the Gran Sasso Laboratory [9], a scintillator detector which employs as active detection medium 300 tons of pseudocumene-based scintillator. The intrinsic high luminosity of the liquid scintillation technology is the key toward the goal of Borexino, the real time observation of sub-MeV solar neutrinos through  $\nu$ -e elastic scattering, being the  ${}^7\text{Be}$  component the main target. However, the lack of directionality of the method makes it impossible to distinguish neutrino scattered electrons from electrons due to natural radioactivity, thus leading to the other crucial requirement of the Borexino technology, e.g. an extremely low radioactive contamination of the detection medium, at fantastic unprecedented levels.

The active scintillating volume is observed by 2212 PMTs located on a 13.7 m diameter sphere and is shielded from the external radiation by more than 2500 tons of ultrapure water and by 1000 tons of hydrocarbon equal to the main compound of the scintillator (pseudocumene), to ensure zero buoyancy on the Inner Vessel containing the scintillator itself, which consists of a nylon balloon, very thin (125  $\mu\text{m}$ ) to keep the Rn emanation at very low level. Of paramount importance for the success of the experiment are also the

many purification and handling systems, which were designed and installed to allow the proper manipulation of the fluids at the exceptional purity level demanded by Borexino.

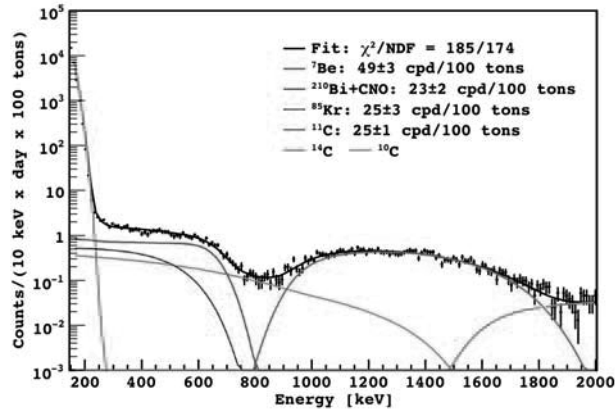
When data taking started in May 2007, it appeared immediately that the daunting task of the ultralow radioactivity was successfully achieved, representing *per se* a major technological breakthrough, opening a new era in the field of ultrapure detectors for rare events search. The main radiopurity achievements are summarized in Table 1.

Table 1 – Radiopurity of the key components of the Borexino detectors

	Material	Typical conc. of raw materials	Radiopurity levels in the Bx scintillator	
$^{14}\text{C}$	scintillator	$^{14}\text{C}/^{12}\text{C} < 10^{-12}$	$^{14}\text{C}/^{12}\text{C} \approx 2 \cdot 10^{-18}$	
$^{238}\text{U}$ , $^{232}\text{Th}$ equiv.	- Underground dust - stainless steel	$\sim 1$ ppm $\sim 1$ ppb	$10^{-17} - 10^{-18}$ g/g	
$\text{K}_{\text{nat}}$	- Underground dust	$\sim 1$ ppm	$< 10^{-14}$ g/g	
$^{222}\text{Rn}$	- external air - underground air	$\sim 20$ Bq/m <sup>3</sup> 40-100 Bq/m <sup>3</sup>	$< 1$ $\mu\text{Bq}/\text{m}^3$	
$^{85}\text{Kr}$ $^{39}\text{Ar}$	in N <sub>2</sub> for stripping	$\sim 1.1$ Bq/m <sup>3</sup> $\sim 13$ mBq/m <sup>3</sup>	$\sim 0.16$ mBq/m <sup>3</sup> $\sim 0.5$ mBq/m <sup>3</sup>	
$^{222}\text{Rn}$ $^{238}\text{U}$ , $^{232}\text{Th}$	LNGS – Hall C water	$\sim 50$ Bq/m <sup>3</sup> $\sim 10^{-10}$ g/g	$\sim 30$ $\mu\text{Bq}/\text{m}^3$ $\sim 10^{-14}$ g/g	Bx water

The obtained level of purity implies that, once selected by software analysis the design fiducial volume of 100 tons and upon removal of the muon and muon-induced signals (also by means of a muon veto installed in the shielding water), the recorded experimental spectrum is so clean to show spectacularly the striking feature of the  $^7\text{Be}$  scattering edge, i.e. the unambiguous signature of the occurrence of solar neutrino detection.

