Solar Neutrinos and the Borexino experiment

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Abstract. Solar neutrinos are produced in the core of the Sun in different nuclear reactions all based on the conversion of hydrogen into helium, releasing energy and making the Sun shine. Until now, the observation of solar neutrinos has demonstrated: a) the nuclear origin of the Sun’s energy; b) that the $\nu_e$ produced were undergoing lepton flavor transformation into $\nu_\mu$ or $\nu_\tau$, the neutrino oscillation mechanism. In the recent years, the Borexino experiment, in the Gran Sasso underground laboratory, has made significant contributions to the solar neutrino spectroscopy: first observation and precision measurement of the $^7$Be neutrinos, first observation of the pep reaction, stringent limit on CNO neutrinos, observation of $^8$B neutrinos with a 3 MeV threshold. These measurements reinforce the so-called LMA solution of the neutrino oscillation explaining the solar $\nu_e$ survival probability as a function of energy.

1. Introduction

Solar neutrinos are an important field in particle astrophysics, at the frontier between astrophysics and particle physics. From 1938, the pioneering work of Bethe and others showed that the energy generated by stars comes from the fusion of light nuclei into heavier ones in thermonuclear reactions in their cores. Two cycles of reactions, the pp cycle and the CNO cycle were developed, the pp one being largely dominant in the Sun and Sun-like stars. These reactions emit neutrinos $\nu_e$ with different energy spectra in the range 0-15 MeV. Their detection allows to “see” the core of the star and help to understand “how the Sun shines”. Solar modelling has been developed from the 60’s, in particular under the impulse of J. Bahcall. In 1967, R. Davis installed the first radiochemical experiment in a deep mine and soon after observed the first solar neutrinos. However, the measured rate, significantly smaller than the solar model predictions, gave rise to the so-called solar neutrino problem. Other experiments, the radiochemical gallium ones, and the large Cherenkov experiments confirmed the deficit. The solution came in 2001 from the SNO experiment which showed that the $\nu_e$ produced in the Sun had been transformed into $\nu_\mu$ or $\nu_\tau$, via the neutrino oscillation mechanism including the MSW effect. From 2007, the Borexino experiment, a large scintillator detector at the Gran Sasso underground laboratory, started to take data, to significantly contribute to the solar neutrino spectroscopy.

In section 2, we first describe solar models, how nuclear reactions produce neutrinos and what is the expected flux of solar neutrinos. Section 3 is devoted to the different solar neutrino experiments, how
appeared the solar neutrino problem and how it has been solved. The Borexino experiment is described in section 4 and its main results in section 5.

2. Solar models

The modelling of the solar interior consists of describing the evolution of the Sun from its formation, about 4.6 Gyr ago, to the present day. Following the pioneering work of Bahcall [1], solar models called standard (SSM) use the most simple physical hypotheses and the best available input physics. It is assumed: a) that energy is generated by nuclear reactions in the core of the star ($r < 0.25 \, R_\odot$), and is transported by radiation in the central part and by convection in the outer part ($r > ~0.7 \, R_\odot$); b) a spherical symmetry, no rotation and no magnetic field; c) that the initial solar interior is chemically homogeneous.

The basic evolution equations (see for example [2]) are: a) the hydrostatic equilibrium between the outward radiative pressure force and the downward gravitational force; b) the thermal equilibrium between the energy produced by nuclear reactions and the energy flux emerging. The opacities govern the transport of energy in the radiative zone and require detailed calculations of atomic physics corresponding to several physical scattering processes between photons and electrons. They depend on the local chemical composition density and temperature.

The Sun is made essentially of hydrogen and helium and there is a small fraction (few %) of heavier elements. The knowledge of solar surface abundances is fundamental for modelling. These abundances are generally considered as reflecting the initial composition of the Sun for most of the elements. The direct spectroscopic observation of the solar photosphere is completed by the chemical analysis of meteorites. Surprisingly, $^4\text{He}$ cannot be measured since the temperature of the photosphere (5800 K) is too small. Its abundance is deduced from models or from helioseismological measurements. (Helioseismology studies the periodical solar oscillations observed at the surface of the Sun; they are due to acoustic waves which are excited by pressure forces and propagate in the interior of the Sun.)

