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# The solar neutrino problem after the GALLEX artificial neutrino source experiment

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## Abstract

Using an intense artificial neutrino source (more than 60 PBq), the GALLEX solar neutrino collaboration has recently checked that its radiochemical detector was fully efficient for the detection of solar neutrinos. After this crucial result, we review the status of the solar neutrino problem with emphasis on how neutrino oscillations may explain (through the MSW effect) the different deficits observed in the four existing experiments.

# 1 Introduction.

The longstanding solar neutrino problem consists of the deficit observed by the experiments compared to the predictions of the solar models. The problem was first seen in the results of the chlorine experiment [1] and of the Kamiokande experiment [2], and has been more clearly defined in the last years with the results of GALLEX and SAGE.

In June 1992, the first results of the radiochemical GALLEX experiment showed a deficit of solar neutrinos (about 2/3 of the predictions), but also constituted the first evidence for the detection of the primary pp neutrinos produced in the pp fusion reaction in the core of the Sun [3, 4]. The deficit observed by GALLEX has been confirmed just after by the other gallium experiment (SAGE) [5]. Since this date the two gallium experiments have continued to take data and the errors (statistical but also systematic) have been reduced, inducing a deficit which is now more than $3\,\sigma$ significant.

The consequences of these deficits are crucial for particle and astrophysics and it is very important to check the whole experimental technique (extract and count few atoms from few tens of tons of solution). The GALLEX experiment has proceeded during the summer 1994 to expose its detector to an artificial neutrino source whose activity was known and its results have clearly validated the deficit observed by GALLEX.

For a long time the deficit was attributed to a $^{8}$B neutrinos deficit, but it seems today that it concerns mainly the $^{7}$Be neutrinos. It appears more and more difficult for solar model builders to reconcile the measurements with the predictions, and the appealing solution is now the neutrino oscillation through the MSW mechanism.

Section 2 will describe the experiment performed by GALLEX using the $^{51}$Cr artificial neutrino source and its results. Section 3 will present the present status of the solar neutrino problem. Section 4 will be devoted to a study of the neutrino oscillation solution, and section 5 will conclude.

# 2 The GALLEX artificial neutrino source.

Solar neutrinos produce about 0.7 $^{71}$Ge atom per day in the 30 ton gallium target of the GALLEX detector [4], a small amount which has to be extracted and counted. The necessity to check the whole experimental procedure of this radiochemical experiment using an artificial neutrino source was already included in the proposal in 1985 [6]. The operation consists in extracting and counting a small number of $^{71}$Ge which have been produced by the source and to compare the obtained number with the number expected from the known activity of the source.

The nuclide chosen by the GALLEX collaboration is $^{51}$Cr . It emits monoenergetic 750 keV neutrinos (branching ratio = 90 %), an energy close to the mean energy of solar neutrinos interacting in the gallium target, and 430 keV neutrinos + 320 keV gammas (b.r. = 10 %); the measurement of the 320 keV gamma line allows one to determine the activity of the source, i.e. the number of emitted neutrinos. $^{51}$Cr (half-life = 27.7 days) is produced by neutron capture on $^{50}$Cr in a reactor. Unfortunately $^{50}$Cr is only 4.35 % of the natural chromium and most of the neutrons of the reactor interact with the other chromium isotopes. Chromium enriched in $^{51}$Cr (about 40 %) and depleted in $^{53}$Cr (about 1 %) was produced by the Kurchatov Institute in Moscow, in the form of $CrO_3$. The oxyde was then electrolyzed and the chromium metal broken into irregular chips of $\sim 1\,\mathrm{mm}^3$ volume.

36 kg of chromium chips were irradiated for 23.8 days in the Siloé reactor (operated by CEA in Grenoble). The activity of the source was measured by several techniques [7] and found to