For the quantitative extraction of the  $^7\text{Be}$  flux, the spectrum is fitted to a global signal-plus-background model. The fit output for the 192 days data sample released up to now by the Collaboration [5] is reported in Fig. 1 (the results in the legenda are conventionally expressed in counts/day/100 tons of scintillator). Taking into accounts the systematic uncertainties, the  $^7\text{Be}$  evaluation is  $49 \pm 3_{\text{stat}} \pm 4_{\text{sys}}$  counts/day/100 tons, hence a 10% precision measurement, which translates into a  $^7\text{Be}$  flux of  $(5.08 \pm 0.25) \cdot 10^9 \text{ cm}^{-2}\text{s}^{-1}$ , very well in agreement with the prediction of the high metallicity BPS08(GS98) Standard Solar Model [8]. For comparison, the detected count rate in case of absence of oscillations would have been  $74 \pm 4$  counts/day/100 tons. The resulting  $\nu_e$  survival probability at Earth at the  $^7\text{Be}$  energy is  $P_{\nu_e} = 0.56 \pm 0.10$ .



**Fig. 1:** Fit of the Borexino data in the energy region 160-2000 keV.

In Fig. 2 the MSW predicted  $P_{cc}$  is shown, together with three experimental points, i.e. the  $^8\text{B}$  from the previous Cerenkov data, the  $^7\text{Be}$  Borexino point and the pp datum as drawn by the comparison of Borexino with the Gallium experiments: altogether from this figure we can conclude that Borexino on one hand confirms within the errors the MSW-LMA solar neutrino oscillation scenario, and on the other provides the first demonstration of the vacuum oscillation in the solar sector, giving the first direct measurement of the survival probability in the low energy vacuum MSW regime.

Other important measurements have been provided by the experiment in its first two years of operation. In [10] the Collaboration published the  $^8\text{B}$  spectrum with a threshold as low as 2.8 MeV (neutrino energy equal to 3 MeV), the lower threshold ever adopted for the  $^8\text{B}$  study, made it possible by the ultralow background achieved in the Borexino fiducial volume<sup>1</sup>; despite the limited statistics, the spectrum reproduces faithfully the expectations from the LMA-MSW solution. The measurement in only one experiment of both the fluxes from  $^7\text{Be}$  and  $^8\text{B}$  allows to obtain the ratio between the survival probabilities in vacuum and in matter:  $1.6 \pm 0.33$ .

<sup>1</sup> After the talk of G. Ranucci at the CERN Workshop on the neutrino Physics, a very recent paper from the SNO collaboration posted on arXiv shows the results on an analysis on  $^8\text{B}$  with a lower threshold down to 3.5 MeV of electron kinetic energy.