More details on the physics included in solar models can be found for example in references [1-3]. The model calculation itself is an iterative procedure which consists of chain of successive stellar evolution equations. It must reproduce some important parameters of the Sun as its mass ($2 \times 10^{33}$ g), its luminosity ($L = 3.8 \times 10^{26}$ W) and its radius (700 000 km), but also to account for the helioseismological measurements which can be characterized at first order by a single parameter, the sound speed in the solar interior (derived by inverting measurements of the p-mode oscillation frequencies).

In the core of the Sun, the temperature is sufficiently high (about $15 \times 10^6$ K) to initiate the hydrogen burning with the important primary fusion reaction between two protons: $p + p \rightarrow ^3\text{He} + e^+ + \bar{\nu}_e$, which produces the so-called pp-neutrinos, (low energy neutrinos 0-420 keV). Then follows a complicated sequence of nuclear reactions (see for example [1]) producing other neutrinos, particularly medium energy beryllium neutrinos (0.862 MeV) and high energy boron neutrinos (0 to 14 MeV). All these reactions can be summarized by a single one in which four protons combine into a $^4\text{He}$ nucleus: $4p + 2e^- \rightarrow ^4\text{He} + 2\nu_e + 27 \, \text{MeV}$. This cycle of reactions is called the pp cycle and produces more than 98% of the energy of the Sun (see Fig. 1). The remaining is due to the CNO cycle which plays an important role in more massive stars where the central temperature is higher.
Many solar models have been built in the past. Most of the different codes are now validated since similar results are obtained when using the same inputs for nuclear cross sections, opacities, equation of state. Among the improvements we should quote the introduction of element diffusion processes (the stronger pull of gravity on helium and heavy elements caused them to diffuse slowly toward the solar center relative to hydrogen) and discussion on screening (the plasma polarization due to free electrons clustering around ions lowers the repulsive Coulomb barrier, and the nuclear reaction rates are enhanced by a so-called screening factor). An important improvement at the end of the 90‘s concerned the input coming from nuclear-fusion cross sections that are most important for solar energy generation; following a workshop in Seattle, most of the specialists have agreed on the best values to use in the models, taking into account the most recent experimental developments. An update of this work has been recently published [4].

The present debate in the community concerns the content of elements heavier than helium, called the metallicity $Z$ (or the ratio $Z/X$ where $X$ is the hydrogen content). Until recently, the best determination of $Z$ [5] (GS98) was $Z/X=0.0229$. A recent update [6] (AGS09) provides a value $Z/X=0.0178$ significantly lower. There would be no discussion if the so-called low metallicity option was not in good agreement with the helioseismological observations, in the contrary of the high metallicity one. Until the problem is solved (either experimentally or in the models), it becomes usual to refer to the high $Z$ SSM or low $Z$ SSM. Table 1 shows the predictions of the latest SSM calculations by Serenelli et al. [7]. Among other calculations, we quote the paper by Turck-Chièze et al. [8], which provides similar results.

Table 1. Main solar neutrino fluxes (from [7]).

| Reaction               | $E_{\nu}^{\text{max}}$ (MeV) | High $Z$ (GS98) | Low $Z$ (AGS09) | Units          |
|------------------------|-------------------------------|-----------------|-----------------|---------------|
| $p + p \rightarrow ^2H + e^+ + \nu_e$ | 0.42                           | 5.98 (1±0.06)  | 6.03 (1±0.06)  | $10^{10}$ cm$^{-2}$s$^{-1}$ |
| $p + e^- + p \rightarrow ^2H + \nu_e$ | 1.44                           | 1.44 (1±0.12)  | 1.47 (1±0.12)  | $10^9$ cm$^{-2}$s$^{-1}$ |
| $^7Be + e^- \rightarrow ^7Li + \nu_e$ | 0.862                          | 5.00 (1±0.07)  | 4.56 (1±0.07)  | $10^9$ cm$^{-2}$s$^{-1}$ |
| $^8B \rightarrow ^8Be + e^+ + \nu_e$ | $\sim$15                      | 5.58 (1±0.14)  | 4.59 (1±0.14)  | $10^9$ cm$^{-2}$s$^{-1}$ |
| $^{13}N \rightarrow ^{13}C + e^+ + \nu_e$ | 1.20                           | 2.96 (1±0.14)  | 2.17 (1±0.14)  | $10^9$ cm$^{-2}$s$^{-1}$ |
| $^{15}O \rightarrow ^{15}N + e^+ + \nu_e$ | 1.73                           | 2.23 (1±0.15)  | 1.56 (1±0.15)  | $10^9$ cm$^{-2}$s$^{-1}$ |
Figure 2 displays the solar neutrino spectrum coming from SSM, with the corresponding theoretical errors.

