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Neutrino Physics/Physique des neutrinos

Solar neutrinos

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Abstract

Several decades of studies of solar neutrinos lead now to clear indications that oscillation between ν_e produced in the core of the Sun and other flavours (ν_μ or ν_τ) is the correct explanation of the deficit observed by all experiments. This implies that neutrinos are massive, in contradiction with the minimal standard model of particle physics. Moreover, thanks to the SNO experiment, we know that solar models built by astrophysicists predict correctly the flux of neutrinos. ***To cite this article: M. Cribier, T. Bowles, C. R. Physique 6 (2005).***

Résumé

Les neutrinos solaires. Plusieurs décennies d'études des neutrinos solaires ont apporté la preuve que l'oscillation entre les ν_e produits au cœur du Soleil et d'autres saveurs (ν_μ ou ν_τ) est l'explication du déficit observé expérimentalement. Ceci implique que les neutrinos sont massifs, en contradiction avec le modèle standard minimal de la physique des particules. En outre, grâce aux derniers résultats de l'expérience SNO, nous savons que les modèles solaires construits par les astrophysiciens prédisent correctement le flux de neutrinos. ***Pour citer cet article : M. Cribier, T. Bowles, C. R. Physique 6 (2005).***

Keywords: Solar neutrinos; Neutrino flavour; Flavour oscillations

Mots-clés : Neutrinos solaires ; Saveur des neutrinos ; Oscillations des saveurs

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1. Introduction

Solar neutrinos have been extensively studied, theoretically and experimentally, in the past 40 years. The pioneering works of Bahcall on the one hand and Davis on the other hand were at the origin of the solar neutrino problem: the deficit observed in the chlorine experiment could have an answer either in the solar modelling and our understanding of the energy production in the Sun or in the properties of the elusive neutrinos. We here briefly review the major steps of the story until the final solution to the problem in 2004. We start with the abundant production of neutrinos from nuclear fusion reactions in the core of the Sun. We then describe the different experiments. The radiochemical chlorine experiment provided the first detection of solar neutrinos but in an amount low compared to that expected. The proof that observed neutrinos were of solar origin was given by the Kamiokande experiment. In the 1990s, gallium experiments were the first to detect to the primordial and

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most abundant component. The SuperKamiokande experiment accurately measured the elastic scattering of high-energy solar neutrinos but did not observe any specific signature (spectral distortion or time variations) that would provide strong evidence for neutrino oscillations. Finally, the SNO experiment was able to measure all neutrinos irrespective of their flavour, showing that model predictions were correct and that neutrino oscillation between flavours was responsible for the results obtained. This last hypothesis was finally confirmed by KamLAND which observed the oscillation of antineutrinos from nuclear reactors.

2. Production of neutrinos in the Sun

Since the work of Hans Bethe in the 1930s, the fusion of hydrogen into helium by nuclear reactions has been generally accepted as the means by which energy is produced inside the stars of the main sequence, like the Sun, thanks to the central temperature of about 15×10^6 K. The released energy is slowly transported (10^6 years) to the surface by radiative and convective processes. In contrast, neutrinos, which are also produced by these nuclear reactions, and carry away about 3% of the produced energy, reach the Earth only 8 minutes after they are produced.

Solar modelling 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' use the most simple physics hypotheses and the best available input physics. It is assumed that: (a) energy is generated by nuclear reactions in the core of the Sun; (b) there is spherical symmetry, no rotation, and no magnetic field; (c) the initial solar interior is chemically homogeneous. The basic evolution equations are: (a) the hydrostatic equilibrium between the outward radiative pressure force and the inward gravitational force; and (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 scattering processes between photons and electrons.

The model calculation itself is an iterative procedure which consists of chains of successive stellar evolution equations. It must reproduce not only the luminosity, radius, and surface temperature, but also the precise helioseismological measurements which can be characterized at first order by a single parameter, the sound speed inside the Sun.

In the Sun, the initial reaction is the process:

$$pp \to {}^2\mathrm{H} + e^+ + \nu_e \tag{1}$$

that produces a continuous spectrum of neutrinos ν_e up to 420 keV (called ν_{pp}). This reaction is a weak interaction process at this energy and stars like the Sun slowly burn their nuclear fuel. In the Sun, the process has lasted 4.5 billions years so far and will continue for about the same period of time. The deuterons formed quickly combine with a proton to form ^{3}He; two ^{3}He then fuse into the stable ^{4}He. In 15% of the reactions ^{3}He combine with already existing ^{4}He to produce a ^{7}Be nuclei; ^{7}Be nucleus is unstable and decays by electron capture, producing a monoenergetic line of neutrinos (called ν_{Be}) at 861 keV (with another line at 384 keV in which a gamma is also emitted). Before the ^{7}Be decays, it can capture a proton (with a very small probability) and produce a ^{8}B nucleus, which itself decays:

$$^8\mathrm{B} \to {}^8\mathrm{Be}^* + e^+ + \nu_e$$

The energy of the emitted neutrino (called ν_{B}) extends up to 14 MeV.