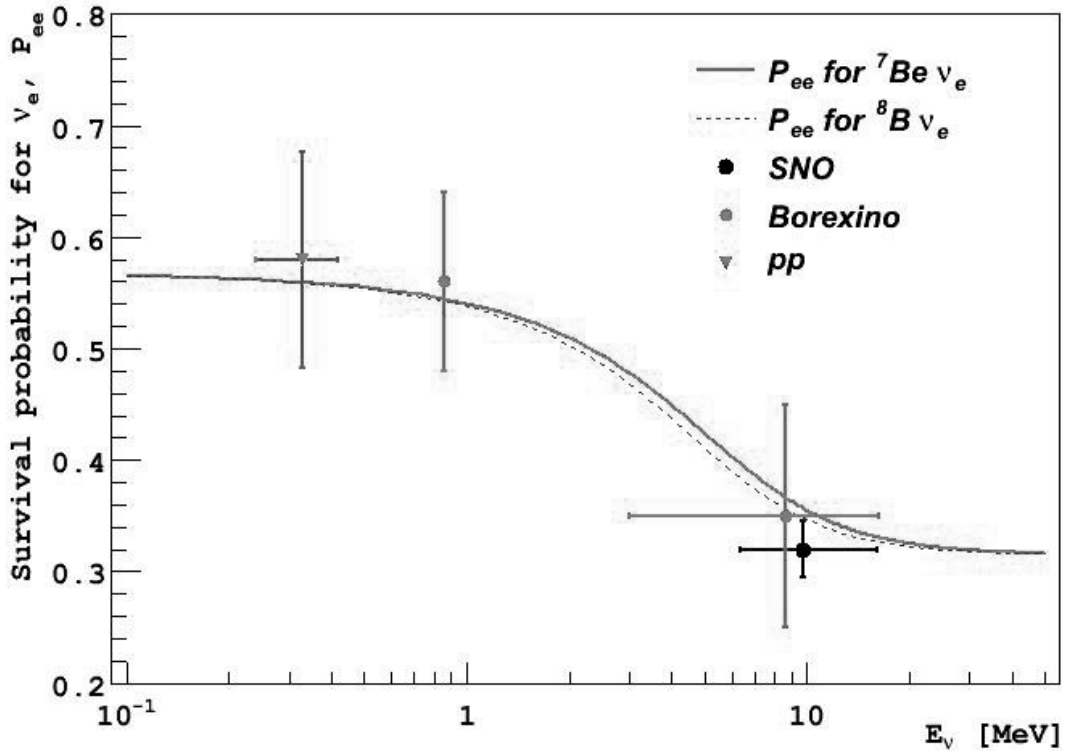


Fig. 2:  $\nu_e$  survival probability curve together with three experimental points inferred from Borexino, Cerenkov and Gallium data.

Furthermore, by exploiting the accumulated counts in the  ${}^7\text{Be}$  energy region, the day-night asymmetry of the neutrino signal has been carefully evaluated, obtaining as asymmetry parameter the value  $\text{ADN} = 0.02 \pm 0.04$ , hence perfectly in agreement with the expected absence of the asymmetry. Furthermore, the measure of the  ${}^7\text{Be}$  flux can be used jointly with the solar luminosity condition and the results of the other experiments to put tight constraints on the pp and CNO fluxes, obtaining respectively  $f_{\text{pp}} = 1.005 (+0.008 - 0.002)$  ( $1\sigma$ ) and  $f_{\text{CNO}} < 3.80$  (90% C.L.), where  $f$  is the ratio between the measured and the SSM predicted flux values.

The shape of the  ${}^7\text{Be}$  recoil electron spectrum allows the determination of the best limit for the effective  $\nu$ -electron scattering. In fact the  $\nu$ -electron scattering is induced by a mixture of the three neutrinos which interact with the electron with different cross sections. Taking into account the recent result obtained by the GEMMA experiment [11] on reactor  $\bar{\nu}$  ( $< 3.2 \cdot 10^{-11} \mu_B$ ), it is possible to obtain the limit for  $\nu_\mu$  ( $< 12 \cdot 10^{-11} \mu_B$ ) and  $\nu_\tau$  ( $< 12.5 \cdot 10^{-11} \mu_B$ ), by far the best obtained until now.

At present neutrino oscillations have been identified as the leading mechanism for solar neutrino observations. However, it has been pointed out [12] that non-standard interactions (NSI) might play some role. By means of NSI we mean flavour-diagonal or flavour-changing neutrino transitions due to neutrino-fermion interactions in the interior of the Sun. It is found that the transition region between the LMA vacuum and matter regime is sensitive to such effects. Therefore, Borexino and future experiments which aim to probe the survival probability at about 1 MeV could shed light on these sub-leading mechanisms. This option will turn again the solar neutrino search to the study of fundamental interactions of elementary particles as it has been for the case of neutrino mixing and oscillations.

Many further solar measurements are prospectively possible in the next years of running of the detector.  ${}^7\text{Be}$  can be pin pointed to an accuracy of 5% (with respect to the 10% uncertainty of the measurement reported here), providing the final, high accuracy, low energy validation (or invalidation) of the

MSW-LMA solution; moreover the statistics of the  $^8\text{B}$  neutrino study will be increased, and the possibility to investigate the extremely challenging pep and CNO fluxes will be pursued. This last task will require to cope with the background represented by the  $^{11}\text{C}$  cosmogenic signals, exploiting the triple fold coincidence strategy already devised by the Collaboration in [13].