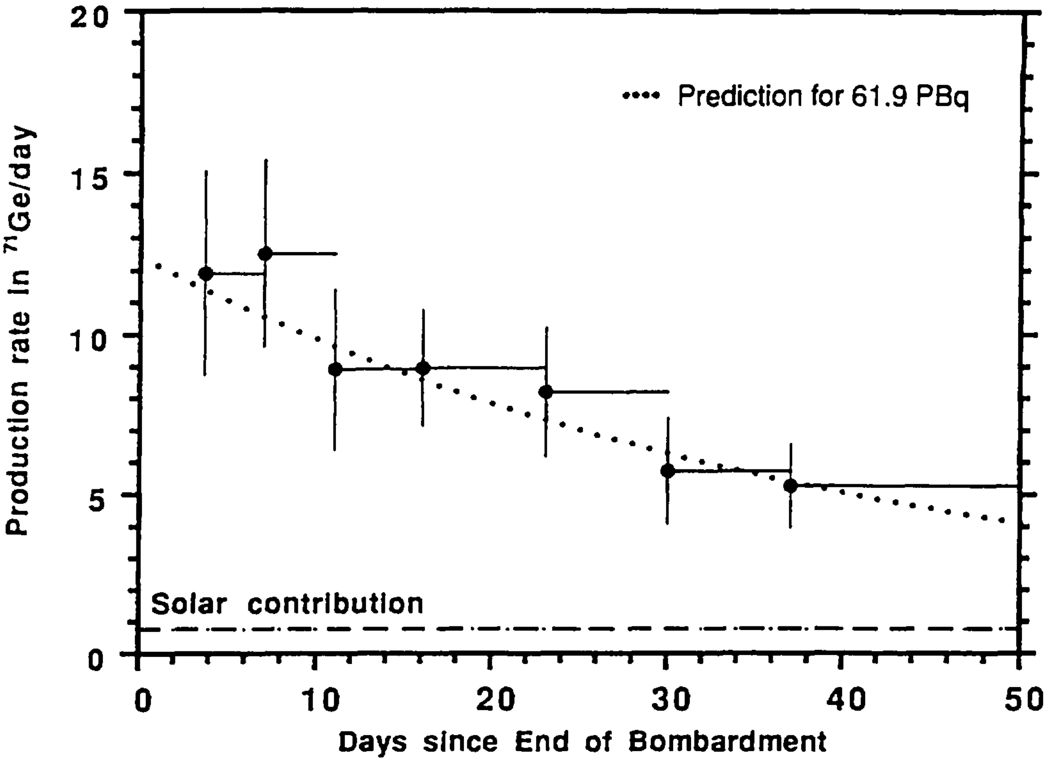

Figure 1: *Number of $^{71}$Ge atoms produced per day during the course of the source experiment (first 7 runs only). The points for each run are plotted at the beginning of each exposure, with the horizontal lines showing the duration of the exposures. The dotted line, which decreases with the known half-life of $^{51}$Cr, is the prediction from the known activity of the source. The dashed line corresponds to the constant 0.78/day production rate due to solar neutrinos and side reactions.*

be equal to 61.9 ± 1.2 PBq.

The source itself, made by the irradiated chromium and shielded by 8.5 cm of tungsten, was installed in the reentrant tube in the GALLEX target tank at the Gran Sasso Underground Laboratory for more than 3 months during the summer 1994. During this period, 11 germanium extractions were performed.

Figure 1 presents the preliminary results of the first 7 runs, plotted at the time that the exposure to the source neutrinos began. The fitted half-life of the $^{51}$Cr obtained with the maximum likelihood method from these $^{71}$Ge data is 24.4 ± 7.1 days, in agreement with the nominal value. The curve in figure 1 is the number of $^{71}$Ge atoms produced per day predicted from the measured value of the source, 61.9 PBq, assuming the known half-life of $^{51}$Cr plus the known 0.78 $^{71}$Ge atoms per day produced by solar neutrinos and side reactions [4].

From the global analysis of the first 7 source exposures, we deduce a mean initial source strength of 64.1 ± 6.6 (statistical) ± 3.3 (systematic), i.e. 64.1 ± 7.4 PBq after adding quadratically the statistical and systematic error. This value is to be compared with the directly measured $^{51}$Cr source strength. The ratio of these values is $R = 1.04 \pm 0.12$, where the quoted error includes the experimental errors in $^{71}$Ge counting and in the source activity determinations, but does not include errors in the neutrino-absorption cross-sections.

More details can be found in [7].