Many solar models have been built in the past years (see, for example, [1,2] for the most quoted and regularly updated ones). The discrepancies between the predictions of the different models have been considerably reduced and now agree quite well. The standard solar model flux predictions are displayed in Fig. 1. They correspond to a flux on Earth as large as $65 \times 10^9\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

3. Detection of solar neutrinos

Solar neutrinos are produced as electron neutrinos (ν_e) in the nuclear reactions in the Sun, and the first detectors built were mostly sensitive to this neutrino flavor; they were based on the inverse beta-decay reactions where the target nucleus (A, Z) is turned into the nucleus $(A, Z + 1)$ and used targets sensitive to neutrinos like ^{37}Cl or ^{71}Ga. The selectivity of the reaction to neutrinos is a great help and so far only these detectors have been able to measure the low energy components of the solar neutrinos (below 1 MeV). These radiochemical experiments collect the produced radioactive atoms over several weeks or months and the counting of the decay of the daughter nucleus lasts several months (to allow a precise determination of the background).

Real time experiments based on neutrino interactions in normal or heavy water bring crucial information, thanks to the sensitivity to all neutrino flavours. Moreover the large target mass allows a precise determination of the individual fluxes (although the measurements are restricted to the most energetic part of the solar neutrino spectrum).

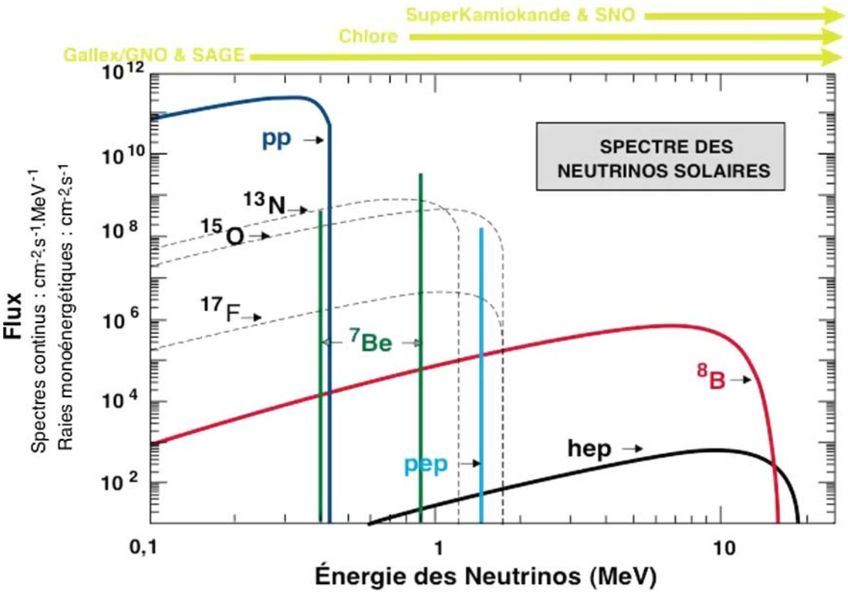

Fig. 1. Solar neutrino energy spectrum (adapted from Bahcall [1]). Neutrino fluxes from continuum sources are in $\text{cm}^{-2}\,\text{s}^{-1}\,\text{MeV}^{-1}$. Line fluxes (for pep and Be neutrinos) are in $\text{cm}^{-2}\,\text{s}^{-1}$. The insert gives the sensitivity interval of the different detectors.

In any case, radioactive backgrounds of different origins (internal, external, cosmogenically produced) have to be kept at a very low level. All these experiments are installed deep underground to reduce parasitic reactions induced by cosmic rays and which could simulate solar neutrino interactions. Special care must be taken in the selection of materials entering the detector and purification of the target from radioactive elements is mandatory.