Finally, the extremely low  $^{14}\text{C}$  level, coupled to the good achieved energy resolution, opens also a possible exploration window between 200 and 240 keV in which the observation of the fundamental pp flux can be attempted.

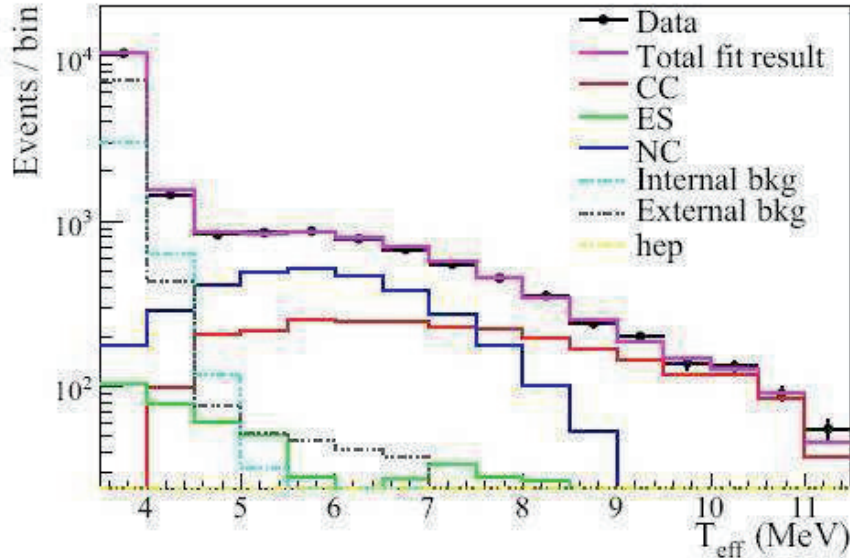
For what concerns the Standard Solar Model the Borexino results seems in favor of the high metallicity solution, but the errors are still too large for an effective discrimination. A measurement of  $^7\text{Be}$  flux with a total error  $\leq 5\%$ , as pursued by the Borexino analysis, will give an important help in solving the SSM metallicity puzzle.

### 3.2 SNO

The SNO (Solar Neutrino Observatory) water Cerenkov experiment [14], located in Sudbury, Canada, is now completed, with the heavy water being returned to the owner until the very last drop. Based on multiple CC, NC and elastic scattering detection of solar neutrinos, the key advance provided by SNO in the field was the model independent proof that neutrinos from the Sun undergo flavour conversion. The experiment evolved through three phases, characterized by different detection procedures of the neutrons signalling the occurrence of the neutral current reactions: a pure heavy water phase, a salt phase and the final  $^3\text{He}$  counters stage.

The estimated NC, CC and ES fluxes over the three phase are statistically in agreement, with the exception of the ES measure of the  $^3\text{He}$  stage, lower than the previous results, but consistent with being a downward statistical fluctuation. Also, in the latest  $^3\text{He}$  measurement procedure the ratio NC/CC resulted equal to  $0.301 \pm 0.033$ , slightly lower than the previous phases. While including these updated data in the global solar + KamLAND analysis, the SNO collaboration finds, in addition to the oscillation parameter values cited in §2, also an accurate determination of the  $^8\text{B}$  flux,  $\phi_{8B} = 4.91 \times 10^6 \text{ cm}^2 \text{ s}^{-1} (\pm \approx 7\%)$ . It has to be noted, in particular, that the errors on the  $^8\text{B}$  flux and consequently on the  $\theta_{12}$  angle have been reduced of almost a factor two by the  $^3\text{He}$  measurement, as effect of the different systematic and minimal correlation of the NC and CC measures in this phase.

As explained in footnote 1, recently the SNO Collaboration has released the so called LETA (low energy threshold) analysis, pushing the  $^8\text{B}$  threshold down to 3.5 MeV (electron kinetic energy). To do so it is required to model accurately down to that energy the several background components, they are 17, that can be identified within the data and which accompany the three CC, NC and ES signal components. In Fig.3 how such a modelling can be accomplished is shown. More insights in this topic can be found in [15].



