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Recent Results on Solar Neutrinos

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Important solar neutrino results came recently from Borexino, SNO and Super-Kamiokande. Borexino is a massive, calorimetric liquid scintillator detector installed at the underground Gran Sasso Laboratory. With its unprecedented radiopurity levels achieved in the core of the detection medium, it is the only experiment in operation able to study in real time solar neutrino interactions in the challenging sub-MeV energy region. The recently achieved precise measurement of the ^{7}Be solar neutrino flux and the results concerning the pep, ^{8}B and CNO fluxes, together with their physics implications, are described in this work. The low threshold results on the ^{8}B flux stemming from SNO and Super-Kamiokande are discussed, as well.

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[1] Speaker

1. Introduction

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, in the case of the Sun the vast majority of the energy (>98%) is coming from the pp chain, while the CNO contribution is estimated to less than 1.6 %.

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 the late John Bahcall [1]; 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 spoiled as a consequence of the controversy raised regarding the surface 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 of the surface [2].

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 the scene more recently, Borexino at the Gran Sasso Laboratory, conceived by the late Raju Raghavan, which introduced in this field the liquid scintillation detection approach.

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 so called 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 analysis of the results from the solar experiments and from the KamLAND antineutrino reactor experiment pin points with high accuracy the values of the oscillations parameter within the LMA (large mixing angle) region of the MSW solution [3].

In the rich and successful framework of this mature field, the more recent results are those stemming from the low energy threshold re-analysis of the SNO data, from the phase IV of Super-Kamiokande, and from Borexino. In particular, the Borexino results are of special interest, since not only bring additional, strong evidence to the oscillation scenario, but represent also its first validation in the previous un-accessible sub-MeV Vacuum regime, through the direct measurement of the 0.862 MeV ^{7}Be and 1.44 MeV pep solar neutrino lines, made possible by the fantastic unprecedented background level reached by the experiment. Therefore in the following we describe first, and at length, the Borexino case.

2. Characteristics of the Borexino experiment

Borexino at the Gran Sasso Laboratory [4] is 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 νe elastic scattering, being the ^{7}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, to a degree never reached before.

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 water and by 1000 of hydrocarbon equal to the main compound of the scintillator (pseudocumene), to ensure zero buoyancy on the thin Nylon Inner Vessel containing the scintillator itself. Of paramount importance for the success of the experiment are also the many purification and handling systems, which were designed and installed to ensure the proper manipulation of the fluids at the exceptional radiopurity 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 achieved ultra-low background implies that, once selected by software analysis the design fiducial volume of 100 tons and upon removal of the muon and muon-induced signals, the recorded experimental spectrum is so clean to show spectacularly the striking feature of the ^{7}Be scattering edge, i.e. the unambiguous signature of the occurrence of solar neutrino detection.

The previous data release of June 2008 [5] led to an evaluation of the ^{7}Be flux characterized by a 10% precision. Recently such a determination has been updated to a 5% precision, and has been complemented with the measurement of the associated day-night asymmetry. Borexino has then moved towards the full spectroscopy of the solar neutrino components, with the estimates of the ^{8}B and pep fluxes.

3. Detector response

Several steps are required to extract from the raw data the quantitative information of interest regarding the solar neutrino fluxes of interest: the raw signals must be converted into meaningful amplitude variables, of the total accumulated signals only those satisfying the scintillation event acceptance criteria are kept, the data spectrum is constructed by accepting only events which are reconstructed within a fiducial volume far from the wall of the containment vessel, and finally the spectrum is fitted to a global signal-plus-background model in which the quantity to be evaluated, e.g. the ^{7}Be or pep flux, is a fit parameter.

In particular the challenging task to obtain a 5% ^{7}Be precise measurement required a huge effort in term of detailed understanding of the detector response. This has been accomplished through two coordinated efforts, i.e. an intensive, careful calibration campaign and the development of a complete MC able to reproduce accurately the detector features.

3.1 Calibration

The calibration of the detector has been accomplished both to characterize the energy and time response of Borexino. A plurality of sources have been deployed in several locations within the liquid scintillator: gamma sources producing monoenergetic lines spanning the energy range of interest from 0.122 to 1.4 MeV, a Radon source realized by filling with liquid scintillator taken from the Inner Vessel a small quartz vial which was successively loaded with Radon, and an Am-Be neutron source.