The difference in thresholds of the experiments performed with different techniques offers a rather complete knowledge of the main components of the solar neutrinos: the gallium experiments are dominated by events induced by pp-neutrinos ($\approx 50\%$ of the signal), while the chlorine target is mainly sensitive to ν_{B} neutrinos (but also sees the ν_{Be} neutrinos). Normal and heavy water experiments are sensitive only to the upper part of ν_{B} (see Fig. 1).

3.1. Radiochemical experiments

The chlorine experiment started in 1968 in the Homestake gold mine in South Dakota (1480 m underground) and took data until 2001 when it was dismantled. For his pioneering work, R. Davis used a target of 610 tons of C_2Cl_4. The threshold (814 keV) of the reaction:

$$\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$$

allows this detector to be sensitive to ν_{Be} and ν_{B}. Every three months the radioactive ^{37}Ar, which are produced at a rate of one atom every two days, were flushed and collected in a proportional counter. The predicted rate is 8.5 ± 1.8 SNU[1] [1,2], whereas the average rate measured over 25 years is 2.56 ± 0.16 (stat.) ± 0.16 (syst.) SNU [3]; approximately 750 ^{37}Ar decays have been counted. This result, in clear contradiction with the prediction, was at the origin of the longstanding solar neutrino problem.

Two gallium experiments have been built. They use the reaction:

$$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$$

with a threshold low enough (233 keV) to be sensitive to a large fraction of the most abundant ν_{pp} component produced in the primary reaction (1). SAGE [4] uses 60 tons of metallic gallium in the Baksan laboratory (Russia) and GALLEX/GNO [5,6] 30 tons of gallium in the form of a gallium chloride solution in the Gran Sasso Underground Laboratory (Italy). They produced their first results in 1990–92. GALLEX/GNO stopped data taking in 2002 for external nonscientific reasons and only SAGE continues to monitor the pp-neutrino flux. In these experiments the radioactive ^{71}Ge atoms produced (half-life 11.4 days) are

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[1] 1 SNU: 1 interaction per second in a target of 10^{36} atoms of the required isotope.

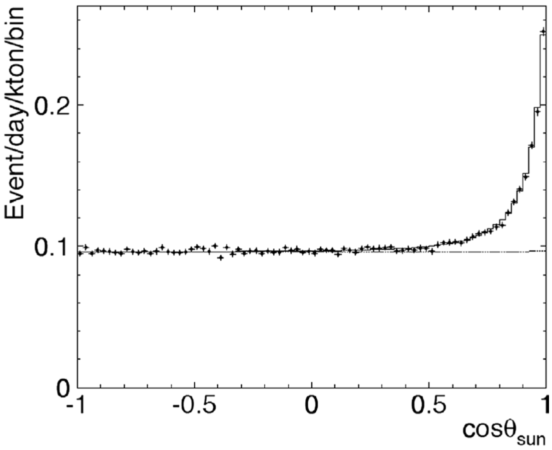

Fig. 2. Plot of the cosine of the angle between the electron momentum and the Sun–Earth direction in SuperKamiokande. The solid line shows the best fit to the data [9].

extracted from the target and converted into a gas GeH_4 to observe its characteristic decays in a miniaturized proportional counter.

The joint result from 123 runs in GALLEX and GNO is 69.3 ± 5.5 (stat. + syst.) SNU (1σ) [6], obtained after having counted about 500 ^{71}Ge produced by solar neutrino interactions. The present SAGE results is very similar: 66.9 ± 5.3 SNU [4,8]. The measured fluxes represent less than 60% of the solar model predictions, 131^{+12}_{-10} SNU [1] and confirmed the solar neutrino problem.

Neutrinos produced by electron capture in ^{51}Cr sources were used to calibrate these gallium detectors and the positive answers demonstrate [7,4] that the response of these detectors to neutrinos is well understood. Recently another artificial neutrino source produced in the decay of ^{37}Ar has been used in the SAGE experiment.

The gallium results prove that the most abundant component of solar neutrinos (ν_{pp}) is present and that the total flux measured is in any case close to the level that can be expected just from the solar luminosity where the whole energy production is attributed to reaction (1).

3.2. SuperKamiokande

From 1987, Kamiokande and later SuperKamiokande [9], were able to measure the upper part of the ν_{B} spectrum with a water Cerenkov detector. The SuperKamiokande experiment consists of 50 000 m^3 of pure water seen by 11 000 photomultipliers tubes (PMT). Neutrinos interact by scattering on the electrons of the target $(\nu_e + e^- \to \nu_e + e^-)$. The Cerenkov light produced by the scattered electron provides information on the energy and direction of the incoming neutrino. The rate for solar neutrinos is about 10 per day. SuperKamiokande started taking data in May 1996 with an energy threshold at 6 MeV, which was later reduced to 5.5 MeV. Several in situ energy calibrations with an electron linear accelerator have been performed.