The close agreement between the numbers of $^{71}$Ge atoms determined in the gallium desorptions and that predicted from the measured $^{51}$Cr source strength provides a quantitative

| Experiment | Experimental results | Solar model predictions | | Experiment/Predictions | |
|---|---|---|---|---|---|
| | | BP [9] | TCL [10] | BP [9] | TCL [10] |
| chlorine [1] | 2.55 ± 0.25 SNU | 8.0 ± 1.0 SNU | 6.4 ± 1.4 SNU | 0.32 ± 0.05 | 0.40 ± 0.10 |
| Kamiokande [2] | 2.7 ± 0.4 $10^6$ cm$^{-2}$ s$^{-1}$ | 5.7 ± 0.8 $10^6$ cm$^{-2}$ s$^{-1}$ | 4.4 ± 1.1 $10^6$ cm$^{-2}$ s$^{-1}$ | 0.48 ± 0.07 | 0.62 ± 0.09 |
| GALLEX [4] | 79 ± 12 SNU | 131.5 ± 7 SNU | 123 ± 7 SNU | 0.60 ± 0.10 | 0.64 ± 0.10 |
| SAGE [5] | 69 ± 13 SNU | 131.5 ± 7 SNU | 123 ± 7 SNU | 0.53 ± 0.10 | 0.56 ± 0.11 |
| gallium GALLEX + SAGE | 74.5 ± 9 SNU | 131.5 ± 7 SNU | 123 ± 7 SNU | 0.57 ± 0.07 | 0.61 ± 0.08 |

Table 1: *Experimental results of the solar neutrino experiments and predictions of the standard solar models of Bahcall and Pinsonneault (quoted BP) and of Turck-Chièze and Lopes (quoted TCL). Numbers are in SNU (1 SNU = 1 solar neutrino unit = $10^{-36}$ capture/atom/s) for radiochemical experiments and in flux units for Kamiokande. Errors quoted are 1$\sigma$.*

demonstration of the overall reliability of the GALLEX experiment. It clearly validates the deficit observed by GALLEX.

## 3 The solar neutrino problem.

Table 1 summarizes the status of the solar neutrino problem (for a recent and more detailed review, see for example [8]). The experimental results for the four solar neutrino experiments which are actually running are displayed in the second column. The two gallium experiments, GALLEX and SAGE, give now very similar results and their combined value is given in the last line. The predictions of the standard solar models by Bahcall and Pinsonneault [9] and Turck-Chièze and Lopes [10] are given in the third and fourth columns. The solar neutrino deficit is clearly seen in the last two columns which show the ratios between the experimental results and the model predictions. This deficit is different for the three types of detectors (chlorine, water and gallium), but they are sensitive to different energy spectra and do not measure exactly the same neutrinos.

In the last two years, the data accumulation by the two gallium experiments has significantly reduced the experimental error and their result is now much more than 3$\sigma$ from the solar model predictions (even if we consider the very recent calculation by Dar and Shaviv [11]). We first try to interpret them in a simple consistent model (see figure 2).

The horizontal lines show the gallium results (full line for the value, dotted line for the 1$\sigma$ error and bold line for the 2$\sigma$ error). The two first columns illustrate the predictions of the solar models [9, 10] for the 6 main different sources of neutrinos, grouped here in four main categories (pp+pep, Be, B, CNO cycle). We build a consistent model (third column) in the following way; we assume that : a) the pp fusion reaction is the dominant energy source of the Sun which means that the ($\nu_{pp} + \nu_{pep}$) flux is given by the solar luminosity; b) the $\nu_B$ flux is given by the Kamiokande observation. It is clearly seen that the space available for the $\nu_{Be}$ flux is very limited.

Analyzing eleven recently-publihed standard models, Bahcall [12] concluded that, if experiments are correct, the $\nu_{Be}$ flux must be less than 50% of the predicted value. Quantitative