The gamma lines and the Radon source, positioned in several hundreds locations, gave an accurate probe of the energy response of the experiment as function of the event position; furthermore they also provided a way to careful calibrate the capability of the time signals from the array of photomultipliers to identify precisely the vertex of the events. To accomplish the latter task it was needed to know a-priori and independently the spatial coordinates of the source. For this purpose the movable arm used to deploy and locate the source within the Vessel was equipped with a red LED; the LED was flashed once reached each desired position: the red light detected by seven CCD cameras made it possible, via a geometrical triangulation algorithm, to determine the source coordinates within an accuracy of ± 2 cm.

Jointly, the energy and spatial measurements obtained throughout the calibration campaign provided an accurate map of the detector response, thus helping to reduce, together with the MC studies (see next subparagraph), the major uncertainties of the previous 10% ^{7}Be flux measurement, whose limiting factors where indeed the errors in the determination of the fiducial volume and of the energy scale.

The source data were paramount also to determine experimentally the detector energy resolution, which has been found to be energy dependent as $5\%/\sqrt{E(\mathrm{MeV})}$.

3.2 MC tuning

The second ingredient at the basis of the precise ^{7}Be, pep and ^{8}B measurements is the accurate Monte Carlo description of the detector. It required a while to develop a full MC code incorporating all the complex details of the light generation and transport in the liquid scintillator, of the behavior of the photomultipliers and of the electronics response. At the end of this complex development path we were able to produce a very complete simulation suited to be confronted with the many outputs stemming from the calibration campaign.

Such a comparison has been extensively used to contrast the source data with the corresponding simulated events; in this way it has been possible on one hand to perform a fine tuning of the MC code, so to ensure the best match between the measured and simulated data, and on the other to quantify precise the crucial, residual uncertainties on the energy scale and the fiducial volume.

4. Results and physics implications

As anticipated before, Borexino has produced so far the measure of three components of the solar neutrino flux, i.e. the ^{7}Be, the ^{8}B and the pep fluxes, as well as a tight limit on the CNO neutrinos.

4.1 The ^{7}Be flux

The fit output for the latest 740.7 days data sample released by the Collaboration in [6] is reported in Fig. 1 (the results in the legenda are conventionally expressed in counts/day/100 tons of scintillator; they do not coincide exactly with the final result, which is obtained instead from the average of many fits like that in the figure, differing each other in some of the underlying assumptions). Taking into accounts the systematic errors, computed from the above mentioned uncertainties affecting the energy scale and the fiducial volume selection, the ^{7}Be evaluation is $46 \pm 1.5_{stat}(+1.5-1.6)_{sys}$ counts/day/100 tons: hence, summing quadratically the two errors, a remarkable 5% global precision has been achieved in this critical measurement. By assuming the MSW-LMA solar neutrino oscillations, the Borexino result can be used to infer the ^{7}Be solar neutrino flux. Using the oscillation parameters from [7], the detected ^{7}Be count rate corresponds to a total flux of $(4.84 \pm 0.24) \cdot 10^9$ cm^{-2}s^{-1}, very well in agreement with the prediction of the Standard Solar Model [2]. For comparison, the measured count rate in case of absence of oscillations would have been 74 ± 5.2 counts/day/100 tons. The resulting electrons survival probability at the ^{7}Be energy is P_{ee}=0.51± 0.07.

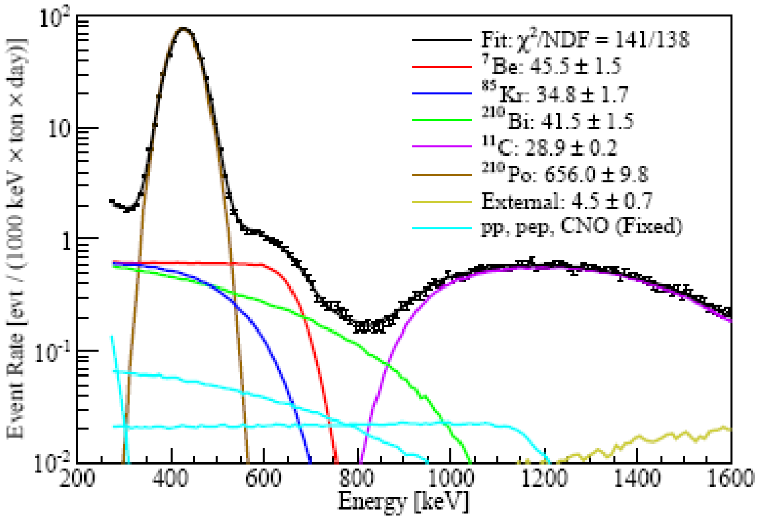

Fig. 1 – Fit of the experimental Borexino spectrum for the extraction of the ^{7}Be flux

4.2 ^{8}B

The distinctive feature of the ^{8}B neutrino flux measurement performed by Borexino [8] is the very low 3 MeV threshold attained, decisively lower than the previous measurements from the Cerenkov experiments.