The SuperKamiokande can measure the energy of the neutrinos as well as the direction of arrival. These detectors established beyond doubt that the solar neutrinos are indeed originating from our Sun (see Fig. 2); moreover, although the measured flux is only 40% of that expected [9], it established that the small branch producing ν_{B} (which is insignificant in terms of energy production) is operating in the Sun, and thus that ν_{Be}, the precursor of ν_{B} must be also present in the Sun.

The result [9] after 1496 days is a measurement of the flux of ν_{B} at $2.35 \pm 0.02(\text{stat}) \pm 0.08(\text{syst}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$, i.e., $(40.6 \pm 1.5)\%$ of the predicted flux [1,2]. The number of events attributed to solar neutrinos in SuperKamiokande for the period 1996–2001 is 22 400: the impressive statistics allow several detailed studies. Sensitive search for a day/night asymmetry, predicted in case of possible effects due to passage of neutrinos through the matter of the Earth, have been performed. The present result is:

$$\frac{D-N}{(N+D)/2} = -0.021 \pm 0.020(\text{stat.})^{+0.013}_{-0.012}(\text{syst.})$$

and does not show any significant asymmetry. Checks of the energy distribution have also been made: apart from the highest points in energy, where contribution from the less precisely predicted solar neutrino component (hep) are expected, the spectrum is consistent with the expected beta spectrum.

Combining the results of the chlorine and Kamiokande/SuperKamiokande experiments leads to an inconsistency. Indeed, assuming the ν_{B} flux as measured by SuperKamiokande, there is no room left for ν_{Be}. In the solar models, this last component is responsible for 15% of the energy production in the Sun and is necessary to produce later ν_B. This is why, at the end of the 1990s, the more exciting solution to the solar neutrino problem was neutrino oscillations: part of the ν_e are transformed into ν_μ or ν_τ; the ν_μ or ν_τ are not seen in the radiochemical detectors, and their interaction cross section in water is 6 times smaller than the cross section for ν_e. We will come back later to this interpretation.

3.3. Sudbury Neutrino Observatory (SNO)

SNO (Sudbury Neutrino Observatory) is a 1000-ton heavy water (D_2O) real-time Cerenkov detector built in a nickel mine in Canada [10]. The detection of electron neutrino uses the following reactions:

$$\nu_e + {}^2\mathrm{H} \to e^- + p + p$$
$$\nu_e + e^- \to \nu_e + e^-$$

In the first reaction, a charged current (CC) reaction, the energy of the electron provides a direct determination of the energy of this neutrino, but with rather limited information about the direction of the incoming neutrino. In the second, an elastic scattering (ES) reaction, limited information is available about the neutrino energy, but the information about the direction of the incoming neutrino is quite good. In addition SNO is able to measure explicitly, for the first time, the flux of the other neutrino flavours, via the neutral current (NC) neutrino induced disintegration of the deuteron into a neutron and a proton:

$$\nu_x + {}^2\mathrm{H} \to \nu_x + p + n; \quad x = e, \mu, \tau$$

A comparison of the rate of the first and third reactions allows one to separately determine the flux of ν_e from the flux of ν_μ and v_τ. The expected rate is about 30 per day for the sum of the three reactions.

The 1000 tons of D_2O is contained within a 12-m-diameter acrylic sphere (Fig. 3). The sphere is at the center of a 17-m-diameter geodesic structure that holds 9500 20-cm-diameter PMTs. This structure is within a 22-m-diameter cavity at a depth of 6010 meters water equivalent (about 2100 m below the surface). The volume outside of the acrylic vessel contains highly purified water (U, Th levels are $< 10^{-13}$ g/g concentration) while the heavy water inside the acrylic vessel is extremely radiopure (U concentration is $\sim 10^{-14}$ g/g and Th concentration is $\sim 2 \times 10^{-15}$ g/g). SNO has measured the NC reaction by observing the capture of the free neutron on deuterium which results in a 6.25 MeV gamma ray that produces Cherenkov light in the detector. SNO has also measured the NC reaction by adding 2 tons of NaCl to the heavy water, resulting in the free neutron capturing preferentially on Cl which results in the emission of several gamma rays totalling 8 MeV. Finally, SNO has recently installed a set of NC detectors, consisting of an array of ^{3}He-filled proportional counters which will allow a more precise determination of the NC rate. In this mode of operation, the free neutrons capture on the ^{3}He give a signal in the proportional counters. This completely separates the NC reaction from the CC and ES reactions.