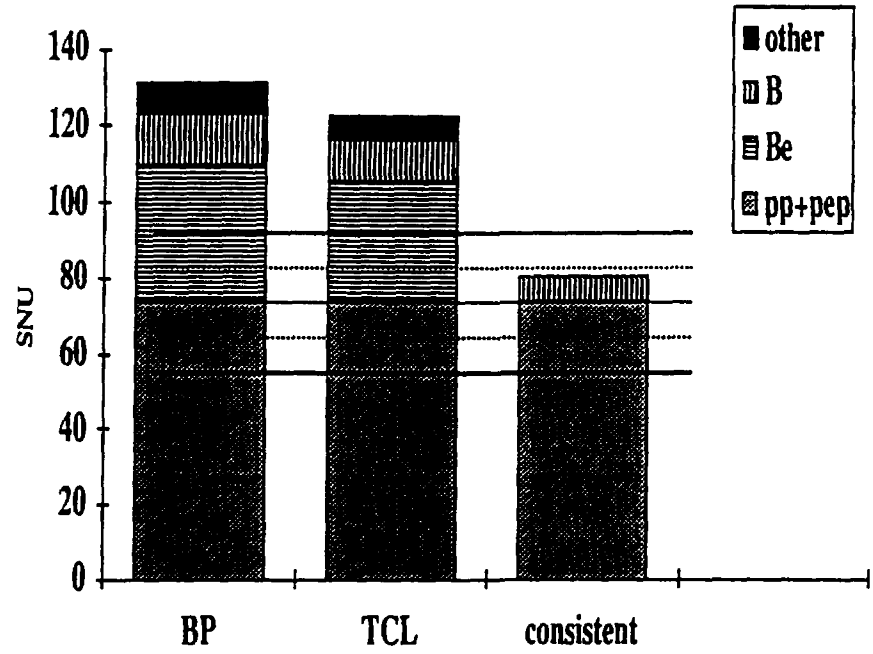

Figure 2: *Gallium results (in SNU) and solar model predictions. The gallium results (full line) correspond to the mean value of GALLEX and SAGE; the dotted (bold) lines define the one (two) $\sigma$ area. [See text].*

calculations (see for example [13, 14, 15]) which plot the $\nu_B$ flux versus the $\nu_{Be}$ flux deduced from the experimental results and from simple solar model independent hypotheses, find a negative value for the $\nu_{Be}$ flux. A typical illustration is given in figure 3, taken from reference [14], which shows the best fit of the data (which extends largely into the negative region for the $\nu_{Be}$ flux), as well as the standard model predictions [9, 10]. The different circles correspond to different non standard solar models. A cooler Sun would reduce the nuclear reaction rate and the neutrino flux (but we have to take into account the luminosity constraints); the dotted line illustrates the predictions for such a model, with a power law dependence of the different fluxes as a function of the central temperature of the Sun $T_c$ ($T_c^{-1.2}$ for $\nu_{pp}$ , $T_c^8$ for $\nu_{Be}$ and $T_c^{18}$ for $\nu_B$ ); the best $\chi^2$ is obtained for a reduction of $T_c$ by 5-7 % but the $\chi^2$ is very bad (more than 10 for 2 dof, i.e. less than 1 % for confidence level). Castellani et al. [16] and Shi et al. [17] reach similar conclusions. Dzitko et al. [18] discuss the screening effect and the nuclear reaction rate in solar models and conclude that some errors could be underestimated, reducing the discrepancy, however not sufficiently to account for the experimental observations.

Global analyses which take into account all the theoretical and experimental errors as well as the correlations have been performed by Fogli and Lisi [19] and Gates et al. [20]. The method by Fogli and Lisi allows one to characterize individually the role of the different input parameters of solar models (nuclear cross sections, luminosity, opacities, metallicity (Z/X)), but none of these parameters can account for the observations.

To conclude this section, the solar neutrino problem is now quantitatively established and we know of no satisfactory nuclear physics or astrophysics solution to the observed deficit.

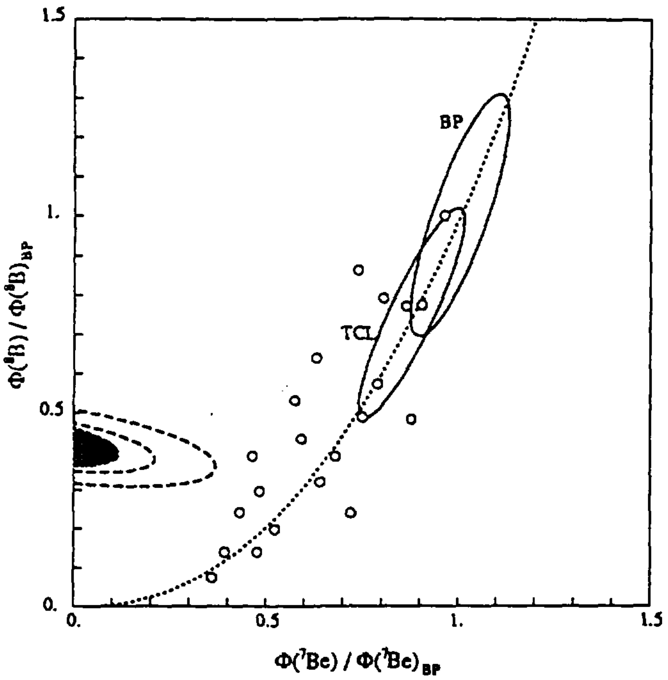

Figure 3: *Combined fit for $\nu_B$ flux versus $\nu_{Be}$ flux (90 % (grey area) and 95 and 99 % (dashed lines)) and predictions of standard solar models by Bahcall and Pinsonneault (BP) and by Turck-Chièze and Lopes (TCL); small circles represent several non standard solar models and the dotted line characterizes the decrease of the fluxes with the central temperature of the Sun. (From [14]).*