The measurement is very challenging, since the total background, both of radioactive and cosmogenic origin, in the raw data is overwhelming if compared to the expected signal. The specific background suppression strategy adopted in this case is based on two ingredients: on one hand a careful MC evaluation of the main radioactive contaminants of relevance for this measure, i.e. ^{214}Bi from Radon and the external ^{208}Tl from the nylon wall of the Inner Vessel, and on the other the "in-situ" identification and suppression of the muon and associated cosmogenic signals.

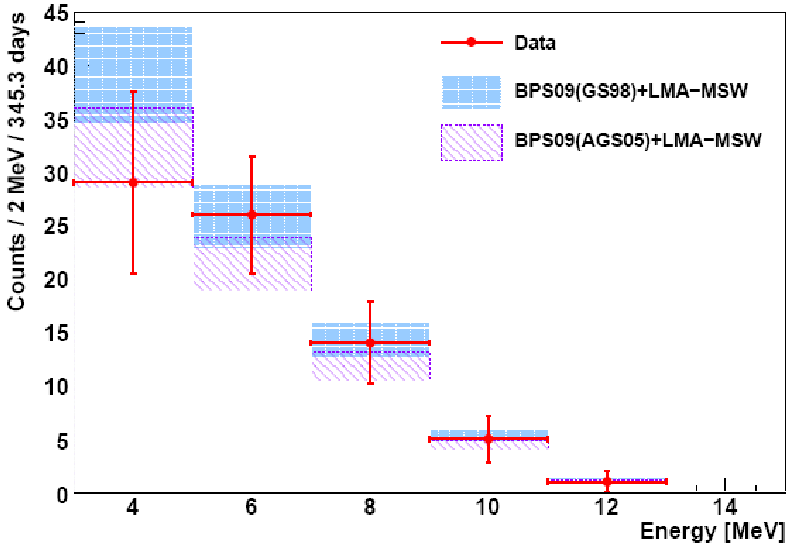

Fig. 2 –Comparison of the final spectrum after data selection and background subtraction (red dots) to Monte Carlo simulations (blue) of oscillated ^{8}B interactions, with amplitude from the Standard Solar Models BPS09(GS98) (high metallicity) and BPS09(AGS05) (low metallicity), and from the MSW-LMA neutrino oscillation model.

The observed ^{8}B rate in the detector is 0.217±0.038(stat)±0.008(sys) cpd/100ton, corresponding to an equivalent flux $\Phi(^{8}B)=(2.4\pm0.4\pm0.1)\times10^{6}$ cm^{-2}s^{-1} , obtained without taking into account the oscillation probability, while the ratio with the flux foreseen by the SSM is 0.88±0.19.

In fig. 2 the rate vs. energy of the ^{8}B selected events is compared with the SSM expectations for low and high metallicity and taking into account the MSW-LMA model. The agreement with the SSM expectation is really good.

4.3 Pep and CNO

By far the most important background in studying pep and CNO solar neutrino fluxes is the ^{11}C decay, a radionuclide continuously produced in the scintillator by the cosmic muons surviving through the rock overburden and interacting in the liquid scintillator. The beta plus decay of ^{11}C originates a continuous spectrum which sits exactly in the middle of the energy region between 1 and 2 MeV which is just the window for the pep and CNO investigation.

Actually, to a less extent also the external background induced by the gammas from the photomultipliers is an obstacle, especially above 1.7 keV.

In [9] a threefold coincidence strategy encompassing the parent muon, the neutron(s) emitted in the spallation of the muon on a ^{12}C nucleus, and the final ^{11}C signal has been devised and described in detail. Such a strategy, once applied to the Borexino data, leads to depurate the raw spectrum of more than 90 % of the unwanted ^{11}C induced scintillation events. The residual spectrum is then analysed via a multivariate fit procedure which accounts simultaneously for the energy spectrum, the radial distribution and the pulse shape discrimination parameter. In the fit the pep and CNO spectra are considered together with all the internal contaminants possibly polluting the raw data in the energy region of interest.

The fit result for the pep rate is 3.13±0.23 (stat.)±0.23 (syst.) counts per day/100ton [10], from which the corresponding flux can be calculated, assuming the current MSW-LMA parameters, as **Φ(**pep)= (1.6±0.3) 10^8 cm^{-2} s^{-1}, in agreement with the SSM: indeed the ratio of this result to the high metallicity SSM predicted value is f_{pep}=1.1±0.2. The resulting electrons survival probability at the pep energy is P_{ee}=0.51± 0.07; finally, it should be underlined that the significance of the pep detection is at the 97% C.L..