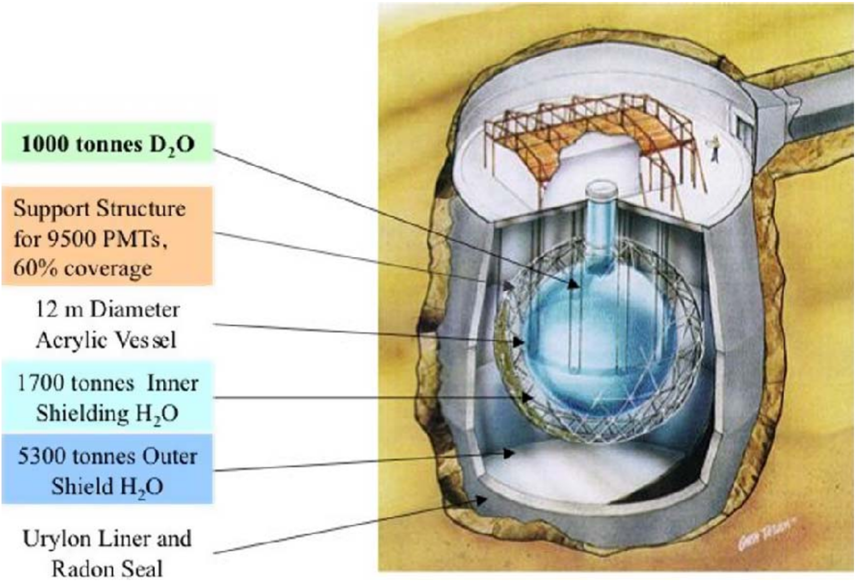

Fig. 3. The SNO detector. The 1000 tons of heavy water is contained in the acrylic vessel located at the center of the detector. A geodesic support structure holds the 9500 PMTs that view the heavy water.

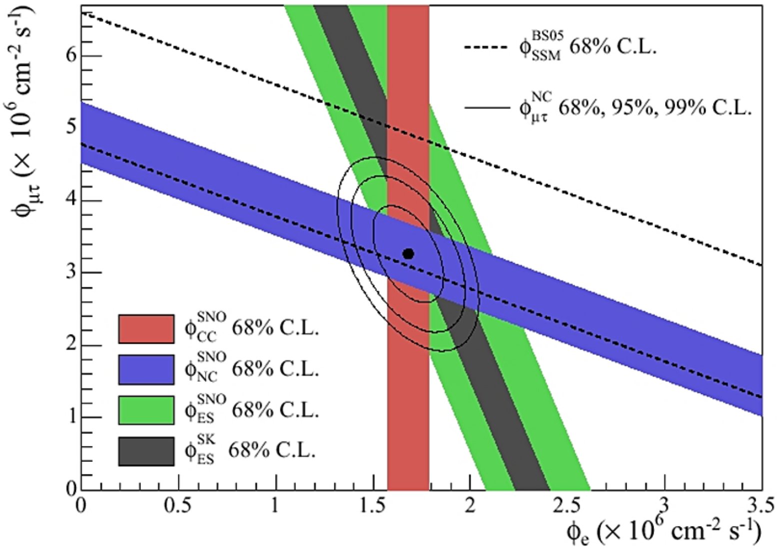

Fig. 4. The flux of ν_B solar neutrinos which are either μ or τ flavour versus the flux of electron neutrinos [10]. The $1-\sigma$ contours of the three reactions (CC, ES, NC) determined by the SNO measurements are shown. The intersection of the reactions defines the ratio of μ or τ and electron neutrinos. Also shown is the contour allowed by the SSM.

SNO has published two sets of data, one with heavy water and a second one with salt added to the heavy water which gives more precise values [10]. The results for the phase with salt are the following, in units of 10^6 cm^{-2} s^{-1}: the total flux measured (NC) is $4.94 \pm 0.21 \pm 0.38$ (all flavours); the ν_e flux (CC) is $1.68 \pm 0.06 \pm 0.08$ and the elastic reaction (ES) is $2.35 \pm 0.22 \pm 0.15$ (very close to the SuperKamiokande result) where the first error is statistical and the second systematic. The results for the phase with pure heavy water were $1.76 \pm 0.05 \pm 0.09$ for the CC reaction, $5.09 \pm 0.44 \pm 0.45$ for the NC reaction and $2.34 \pm 0.23 \pm 0.15$ for the ES reaction. The results of the two phases are completely in agreement.