**Fig. 3:** Individual SNO signals separated into the three neutrino interactions, internal backgrounds (within the D2O volume), external backgrounds and hep neutrino events.

It should be added that the LETA analysis proved to be extremely beneficial on one hand in further tightening the error both on  $\theta_{12}$  and on  $\phi_{8B}$ , and on the other, in the context of a full 3  $\nu$  analysis, in shedding more light on the recently emerged hint [4] for a non zero  $\theta_{13}$ .

### 3.3 Super-Kamiokande

Super-Kamiokande [16] is still currently taking data. The long history of this detector started in 1996 and evolved through four phases: the first phase lasted until the PMT incident of November 2001 and produced the most accurate measure up to now of the  $^8\text{B}$  flux via the ES detection reaction. The phase II with reduced number of PMTs, from the end of 2002 to the end 2005, confirmed with larger error the phase I measurement. After the refurbishment of the detector back to the original number of PMTs, the third phase lasted from the middle of 2006 up to the middle of 2008. After that, an upgrade of the electronics brought the detector into its fourth phase, ready for the T2K beam experiment. It is important to highlight the evolution of the energy threshold (total electron energy) in all the phases: 5 MeV in phase I, 7 MeV in phase II, 4.5 MeV in phase III and 4 MeV targeted for phase IV.

The reduction of the threshold for  $^8\text{B}$  acquisition and analysis is crucially linked to the radiopurity of the detector, being the radon in the Fiducial Volume the main limitation in this respect. Analysis of the data of the phase III is very promising in term of finally achieving the 4.5 MeV threshold, while the Collaboration is working further on the background to reach the ultimate goal of 4 MeV in the phase IV. Fig. 4 exemplifies the aimed background suppression in the FV.

The low energy threshold results that Super-Kamiokande will eventually produce will be, similarly to what illustrated for SNO, of paramount importance to further probe the LMA-MSW solution, in particular if the expected upturn of the low energy portion of the  $^8\text{B}$  spectrum will be identified. It is worth remind that such an up-turn is the expected imprint on the spectrum of the transition of the  $\nu_e$  survival probability from the high energy matter-dominated region to the low energy vacuum-driven regime. Said in other words, the low threshold determination of the  $^8\text{B}$  spectrum is a way to probe directly the transition portion of the survival probability curve.

In the framework of this effort, the Collaboration plan to reach a 2 sigma level of discovery (or exclusion) of the spectrum upturn after two years of data taking in the phase IV with reduced background [17].