![Solar Neutrino Spectrum](image)

**Figure 2.** Solar neutrino spectrum (from [7]).

### 3. The solar neutrino problem (1968-2001)

The detection of solar neutrinos started in 1968 with the famous radiochemical chlorine experiment, settled by R. Davis and his collaborators in the Homestake gold mine (South Dakota, USA). Almost twenty years were necessary to have a second solar neutrino experiment working, the real time Kamiokande experiment, in the Kamioka mine (Japan), replaced in April 1996 by the giant SuperKamiokande detector (50 000 tons of water). These two experiments are sensitive only to the most energetic solar neutrinos (mainly $^8$B neutrinos). Radiochemical detectors using gallium as a target and sensitive to the low energy neutrinos, started in 1990-1991, SAGE, in the Baksan Underground Laboratory (Caucasus, Russia) and GALLEX (followed by GNO for Gallium Neutrino Observatory since 1998), in the Gran Sasso Underground Laboratory (Italy). Another large experiment, sensitive only to $^8$B neutrinos, started in fall 1999 and provided its first and beautiful results in June 2001 : the Sudbury Neutrino Observatory SNO (Ontario, Canada), which uses heavy water as a target. The Borexino experiment, also in the Gran Sasso and mainly sensitive to beryllium neutrinos, started in 2007.

The solar model predictions for the different detectors are obtained by making the convolution of the predictions for the flux (see table 1) with the cross sections (see [3] for an illustration of the cross sections as a function of the energy).

#### 3.1 The radiochemical chlorine experiment

Davis uses the reaction $\nu_e + ^{37}$Cl $\rightarrow ^{37}$Ar + e$^-$ (threshold 0.814 MeV) to catch solar $\nu_e$. The produced $^{37}$Ar isotopes decay by electron capture with a half-life of 35 days. A big tank containing 615 tons of perchlorethylene was settled at a depth of about 4100 hg/cm$^2$ of standard rock to shield against cosmic rays. A run consists in three main steps : the exposure to solar neutrinos (about two months), the argon extraction and the counting of the $^{37}$Ar. More than hundred runs have been performed since 1968, and since the beginning, the experiment has observed less neutrinos than expected. The final result is (2.56
± 0.16 (stat.) ± 0.16 (syst.) SNU [9], significantly smaller than the predictions of the models (7-8 SNU). [1 SNU = 1 solar neutrino unit = 10^{-36} event/atom/s].

3.2 The radiochemical gallium experiments
The main objective of the two radiochemical gallium experiments is the detection of the pp neutrinos which are produced in the primary pp fusion reaction. Indeed the reaction $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$ has a threshold of 233 keV only, significantly below the maximum value for the fundamental pp neutrinos (420 keV). GALLEX/GNO uses as a target a solution of GaCl$_3$ and SAGE directly the gallium metal. $^{71}\text{Ge}$ is extracted from the target and its decay observed in small proportional counters. The final result for GALLEX after 65 solar runs (May 1991 - January 1997) is $73.1 \pm 6.0$ (stat.) $\pm 4.0$ (syst.) SNU [10] and for GNO after 58 solar runs (1998 - 2003) is $62.9 \pm 5.5$ (stat.) $\pm 2.5$ (syst.) SNU [11], i.e. less than 60% of the predictions of SSM (125-130 SNU). The reliability of the detector has been checked with a high intensity (more than 60 PBq) artificial $^{51}\text{Cr}$ neutrino source ($^{51}\text{Cr}$ decays by electron capture and emits 750 keV neutrinos). The present SAGE result after 168 solar runs (1990 - 2009) is $65.4 \pm 3.0$ (stat.) $\pm 2.8$ (syst.) SNU [12], i.e. very similar to the GALLEX/GNO value. A calibration has also been performed, using 500 g of highly enriched chromium (86% of $^{50}\text{Cr}$), also validating the solar neutrino result of the SAGE experiment.