Fig. 4 shows the flux of ν_μ and ν_τ neutrinos versus the ν_e flux, as obtained from the SNO data.

SNO has reported that about two-thirds of the ν_B solar neutrinos that are formed in the Sun as electron neutrinos arrive at the Earth as muon or tau neutrinos. This provides clear evidence (at more than 5 sigma) of the oscillation of neutrinos (see next section). In addition, the total ν_B flux of all flavours agrees quite well with the SSM prediction.

4. Interpretation of the solar neutrino experiments in terms of neutrino oscillation

4.1. Summary of experimental results

The summary of the results of all the experiments together with the predictions of the standard model is displayed in Fig. 5.

4.2. Neutrino oscillations and MSW mechanism

Oscillation of neutrinos occurs if neutrinos are massive and if the neutrino mass eigenstates do not coincide with the flavour eigenstates (ν_e, ν_μ, ν_τ) [12]. The oscillation from one flavor to another depends on two parameters: the degree of mixing (described by a mixing angle θ) between the two flavors and the masses of the two neutrinos involved (described by Δm^2, the difference of the squared neutrino masses). The solar neutrino experiments provide a determination of Δm^2 and θ for the oscillation of ν_e to ν_μ or ν_τ.

A nontrivial modification of the oscillation takes place inside the very dense matter of the Sun: the MSW effect [13] induced by the coherent scattering of the neutrinos as they traverse matter in the Sun. Due to the presence of electrons in the matter, ν_e has a different scattering probability than the other species. This can be understood as a different index of refraction of ν_e than ν_μ (or ν_τ) due to scattering on electrons, hence the phase associated with the index of refraction must be included in the quantum mechanical equations for oscillation. If the density decreases as the neutrinos traverse matter, a resonant amplification of the oscillations can take place leading to a complete disappearance of the neutrinos as ν_e and the consequent appearance of other species (ν_μ or ν_τ). The effectiveness in the Sun depends on the precise values of the unknown masses of the neutrinos,

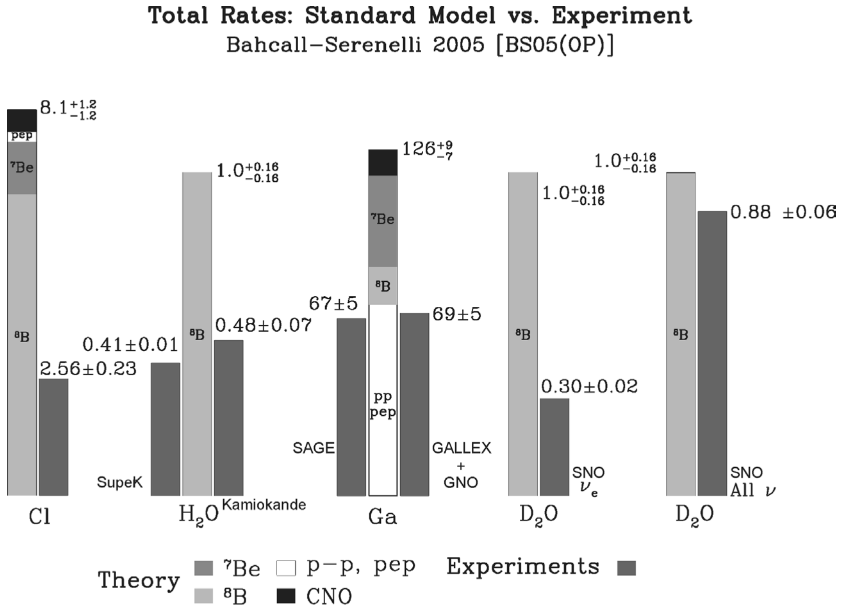

Fig. 5. Comparison of measured rates and standard solar model predictions for solar neutrino experiments [11].

of their energy, and on how they mix between the different species. Moreover, the resonant nature of the MSW effect has the consequence to extend the sensitivity of solar neutrinos experiments to small values of the mixing angle θ.

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. Taking into account the experimental errors, each experiment defines its own triangular region in the Δm^2 versus mixing angle plane: inside these domains the flux of the standard model of the Sun folded by the suppression induced by the oscillation is compatible with the experimental result. Their overlap defines the allowed areas within a given confidence level.