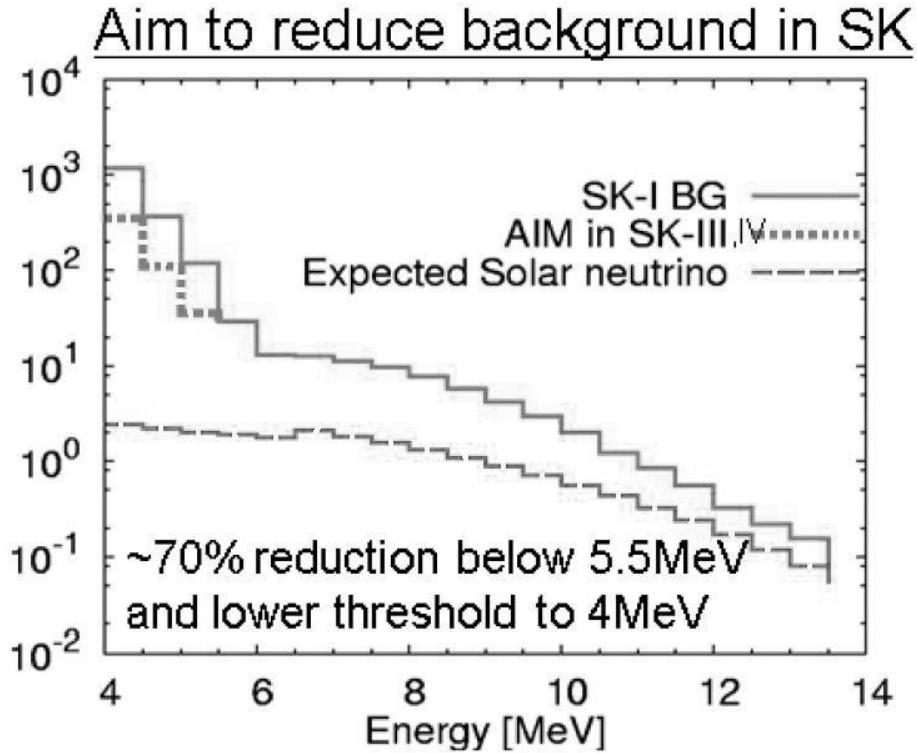


Fig. 4: Aimed reduction of the Fiducial Volume background in the phase III and IV of Super-Kamiokande

### 3.4 Summary of the expectations for improvements on the knowledge of the neutrino oscillations parameters

In summary, still important insights can be gained on the neutrino oscillation properties from the data of the running solar experiments. Borexino will further confirm the low energy portion of the LMA solution with the forthcoming  $^7\text{Be}$  high precision measurement. Moreover the potential measurements of the pp and pep fluxes would allow to sample independently other two points of the  $\nu_e$  survival probability curve.

The LETA low energy threshold is likely the last legacy of SNO to the solar neutrino field, prior to the beginning of a completely new experimental program (SNO+). The important outputs that it has provided are a more accurate determination of  $\theta_{12}$ , as well as of the  $^8\text{B}$  flux, and a confirmation of the current indication for a non zero  $\theta_{13}$  angle.

Finally, the low energy threshold results that Super-Kamiokande will obtain after the planned background reduction will be crucial for an additional check of the LMA-MSW solution, especially through the observation of the predicted upturn of the low energy portion of the  $^8\text{B}$  spectrum, not yet identified up to now.

Therefore, the already vast achievements related to the neutrino oscillation properties stemmed from the solar experiments will be significantly enhanced by this new round of expected results, contributing to further strengthen the basis upon which the next generation of precision measurement experiments will operate over the next decade to go ahead with the high accuracy determination of the parameters of the PNMS mixing matrix.

## 4 Plans for future solar experiments

A series of new solar experiments are being planned or prepared, with some of them likely ready to produce very interesting new results in the imminent future, e.g. KamLAND and SNO+.



## 4.1 KamLAND

KamLAND, after the results achieved with the reactor antineutrino experiment [18], is aggressively moving towards the solar phase of its program. To do so the Collaboration requires to suppress the otherwise overwhelming low energy background, which would definitively prevent the identification of solar neutrinos. The achievement of this target is based upon the on-line purification of the liquid scintillator via a dedicated purification system very similar to the ones developed by Borexino: two purification cycles have been already accomplished, bringing the background to a level marginally close to that needed specifically for the detection of  $^7\text{Be}$  neutrinos. The collaboration is actively debating whether to continue with the purification or to develop a strategy focused to the study of the double beta decay.

In the case that the KamLAND Collaboration will continue to pursue the solar neutrino goal, the first target of the detector are the  $^7\text{Be}$  neutrinos, followed by the pep and CNO neutrinos, for which a special deadtimeless electronics has been installed, able to detect with high efficiency neutrons and thus providing the basis for the triple fold coincidence mentioned above, in the framework of Borexino, for the  $^{11}\text{C}$  suppression.

## 4.2 SNO+

SNO+ [19] is the new experiment that will replace SNO. It is a liquid scintillator detector, as well, that can go on line soon thanks to the massive re-use of the SNO hardware. In particular the adoption of a new liquid scintillator, linear alkyl benzene, featuring the great advantage of being acrylic-compatible, will allow the re-use of the SNO acrylic vessel. Only the support system will have to be built from scratch in order to cope with the different buoyancy condition with respect to the heavy water situation. The other major piece of equipment to realize is the purification system. The project has been funded for these major items on June 2009, with the perspective to start data taking in 2011. The solar phase will be targeted mainly to pep and CNO detection, profiting of the depth of SNOLAB which suppress enormously the cosmogenic  $^{11}\text{C}$  background. It should be, however, highlighted that the main goal of SNO+ will be the double beta decay with Neodymium dissolved in the scintillator, and currently it is not yet decided whether the solar phase will come before or after the Neodymium phase.