3.3 The real time SuperKamiokande experiment
The Kamiokande and SuperKamiokande experiments are based on elastic neutrino scattering (ES) : $\nu_e + e^- \rightarrow \nu_e + e^-$. The scattered electron is detected through the Cerenkov light emitted and its direction is strongly correlated with the direction of the incoming neutrino. The detection threshold is about 5 MeV and they are sensitive only to the high energy boron neutrinos. The Kamiokande detector (2140 tons of ultra-pure water) started to register solar neutrino data at the end of 1986. Its great success has been the observation of 12 neutrino events from the supernova SN1987A on February 23, 1987. The results on solar neutrinos showed a deficit of about 50% compared to the SSM predictions [13]. Since April 1996, it has been replaced by the SuperKamiokande detector: 50 000 tons of water viewed by more than 11 000 photomultipliers covering 40% of the inner surface. The data obtained after background reduction are compared to a Monte-Carlo prediction of the SSM. The present result for SuperKamiokande, which completely supersedes the old Kamiokande result, in terms of measured neutrino flux (in units of $10^6$ cm$^{-2}$ s$^{-1}$) is $2.39 \pm 0.04$ (stat.) $\pm 0.05$ (syst.) [14] compared to about 5 for solar models. It confirms the deficit of solar neutrinos first observed in the radiochemical experiments. SuperKamiokande proceeded to a lot of experimental checks and to a calibration of its detector with a LINAC, using electrons between 4.89 and 16.09 MeV. Improvements in the detector will allow to reduce the threshold to about 4 MeV.

3.4 The solar neutrino problem
The longstanding solar neutrino problem consists of the deficit observed by the experiments compared to the predictions of the solar models. It is illustrated on Figure 3 where the data of the chlorine, gallium and (Super)Kamiokande experiments are shown in blue and the predictions of the SSM in color. For more than 20 years, the explanation in the observed deficit (assuming that the experimental results are correct, after all the checks which have been performed) has been searched in the deficiencies of the solar models. Many ideas more or less exotic have been suggested to reduce the central temperature of the Sun, strongly correlated to the flux of boron neutrinos. However, these models have been and are severely constrained by the helioseismology measurements either the SSM by Bahcall et al. [15] or the seismic model [16]. Simple arithmetic mixing the results of the experiments was conducing to a disappearance of the beryllium neutrinos, difficult to understand with standard physics (see for example [17]). This was the situation in 2001.
3.5 The Sudbury Neutrino Observatory

A new real time experiment, SNO (Sudbury Neutrino Observatory), started to take data in 1999 in Canada (and has been active until 2007). With a threshold of about 5 MeV, it was sensitive only to the boron neutrinos. The experiment consisted in 1000 tons of heavy water D₂O surrounded by 4 m of purified light water H₂O. The Cerenkov light emitted by the electrons was detected by 9500 photomultipliers. The detector was installed in a deep nickel mine (2070 m underground). A major challenge of SNO has been to reduce the backgrounds at a very low level. The experiment was sensitive to three different reactions: a) the charged current (CC) reaction on deuterium \( \nu_e + d \rightarrow e^- + p + p \); this reaction is signed by the measurement of the electron whose energy is directly related to the neutrino energy by the relation \( E_e = E_\nu - 1.44 \text{ MeV} \); b) the neutral current (NC) reaction on deuterium \( \nu_x + d \rightarrow \nu_x + p + n \); this reaction, equally sensitive to all neutrino species is signed by the measurement of the neutron and has a threshold of 2.2MeV; different elaborated techniques have been used for the neutron measurement; c) the elastic reaction (ES) on electrons \( \nu_x + e^- \rightarrow \nu_x + e^- \) (x=e,\( \mu \),\( \tau \)), as in Super Kamiokande, sensitive to all neutrino species, but with reduced sensitivity for \( \nu_\mu \) and \( \nu_\tau \) by a factor about 6.