Before the SNO results, the global fit of the overlap was leading to three solutions involving the MSW mechanism: the small angle solution (SMA) with Δm^2 around 6×10^{-6} eV^2 and $\tan^2\theta$ around 6×10^{-4}, the large angle solution (LMA) with Δm^2 around 4×10^{-5} eV^2 and $\tan^2\theta$ around 0.3 and the LOW solution with Δm^2 around 8×10^{-8} eV^2 and $\tan^2\theta$ around 0.7. Combining the SNO results with the results of the other solar neutrino experiments provides a single set of oscillation parameters that are consistent with the large mixing angle solution (LMA) and values of the parameters $\Delta m^2 = 3.7\times10^{-5}$ eV^2 and $\tan^2\theta = 0.4$. However, this is not the end of the story.

4.3. The KamLAND reactor experiment

The result of SNO established clearly the phenomenon of oscillations in the sector of neutrino and narrow the range of values of possible oscillation parameters to the LMA region; these values offer a possibility to observe a suppression of electron antineutrinos ($\bar{\nu}_e$) emitted by nuclear power plants (see [14] for reactor antineutrinos).

The Kamioka Liquid Scintillator Antineutrino Detector (KamLAND) is located in the Kamioka underground laboratory in Japan. With 1000 t of liquid scintillator KamLAND measures the interaction rate and energy spectrum of $\bar{\nu}_e$ coming from Japanese and Korean reactors using the inverse β-reaction $\bar{\nu}_e + p \to e^+ + n$. The flux-averaged mean baseline is about 180 km. KamLAND, with a live time of 766.3 ton-yr, recently published [15] an accurate measurement of the reactor $\bar{\nu}_e$ flux and spectrum. By itself, it provides an unambiguous evidence for the oscillation of reactor antineutrinos with parameter values also located in the LMA region pointed out by solar neutrinos. The shape of the energy spectrum measured by KamLAND is inconsistent with the energy spectrum of reactor $\bar{\nu}_e$ in the absence of oscillations at the 99.6% C.L. For a constant baseline L the electron antineutrino survival probability:

$$P_{ee} = 1 - \sin^2(2\theta) \times \sin^2\left(\Delta m^2 \frac{L}{E_\nu}\right)$$

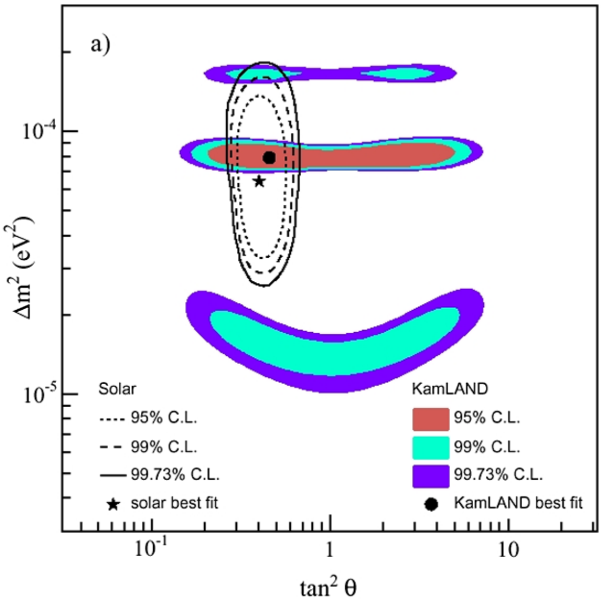

Fig. 6. Neutrino oscillation parameter allowed region (Δm^2 versus mixing angle) from combined analysis of solar neutrino experiments and KamLAND reactor antineutrino experiment [15].

depends on the antineutrino energy E_ν, and spectral distortions are a characteristic signature of the oscillation effect. This result disfavours strongly alternative explanations other than oscillations, such as resonant spin-flavour conversion, flavour changing neutral currents, neutrino decays or oscillations into sterile neutrinos.

The results from KamLAND in terms of oscillation are completely consistent with those from the solar neutrino experiments. A combined analysis (solar neutrino experiments and KamLAND) provides a good measurement of the oscillation parameters (see Fig. 6). The precision on Δm^2 comes from KamLAND and a good determination of the mixing angle from the solar neutrino experiments. Other global analyses have been performed and give similar results (see, for example, [16]). The present best values of the parameters are: $\Delta m^2 = (8.2 \pm 0.3) \times 10^{-5}$ eV^2 and $\tan^2\theta = 0.39 \pm 0.05$.