## 4.3 LENS

While KamLAND and SNO+ represent the imminent and near future perspectives for new sub-MeV solar neutrino results, it should be mentioned that there are other experiments in the R&D phase with great potentialities for future interesting outputs in this field. In this framework a special mention is due to LENS [20], which is the modern version of the old idea for an Indium experiment. The experimental tool used for the detection of solar neutrinos is the tagged capture of  $\nu_e$ 's on  $^{115}\text{In}$  via charged current :  $\nu_e + ^{115}\text{In} \rightarrow ^{115}\text{Sn}^* + e^- \rightarrow ^{115}\text{Sn} + 2\gamma$ . The low Q of the reaction (114 keV) allows in principle the full solar neutrino spectroscopy, including the pp neutrinos, see Fig. 5. Time and space coincidence, the former intrinsic to the detection reaction and the latter realized via a granular detector design, which can be useful in fighting against the background, especially the one produced by the beta decay of  $^{115}\text{In}$  at the level of 0.25 Bq/g. The bremsstrahlung of the emitted electrons can mimic the coincidence gammas, triggering fake events due to the high accidental level. R&D results very promising in term of stability of the Indium loaded scintillator and background rejection have been recently presented [21].

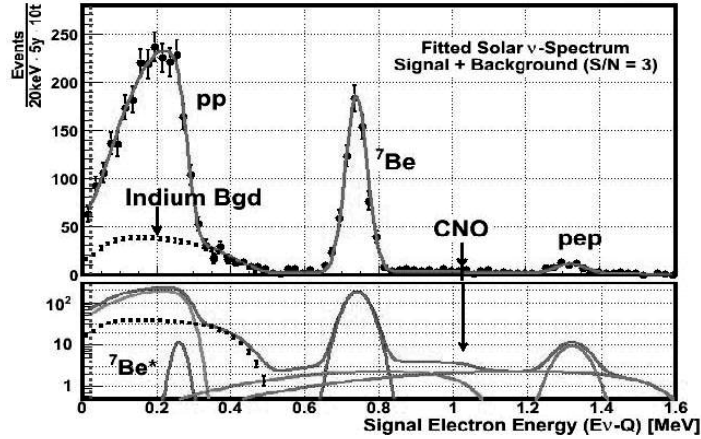


Fig. 5: Example of the predicted spectrum detected by LENS

#### 4.4 Multidisciplinary projects

Other three projects that deserve to be mentioned are CLEAN, XMASS and MOON. They are multidisciplinary projects which have within their potential physics reaches double beta decay, dark matter and solar neutrino investigations.

The basic idea of CLEAN [22] is to take advantage of the fact that both neon or argon scintillate when exposed to radiation. When an energetic charged particle (such as the recoil from a neutrino-electron scattering event) passes through the liquid noble gas, it will produce scintillation light in the extreme ultraviolet range, that can be detected using a combination of a wavelength shifting fluor and a photomultiplier tube. Liquid neon has a number of advantages for detecting neutrinos or other weakly interacting particles. Because neon has no long-lived isotopes, it has no inherent radioactivity to create backgrounds in a sensitive detector. This separates neon from heavier noble gases which do contain radioactive isotopes and from organic scintillator materials which inevitably contains beta radiation from  $^{14}\text{C}$ . Neon also has very low binding energies to a variety of surfaces, allowing it to be effectively purified of radioactive contaminants using cryogenic traps. Another advantage is its relative density compared to liquid helium; neon can be used efficiently as a self-shielding medium, while also allowing a smaller detector volume. These characteristics render neon a well suited choice as a neutrino detection medium.

The current effort of the Collaboration is towards the installation within 2009 of a 360 kg detector for dark matter investigation at SNOLAB. In perspective, a 50 tons device targeted especially to the pp solar neutrino detection could be installed at the planned DUSEL underground facility in US.

The original concept of XMASS was proposed in 2000 [23] as a multi-purpose astroparticle and neutrino experiment. A liquid Xenon detector with a 10 ton effective mass can look for dark matter and double beta decay and can also measure solar pp-neutrinos through neutrino electron scattering, as much as CLEAN. As a phase-I experiment, a small scale detector dedicated to look for dark matter, where the mass of the inner volume surrounded by PMTs is 857kg and the fiducial mass is 100~200kg, is being prepared and installed at the Kamioka mine in Japan.