A modification of the same analysis, keeping the pep flux fixed at the SSM value, originates a tight upper limit on the CNO flux, i.e. **Φ(**CNO) $\leq$ 7.4 10^8 cm^{-2} s^{-1} , corresponding to a ratio with the SSM prediction in the high metallicity scenario of f_{CNO} <1.4.

4.4 Physics implications

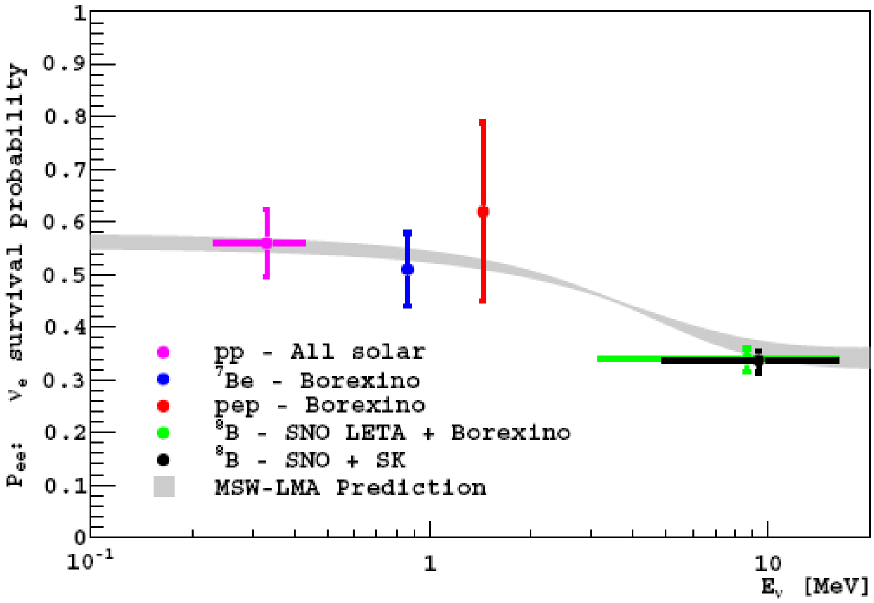

Fig. 3 – Low energy validation of the MSW-LMA solution provided by Borexino

In Fig. 3 the MSW predicted P_{ee} (electron neutrino survival probability) is shown, together with several experimental points, i.e. black the ^{8}B from all solar data, green ^{8}B from Borexino and SNO LETA (see next §6), blue the ^{7}Be Borexino point, magenta the pp datum as drawn by the comparison of Borexino with the Gallium experiments, and red the pep Borexino point: altogether from this figure we can conclude that Borexino on one hand spectacularly confirms the MSW-LMA solar neutrino oscillation scenario, and on the other provides the first direct measurement of the survival probability in the low energy sub-MeV Vacuum MSW regime.

This striking confirmation is also complemented by the measure of the day-night asymmetry of the ^{7}Be flux [11], which is found equal to A_{dn} = 0.001 ± 0.012 (stat) ± 0.007

(syst), fully consistent with zero and hence with the model prediction. It is worth to mention that, by including this measure in the global fit of all solar neutrino experiments, the otherwise surviving LOW region is completely wiped out, even without including the KamLAND data.

5. Super-Kamiokande

The Cerenkov experiment Super-Kamiokande, still taking data, has recently released new results about the ^{8}B flux obtained with threshold lowered to 4 MeV.

The long history of this detector started in 1996 and evolved through four phases: the first phase lasted until a major PMT incident in November 2001 and produced the most accurate measure up to now of the ^{8}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, which contemplates also the accelerator neutrino beam experiment T2K. 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 in phase IV, thanks to the continuously on-going effort to reduce the radon content in water.

The important result provided by Super-Kamiokande is the value of the equivalent ^{8}B flux, obtained converting the all flavor ES measure into an effective neutrino flux without correcting for the oscillation probability; the Super-Kamiokande precise measurement amounts to 2.32 ± 0.04 (stat.) $\pm$ 0.05 (sys.) $\times 10^6$ cm^{-2} s^{-1}, representing a high accuracy confirmation that the electron neutrino flux, which contributes mostly to the result of the experiment, is drastically reduced (about 60%) with respect to the SSM prediction.