## 4 Is neutrino oscillation the solution via the MSW effect ?

The idea that neutrinos could oscillate between their different flavours and explain the deficit observed in the chlorine experiment was been first proposed by Gribov and Pontecorvo. The nuclear reactions in the Sun produce only $\nu_e$ and the detectors are sensitive only to $\nu_e$ (with the exception of Kamiokande which is sensitive to $\nu_\mu$ and $\nu_\tau$ , but with a cross section 7 times smaller). 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 $\Delta m^2$ , the difference of the squared masses of the neutrinos and $\sin^2 2\theta$ , where $\theta$ is the mixing angle.

The case of vacuum neutrino oscillations has been reviewed recently by Krastev and Petcov and Hata [21]. The experimental results constrain $\Delta m^2$ to very small areas at values between $10^{-11}$ and $10^{-10}$ eV$^2$, with a large mixing angle ($\sin^2 2\theta$ above 0.7).

In the case of neutrino oscillations in matter through the so-called MSW effect [22], there is no strong constraint. 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 ($\Delta m^2$ , $\sin^2 2\theta$) plane , since the three targets (chlorine, water and gallium) are not sensitive to the same energy. Their overlap defines the allowed areas within a given confidence level (see figure 4).

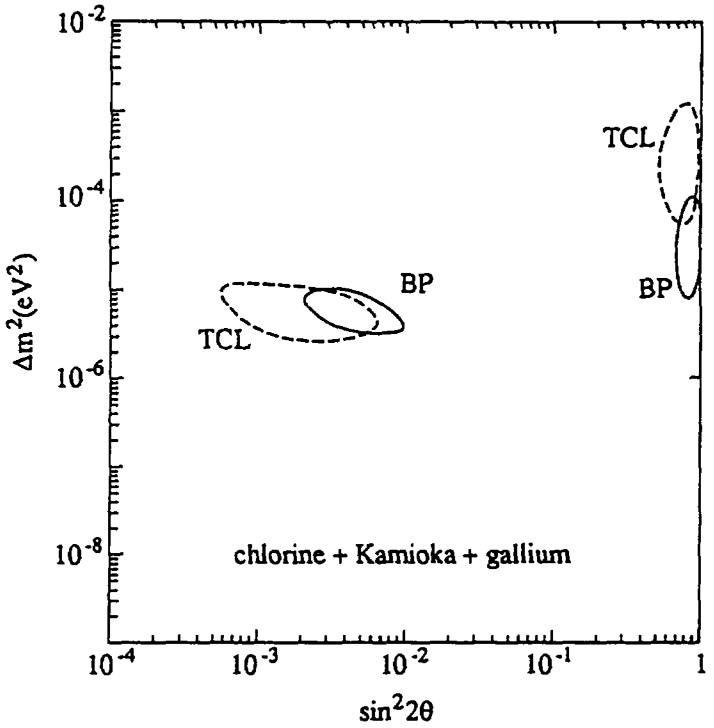

Figure 4: *Regions of the parameter plane of neutrino oscillation allowed by the MSW effect for interpreting solar neutrino experiments (90 % C. L.) for the Bahcall and Pinsonneault (BP) and for the Turck-Chièze and Lopes (TCL) models.*

In all calculations and for all models (see for example [13, 14, 23] as well as the present figure 4), the small angle solution has a very good $\chi^2$ (less than 1 per d.o.f.) independently of the solar model used and the large angle solution, though not excluded, a poorer $\chi^2$. For non standard models (see for example [13, 24]), the small angle solution moves towards smaller mixings if the $\nu_B$ flux is smaller (or if the central temperature is smaller) and towards larger mixings in the opposite case. This last point is illustrated in figure 4 where the TCL model predicts less $\nu_B$ than the BP model.