The experiment presented its first results, like a bolt from the blue, in June 2001 [19]. We quote here the final results [20] (in units of \( 10^6 \text{ cm}^{-2} \text{ s}^{-1} \)): 1.76 ± 0.05 (stat.) ± 0.05 (syst.) for the CC reaction, 2.39 ± 0.24 (stat.) ± 0.12 (syst.) for the ES reaction, 5.09 ± 0.44 (stat.) ± 0.46 (syst.) for the NC reaction. From these measurements, we can observe that: a) the ES flux is in very close agreement with that measured by Super Kamiokande (though with a larger error); b) the CC flux is about 30% lower, giving a first indication that part of the \( \nu_e \) have been transformed; c) the total flux (measured by the NC reaction) is very close to the SSM expectations. Simple arithmetic then gives a \( \nu_\mu \) flux of 1.76 ± 0.05 (stat.) ± 0.05 (syst.) and a \( (\nu_\mu + \nu_\tau) \) flux of 3.41 ± 0.45 (stat.) ± 0.48 (syst.). A combined analysis performed recently [21] gives 5.25 ± 0.16 (stat.) ± 0.12 (syst.). This last value should be considered as “the” measurement of the boron solar neutrino flux, closer to the high Z SSM, but, within errors, low Z SSM cannot be excluded.
3.6 The solution to the solar neutrino problem

The SNO results (completed by the ES SuperKamiokande results) have radically changed our point of view: they show a significant difference between the CC reaction (due to only $\nu_e$) and the ES reaction (due to $\nu_e$ with a weight 1 and to $\nu_x$ or $\nu_\mu$ or $\nu_\tau$ with a weight 1/6). Moreover they measure a boron neutrino flux in close agreement (within errors) with the SSM predictions. This evidence for solar neutrino oscillation changes the nature of the solar neutrino problem and solves it. The idea that neutrinos could oscillate between their different flavours and explain the deficit observed has been first proposed by Gribov and Pontecorvo in the 60’s. The nuclear reactions in the Sun produce only $\nu_e$ and the detectors are sensitive only to $\nu_e$ (with the exception of the ES reaction which is partially sensitive to $\nu_\mu$ or $\nu_\tau$).

A transformation of $\nu_e$ into $\nu_\mu$ or $\nu_\tau$ between the core of the Sun and the detector clearly induces a decrease of the observed $\nu_e$ flux. It becomes then possible to interpret the reduction factors observed experimentally. To do this, one has to rely on the predictions of solar models, calculate the suppression factor and compare with the suppression factors calculated assuming neutrino oscillations. In the two neutrino case, the two parameters of neutrino oscillations are $\Delta m^2$ and $\sin^2 2\theta$, where $\theta$ is the mixing angle. The experimental results constrain $\Delta m^2$ to very small areas at values between $10^{-11}$ and $10^{-12}$ eV$^2$, with a large mixing angle $\sin^2 2\theta$ above 0.7. This solution predicts characteristics variations of the neutrino rates as a function of L/E (L is the neutrino path-length and E its energy). But a new effect has been predicted in 1985, the so-called MSW effect [22]. It consists in an adiabatic transformation of the $\nu_e$ produced in the core of the Sun into $\nu_x$ or $\nu_\nu$, due to the strongly varying density in the Sun between the center and the surface, a quantum mechanical effect. In this case, there is no strong constraint on the oscillation parameters. Because the flavour changing probabilities depend on the neutrino energy and because the various reactions differ sharply in neutrino energies by more than an order of magnitude, the MSW effect has distinguishable effects, depending on the energy weightings, between the different experiments (The energy dependent reduction of the $\nu_e$ flux in the MSW effect induces a distortion of the electron energy spectrum. In the case of $\nu_e$ regeneration in the Earth [23], it may also induce a day-night effect. These two effects depend on the values of the oscillation parameters.)