The recent release [12] of low threshold data had the goal to unravel the existence of the low energy up-turn in the ^{8}B spectrum, which is expected as the imprint of the LMA-MSW electron survival probability. However, the upturn did not show up, the experimental spectrum above 4 MeV being fully compatible with the undistorted spectrum. While this result is puzzling, the poor definition of the data around 4 MeV is such that simply the distortion could be not yet visible. More data hence are needed to further shed light about this point.

6. SNO

While SNO has terminated its operations in 2006, the re-analysis of the recorded data has also recently produced interesting outcomes.

Succinctly, it can be reminded that this detector, located underground in Canada, in the Inco mine at Sudbury, employed heavy water to perform concurrently a neutral current all-flavor measurement, and a charged current electron-neutrino specific measurement: the comparison of the two provided the unambiguous demonstration of the occurrence of the neutrino flavour conversion process. This achievement is the collective output of the three phases in which the experiment evolved, characterized by the 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}He counters stage.

The recent LETA (Low Energy Threshold Analysis) re-processing of the data has further pushed down the analysis threshold, pursuing similarly to Super-Kamiokande the investigation of the survival probability in the 4-5 MeV region, with the aim to unravel the up-turn, if any, of the ^{8}B spectrum. The result obtained in this way, expressed directly in term of the survival probability, is shown in Fig. 4 [13], compared with the MSW-LMA expectation and the Borexino results.

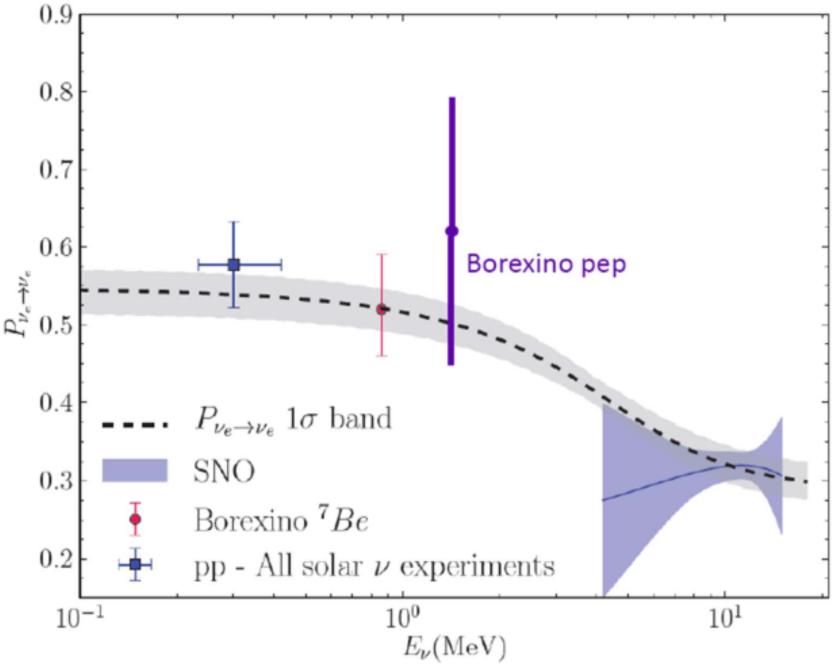

Fig. 4 – Evaluation of the survival probability in the few MeV range through the SNO LETA analysis

The result is clearly intriguing: the best estimate of the survival probability between 4 and 9 MeV seems in disagreement with the expectation (though compatible at 1 sigma level). This outcome, coupled to the absence of the up-turn in the Super-Kamiokande results, points to something new lurking in that energy region. Additional high statistic data, however will be needed to understand what is happening there. In this respect, also the more precise evaluation of the pep rate that Borexino plans to perform within a couple of years will be of fundamental importance.

7. Conclusions

The most recent solar neutrino results stemmed from Borexino, SNO and Super-Kamiokande. The ultra-low background achievement of Borexino, an exceptional breakthrough in the field of techniques for rare processes search, have opened a very sensitive exploration window for sub-MeV solar neutrinos, whose far reaching implications represent in particular a validation of the MSW-LMA oscillation paradigm in the low energy regime, through the precise detection of the ^{7}Be and pep neutrino fluxes. This important outcome is further strengthened by the determination of the absence of day-night asymmetry in the ^{7}Be flux, by the determination with a threshold as low as 3 MeV of the ^{8}B flux, and by the derivation of a tight upper limit on the CNO neutrinos.

The low threshold (4 MeV) recent results of SNO and Super-Kamiokande leave instead open the question whether the electron neutrino survival probability follows in the few MeV range the prediction of the LMA-MSW solution. More data will be needed to ascertain this point.

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