The situation of the solar neutrino flux in the case of the small angle solution is illustrated in figure 5 which shows the probability of $\nu_e$ conversion in the Sun through the MSW effect, superposed to the different solar neutrino fluxes. The $\nu_{pp}$ flux is not suppressed at all. Most of the $\nu_{Be}$ are suppressed as well as the $\nu_{pep}$ and the neutrinos from the CNO cycle (not drawn). The reduction of the $\nu_B$ flux is smoothly decreasing from low energy values to higher ones. It is clear from this figure that the $\nu_{Be}$ can be easily more suppressed than the $\nu_B$ , which cannot be done in any standard or non standard solar model.

Though this neutrino oscillation solution is very appealing, we cannot affirm that it is "the" solution. We have to wait for the forthcoming Sudbury, SuperKamiokande and Borexino experiments, which should be able from 1997, if the small angle solution is the good one, to show either a distortion of the $\nu_B$ spectrum (Sudbury and/or SuperKamiokande), or an excess of neutral current interactions (Sudbury is sensitive to $\nu_\mu$ and $\nu_\tau$ interactions via this process), or a disappearance of the $\nu_{Be}$ (see for example [25]).

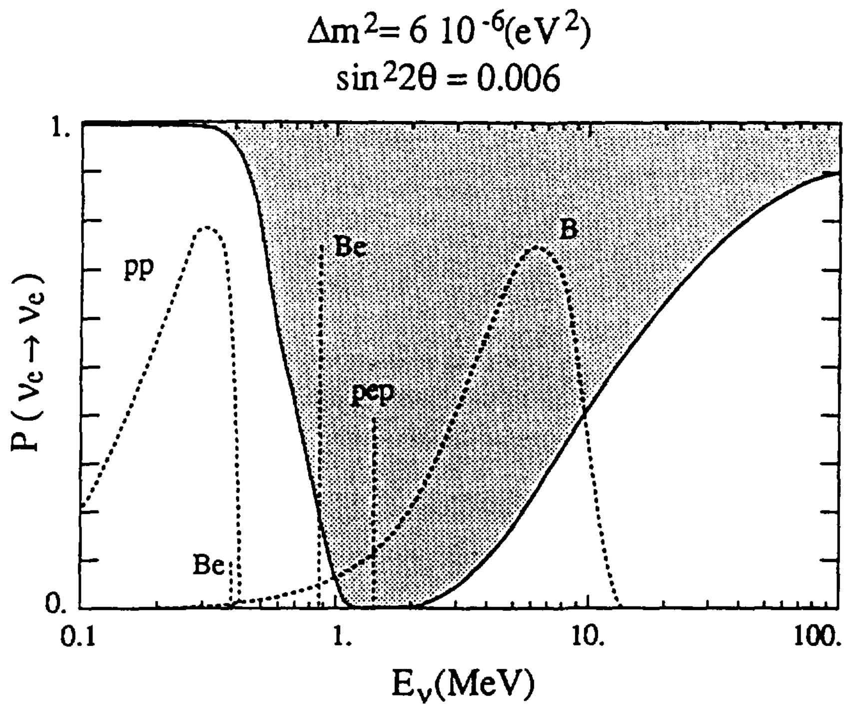

Figure 5: *Probability of $\nu_e$ conversion in the Sun through the MSW effect for the neutrino oscillation parameters which give the best $\chi^2$. The grey area defines the $\nu_e$ suppression zone. Dotted lines correspond to the main solar neutrino fluxes (arbitrary vertical scales).*

## 5 Conclusion

The GALLEX solar neutrino experiment has validated in 1994 its experimental result using an artificial neutrino source. The experimental errors on the two gallium experiments (GALLEX and SAGE) have now been significantly reduced and the value that they observe ($74 \pm 9$ SNU) is more than $3\sigma$ from the predictions of the standard solar models (122-132 SNU). If we believe that the pp fusion reaction is at the origin of the energy produced by the Sun and of its luminosity, the deficit observed is strongly attributed to Be-neutrinos. Astrophysical or nuclear solutions are very unlikely to solve this newly called "Be problem". Neutrino oscillations via the MSW mechanism are a very appealing solution and would imply a small mixing angle ($\sin^2 2\theta$ between $10^{-3}$ and $10^{-2}$) and a $\Delta m^2$ value around $6\,10^{-6}$ eV$^2$. However we have to wait for the forthcoming SNO, SuperKamiokande and Borexino to affirm that it is "the" solution.

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