Taking into account the experimental errors, each experiment defines its own triangular region in the ($\Delta m^2$, $\tan^2 \theta$) plane, since the different targets (chlorine, gallium, heavy and light water) are not sensitive to the same energy. Their overlap defines the allowed areas within a given confidence level. Three possible solutions were emerging: the SMA (small mixing angle) solution, the LMA (large mixing angle solution) and the LOW (low $\Delta m^2$) solution (see for example [24]). After the results of the reactor experiment KamLAND, only the LMA solution survived.

The formalism of neutrino oscillations is developed for example in [25]. In the three-neutrino scheme, there are 3 mixing angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$) and 2 squared-mass differences ($\Delta m^2_{12}$, $\Delta m^2_{33}$). The atmospheric neutrino sector drives $\theta_{23}$ and $\Delta m^2_{23}$. The solar neutrino sector drives $\theta_{12}$ and $\Delta m^2_{12}$. $\theta_{13}$ is driven by the reactor experiments. Figure 4 illustrates the present situation for the solar sector. We observe on the figure that the precision on the angle $\theta_{12}$ comes from solar experiments and the precision on $\Delta m^2_{12}$ comes from KamLAND.
4. The Borexino experiment (2007-20..)

Borexino is a large volume liquid scintillator detector whose primary purpose is real-time measurement of low-energy solar neutrinos (around 1 MeV). It is located deep underground (~3800 meters of water equivalent) in the Gran Sasso underground laboratory.

The Borexino detector [27] consists of a spherical inner detector (ID) containing the liquid scintillator target and of a surrounding outer detector (OD), a large water tank acting both as passive shielding and as an active muon veto. The general layout is presented in Figure 4. At the center, the active scintillator consists of pseudocumene (PC, 1,2,4 trimethylbenzene), doped with 1.5 g/liter of PPO (2,5-diphenyloxazole, a fluorescent dye). The nominal target mass is 278 tons. The scintillator is contained in a thin (125 μm) nylon vessel of 4.25 m radius and is shielded by two concentric inactive PC buffers (323 t and 567 t doped with few g/l of a scintillation light quencher (dimethylphthalate). The two PC buffers are separated by a second thin nylon membrane to prevent diffusion of radon towards the scintillator. The scintillator and buffers are contained in a Stainless Steel Sphere (SSS) with a diameter of 13.7 m. The SSS is enclosed in a 18.0 m diameter, 16.9 m high domed Water Tank (WT), containing 2100 t of ultrapure water. The scintillation light is detected via 2212 8"-photomultiplier tubes (PMTs) uniformly distributed on the inner surface of the SSS. Additional 208 8" PMTs instrument the WT and detect the Cherenkov light radiated by muons in the water shield.
In Borexino, low energy neutrinos ($\nu$) of all flavors are detected by means of their elastic scattering off electrons or, in case of electron antineutrinos, via the inverse beta decay on free protons. The electron (positron) recoil energy is converted into scintillation light which is then collected by the ID PMTs. Borexino is sensitive to neutrinos of at least $\sim 100$ keV in energy, while the inverse beta decay induced by antineutrinos requires a minimum neutrino energy of 1.8 MeV. While cosmic muons crossing the ID deposit much greater energies and create substantially more light, cosmogenic neutrons and radioisotopes induce scintillation signals on a scale similar to neutrino interactions. Position reconstruction of events is obtained from the PMT timing via photon time-of-flight algorithm.

To observe very small signals (typical solar neutrino signals are tens of counts per day or less), Borexino had to achieve very severe requirements in terms of radiopurity. The problem has been addressed by developing suitable purification techniques for scintillator, water and nitrogen, by performing careful material selection, by building and operating a prototype called the Counting Test Facility (CTF). The program has been successful since the final content in U and Th for example is smaller than the design’s values.

Borexino started to take data in May 2007 and the so-called phase-I ended in December 2010. Several calibration phases took place in this period [28]. One year was then devoted to new purification phases, to remove some residual impurities. Phase II started in January 2012. The results presented here correspond to phase-I.

5. Solar neutrino results in Borexino

The main objective of Borexino was the detection of $^7$Be neutrinos. This has been realized soon after the start of the experiment and a precision measurement has been done after three years of data. The radioactive background being significantly lower than expected, the observation of pep neutrinos has been possible, which was not planned at the time of the proposal. Borexino also measured the $^8$B neutrinos with a threshold lower than the large Cherenkov experiments.