The double beta decay and solar neutrino project MOON [24] is based on  $^{100}\text{Mo}$ . The merits of using  $^{100}\text{Mo}$  for solar  $\nu$ 's study are the large capture rate and the high selectivity for the low energy  $\nu$ 's. The low threshold energy of 0.168 MeV and the large response for the solar- $\nu$  absorption allow observation of low energy sources such as pp and  $^7\text{Be}$ . The pp and  $^7\text{Be}$   $\nu$ 's are captured only into the ground state of  $^{100}\text{Tc}$ . The solar  $\nu$  signal can be selected by requiring delayed coincidence with the successive  $\beta$  decay of  $^{100}\text{Tc}$ , and thus natural and cosmogenic backgrounds are reduced substantially.

Research and development programs of solid and liquid scintillators for the MOON detector are in progress. A possible option for the solid scintillator is a supermodule of hybrid plate and fiber scintillators. One module consists of a plate scintillator and two sets of X-Y fiber scintillator planes, between which a thin

$^{100}\text{Mo}$  film of about 20 - 50 mg cm<sup>-2</sup> is interleaved. The fiber scintillators coupled with multi-anode photomultiplier tubes (PMT's) enable one to get the necessary position resolution, the scintillator plate (X-Y plane) with multiple PMT's at both X and Y sides provides an adequate energy resolution to satisfy the physics goals.

## 5 The future role of the solar neutrino field in the neutrino physics

In § 3.4 we summarized the expectation in terms of additional insights in the oscillation parameters from the current generation of solar neutrino detectors. Those potential new results could be surely further strengthened by the proposed experiments described in § 4. In particular the planned abundance of low energy measurements, spanning from the pp to the CNO fluxes, will provide plenty of additional evidences of the matter to vacuum transition predicted by the MSW oscillation solution. Furthermore the intriguing and interesting possibilities linked to the hypothetical neutrino NSI (non standard interactions) scenarios [23] will be probed. Also in this case the tool for this test will be the  $\nu_e$  survival probability curve, whose shape should exhibit significant deviations from the standard MSW expectation in the case of the presence of NSI effects.

Regarding specifically the oscillation parameters, it may be possible that the additional low energy data that will be gathered by the current and forthcoming experiments will contribute to further lower the uncertainty on the  $\theta_{12}$  angle (with possible consequences on the knowledge of  $\theta_{13}$ , as well), even though the actual realization of this perspective will depend upon the true precision measurement that the new experiments will achieve

Though not directly related with the subject of neutrino parameters, there are however other interesting physics outputs connected with the running and future solar experiments that deserve to be mentioned.

First of all the test of the Solar Model, in its high metallicity and low metallicity versions, is an important goal that can be reached via the high precision measurement both of the  $^7\text{Be}$  and  $^8\text{B}$  fluxes. As a matter of fact, the correlation expected by the SSM between the  $^7\text{Be}$  and  $^8\text{B}$  fluxes [8] could be used to tackle the so-called solar abundance problem after high precision measurements. Furthermore, additional checks of the Model can come from the precise detection of the overwhelming pp component. Moreover, geoneutrino and supernova neutrino studies are two fascinating chapters of neutrino investigations that are within the reach of the solar detectors, which indeed are expected to provide important insights in both these areas of neutrino physics.

## 6 Conclusions

Solar neutrino research is a field that, despite the large number of successes already accumulated, is promising for the future many more exciting results.

The insight obtained so far on the neutrino oscillation parameters by the solar experiments will be further deepened by the low energy data provided by Borexino and the future sub-MeV experiments.

Moreover, the precise spectroscopy of the whole low energy spectrum is becoming a real perspective, up to a level that makes it feasible the check of the SSM, hence paving the path for resolving the discrepancy between high Z and low Z models

Finally it should be added that these vast experimental perspectives are completed by the geoneutrino and supernova neutrino study which are within the reach of the solar neutrino detectors thanks to their powerful technological characteristics.

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