5. Future experiments

Although the oscillation mechanism driven by LMA parameters explains quantitatively all present experimental results, it has been tested only with solar neutrinos above ≈ 5 MeV that represent 0.1‰ of the total flux. While the main components (pp and ^{7}Be) of the solar neutrino flux are better understood, they have not been measured directly, and the prediction of LMA is very different below 1–2 MeV. Motivated by these points, several groups are preparing new challenging detectors for solar neutrinos, to complete our understanding of all the components.

Borexino consists of an internal sphere of 300 tons of ultra-pure liquid organic scintillator viewed by 2200 PMTs and shielded from external radiations by 1 m of organic liquid and 3 m of pure water [17]. Although affected by nonscientific decisions, it is presently in the final phase of assembly in the Gran Sasso laboratory. Neutrinos scatter on electrons as in SuperKamiokande, but the interaction is merely signed by the energy of the diffused electron as recorded by the PMTs; the signal from ^{7}Be solar neutrinos will show up as a kind of Compton edge above background. The detecting technique needs a purity of the target in term of radioactive emitters (^{14}C, U, Th) which constitutes a world record, but which has been achieved already in a 5-ton prototype (Counting Test Facility CTF). With such characteristics, it will allow the detection of ν_{Be} at a rate of 10 per day if there is no disappearance of ν_e, and at a rate of 1.7 in the case of complete conversion into the other neutrino species. Borexino is really suited to measure the ν_{Be} component. Seasonal variation are expected, not only the trivial one due to ±7% modulation in Sun–Earth distance (eccentricity) but another induced by the vacuum oscillation if the oscillation length matches the Sun–Earth distance.

A desirable future goal for the study of the low-energy solar neutrinos would be both CC and NC experiments. Several projects to do this are under consideration.

For the measurements via NC, the use of several liquid noble gases is being explored. XMASS [18] aims at a detector of 10 tons of liquid xenon to observe ν_{pp} (10/day) and ν_{Be} (5/day) through elastic scattering on electrons providing scintillation light. Moving step by step this effort will also study ^{136}Xe double beta decay, and will represent a competitive detector for dark matter. An alternative solution, using liquid neon, is explored by the CLEAN collaboration [19], which takes advantage of the absence of long-lived radioactive isotopes in this target. A very original technique has been developed by HERON [20] which uses roton excitation of liquid helium. The advantage is a very efficient rejection of all backgrounds.

Two projects have been studied to detect low energy neutrinos by CC reactions. MOON uses a ^{100}Mo target [21]. The signature consists of a prompt inverse beta followed by the beta decay of the daughter nucleus with a 16 second half-life. The background resulting from the double beta decay of the target drives the design to small individual modules. A detector of 3 tons could count 0.4 events per day (ν_{pp}). In the course of the LENS R&D [22] a detailed study of several potential targets (^{176}Yb, ^{160}Gd, ^{115}In) was performed. They have in common CC detection via an inverse beta decay reaction but with a final state in an excited level of the $(Z+1)$ nuclei, which de-excites by emission of a characteristic gamma; the energy of the final electron is just the neutrino energy reduced by the threshold. The most promising target remains ^{115}In (as proposed long time ago [23]). A test facility has been built at Gran Sasso and used to check properties of liquid scintillator containing a significant loading (above 5%) of indium. Based on these studies, it was realized that high granularity was a necessary condition to fight against the intrinsic background induced by the natural radioactivity of the target. A subset of the collaboration is pursuing an effort toward a detector of 60 tons of indium in 3000 tons of liquid scintillator.

6. Conclusion

Solar neutrino studies represent a wonderful scientific story consisting of incredibly ingenious experiments all over the world, confronting theoretical computations, and mixing of many branches of physics. Fruitful collaborations and healthy competition between scientists, motivated by a single goal, has established an impressive set of results:

- Neutrinos produced in reactions in the core of the Sun are observed on Earth; taking into account the oscillation of neutrinos, the measured flux is in excellent agreement with the theoretical prediction. It is the direct proof that we understand how nuclear fusion of hydrogen is the source of energy of the Sun and other main sequence stars.
- Solar models explain and reproduce all observations of the Sun, ranging from various oscillations mode as measured at the surface, to the most energetic neutrinos. The internal temperature of the Sun is known to better than 5‰.
- Neutrinos oscillate between species and are thus massive. This implies a modification of the minimal standard model of particle physics and opens a window toward Grand Unified Theories.

The pioneering works of Raymond Davis (chlorine experiment) and Masatoshi Koshiba (Kamiokande experiment) were crowned with the Nobel prize in 2002.

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