5.1 $^7$Be solar neutrinos

The signature of the mono-energetic 862 keV $^7$Be neutrinos is a Compton-like edge of recoil electrons at 665 keV. Events are selected after a number of cuts: a) rejection of muons and events less than 300 ms after a muon; b) rejection of electronic noise; c) reconstructed vertex inside a fiducial volume smaller than the full target (about 76 tons instead of 280). The energy spectrum obtained was then
fitted with the solar components (\(^{7}\)Be, pp, pep, CNO) and the backgrounds still present (\(^{85}\)Kr, \(^{210}\)Bi, \(^{11}\)C, \(^{210}\)Po). The solar components other than \(^{7}\)Be were fixed at the level of the high metallicity SSM including the LMA solution of the oscillation scenario. The backgrounds are present at a level of the same order that the expected signal, but are discriminated mainly by the different shape. The result is displayed in Figure 5 which illustrates a typical fit (several methods have been used).

Figure 5 b. Fit of the \(^{7}\)Be solar neutrinos in Borexino. The energy spectrum (black points) is fitted with solar components (\(^{7}\)Be, pp, pep, CNO) and backgrounds (\(^{85}\)Kr, \(^{210}\)Bi, \(^{11}\)C, \(^{210}\)Po). The values of the fitted parameters are [cpd/100 t]. (From [29]).

The final result is for the \(^{7}\)Be signal is: 46 ± 1.5 (stat.) ± 1.5 (syst.) counts/day/100 tons (cpd/100 t). If there was no oscillation, it would be 74 ± 5 cpd/100 t, corresponding to a flux \(\Phi(\text{Be}) = (5.00 ± 0.35) \times 10^8\) cm\(^{-2}\)s\(^{-1}\). This value is in good agreement with the predictions (see Table 1). More details on this analysis can be found in [29,30].

5.2 pep and CNO neutrinos
The detection of pep and CNO neutrinos is even more challenging than that of \(^{7}\)Be, as their expected interaction rates are \(\sim 10\) times lower, few counts per day per 100 tons. The dominant background in the region of interest (1-2 MeV) is \(^{11}\)C (\(\beta^+\) emitter with lifetime of 29.4 min), produced in the scintillator by the interaction of cosmic muons with \(^{12}\)C. With about 4300 muons per day in Borexino, \(~27\) cpd/100 t of \(^{11}\)C are expected. An innovative and specific analysis has been developed to reduce this background without affecting too much the expected signal (see details in [31]).

The energy spectrum has been fitted with the solar neutrino signals and the backgrounds. The result is the following for pep neutrinos: 3.1 ± 0.6 (stat.) ± 0.3 (syst.) cpd/100 t, corresponding to a solar neutrino flux of \((1.6 ± 0.3) \times 10^8\) cm\(^{-2}\)s\(^{-1}\), in good agreement with the SSM (\(~1.45 \times 10^8\) cm\(^{-2}\)s\(^{-1}\)). Due to the similarity between the electron-recoil from CNO neutrinos and the spectral shape of \(^{210}\)Bi, only an upper limit on CNO has been obtained. This limit, 7.9 cpd/100 t, is however, very constraining since it corresponds to a solar neutrino flux smaller than \(7.7 \times 10^8\) cm\(^{-2}\)s\(^{-1}\), just above the SSM predictions (3.5 to \(5 \times 10^8\) cm\(^{-2}\)s\(^{-1}\)). The challenge for the future will be to disentangle the \(^{210}\)Bi from the CNO.

Figure 6a shows the residual energy spectrum after best-fit rates of all considered backgrounds are subtracted, as well as the pep spectrum taken from the best-fit. Figure 6b shows the full \(\Delta \chi^2\) profile for pep and CNO neutrino interaction rates. More information is found in [31].
5.3 $^8$B neutrinos

Solar $^8$B neutrino spectroscopy has so far been performed in large experiments, SuperKamiokande and SNO. However the Cherenkov technique implied to use a threshold of ~5 MeV (reduced to ~4 MeV for the last period of SuperKamiokande). Borexono, using liquid scintillator, could reduce significantly this value to 3 MeV. The dominant background in the energy range of interest (few MeV) originates from spallation processes of high-energy cosmic muons, mainly $^{12}$B, $^6$He, $^8$Li, $^8$He, $^9$C, $^9$Li. Among the daughters of the $^{232}$Th naturally present in the scintillator, $^{208}$Tl decays are the only ones which contribute above 3 MeV.

After a detailed analysis sequence, the result is the following: $0.22 \pm 0.04 \text{ (stat.)} \pm 0.01 \text{ (syst.) cpd/100 t for E>3 MeV}$; in order to compare with Cherenkov experiments, the value for E>5 MeV is $0.13 \pm 0.02 \text{ (stat.)} \pm 0.01 \text{ (syst.) cpd/100 t}$. The corresponding values of the $^8$B solar neutrino fluxes are: $(2.4 \pm 0.4) \times 10^6 \text{ cm}^{-2} \text{s}^{-1} \text{ (E>3 MeV)}$ and $(2.7 \pm 0.5) \times 10^6 \text{ cm}^{-2} \text{s}^{-1} \text{ (E>5 MeV)}$, in good agreement, though with larger errors, with the Cherenkov experiments. Figure 7 shows the corresponding energy spectrum. More details on this analysis are found in [32].
5.4 Borexino and the MSW-LMA solution

The different Borexino measurements have allowed to test and validate the MSW-LMA solution. This can be shown on Fig. 8 which presents the survival probability of solar $\nu_e$ as a function of the energy. The grey line corresponds to the calculation of the oscillation with the parameters of the LMA solution, taking into account the MSW effect ($\sin^2(2\theta_{12})=0.87$ and $\Delta m_{12}^2=7.6 \times 10^{-5}$ eV$^2$); the value on the left (0 MeV) corresponds to the vacuum solution ($1-0.5 \sin^2(2\theta_{12})$) and the value on the right (20 MeV) to the MSW effect ($\sin^2\theta_{12}$). The Borexino data are shown in colour, the pink value at low energy being calculated using all solar neutrino data. All this confirms pretty well the transition between the two regimes.

![Figure 8. Solar $\nu_e$ survival probability as a function of energy. The colour lines correspond to experimental data. The grey line corresponds to the MSW-LMA solution for solar neutrino oscillation. (From [29]).](image)

Borexino also contributed to reinforce the MSW-LMA solution via the study of the day-night effect using the large statistics for $^7$Be events [33]. As said in section 3.6, it is known that solar $\nu_e$ which have been transformed in the Sun via the MSW effect can be regenerated when crossing the Earth if they arrive during the night [23]. This phenomenon depends on the values of the parameters and on the neutrino energy. The measured value of the day-night asymmetry, $A_{dn} = 0.001 \pm 0.012$ (stat.) $\pm 0.007$ (syst.), shows the absence of a significant asymmetry. This allows to reject the, already disfavoured, LOW solution (see section 3.6) at more than 8.5$\sigma$. Combined with the other solar neutrino data it isolates the LMA solution without relying on the assumption of the CPT symmetry in the neutrino sector. More details are found in [33].

5.5 The future of solar neutrinos in Borexino

During the phase II, Borexino will measure with a better precision the $^7$Be neutrinos. But the main effort concerning solar neutrinos will be twofold: a) direct detection of pp-neutrinos, which means a dedicated understanding of the low energy spectrum, dominated by the radioactivity of the $^{14}$C intrinsic to the scintillator; b) observation of CNO neutrinos, which means to disentangle the signal from backgrounds, mainly $^{210}$Bi, with a similar energy spectrum. All this is not guaranteed but the scientific challenge is there.
6. Conclusion

I have briefly presented the fascinating domain of solar neutrinos which contributed significantly in the past 45 years in astrophysics (how the Sun shines, solar modelling) and to particle physics (neutrino oscillation of solar $\nu_e$, mainly via the MSW mechanism). In the past years, the main results came from the Borexino experiment, which realized important achievements towards a complete solar neutrino spectroscopy. The discovery potential in the future remains intact with the challenging pp and CNO direct measurements.

More complete reviews can be found for example in references [18] and [34].

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