Future solar neutrino spectroscopy and neutrino properties

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Abstract

The Gallex result, together with the constraints from the observed value of the solar constant, yields strong limits on the flux of neutrinos from the pp-I termination of the pp-chain, $62 \leq \Phi_{pp+pep} [10^9 \text{cm}^{-2}\text{s}^{-1}] \leq 65$, provided that neutrinos are standard. This conclusion is essentially independent of solar models and it implies that the pp-chain is shifted towards the pp-I termination, in comparison with the SSM predictions. As a consequence, we derive an upper bound on Berillium neutrinos: $\Phi_{Be} \leq 3 \cdot 10^9 \text{cm}^{-2}\text{s}^{-1}$, the violation of this bound being a clear signal of non-standard neutrino properties. We also find that, for a large class of solar models built so as to enhance the pp-I termination, the pep-neutrino flux is stable around $\Phi_{pep} \approx 1.5 \cdot 10^8 \text{cm}^{-2}\text{s}^{-1}$. Detection of pep neutrinos will clearly discriminate standard neutrinos against MSW oscillations, this latter model giving $\Phi_{pep}^{MSW} \leq 3 \cdot 10^7 \text{cm}^{-2}\text{s}^{-1}$.

1. Introduction

New generation experiments are being planned for the detection of monochromatic solar neutrinos, produced in electron capture (${}^7\text{Be}+e^- \rightarrow {}^7\text{Li}+\nu$) and in the pep ($p+e^-+p \rightarrow d+\nu$) reactions [1,2,3]. In this letter we discuss what can be learnt from these future measurements about neutrino properties, independently - as much as possible - of the Standard Solar Model (SSM).

Our discussion will be directly in terms of the main components of the solar neutrino flux: pp and pep-neutrinos from the pp-I termination (flux on Earth $\Phi_p = \Phi_{pp} + \Phi_{\text{pep}}$); ${}^7\text{Be}$ -neutrinos from the pp-II termination (Φ_{Be}); neutrinos from the CNO cycle (Φ_{CNO}) and ${}^8\text{B}$ -neutrinos (Φ_{B}) from pp-III.

We will take the following attitude:

- i) we assume - as a working hypothesis - standard neutrinos (zero mass, no flavor mixing, no decay...).
- ii) Through energy conservation and the assumption of stationary Sun, we use the observed value of the solar constant in order to constrain/determine the total neutrino flux.
- iii) We rely on the SSM as least as possible (as a reference, the results of our standard solar model, hereafter the SSM, are shown in Table I). In particular, again as a working hypothesis, we assume that the SSM is unable to predict the ${}^8\text{B}$ -neutrino flux. This latter we take from experiment, i.e. from the Kamiokande result [4] or from the Chlorine result [5]. A choice is needed since the two experiments give almost conflicting results for standard neutrinos, see for instance refs. [6,7].

In this frame, the Gallex result [8] implies that the very large majority of neutrinos come from the pp-I termination:

$$(1.1) \quad 62 \leq \Phi_p [10^9 \text{cm}^{-2} \text{s}^{-1}] \leq 65,$$

the upper bound being given by the solar luminosity constraint and the lower one essentially from the Gallex result, at 1σ . With respect to the prediction of the SSM ($\Phi_p^{\text{SSM}} = 60 \cdot 10^9 \text{cm}^{-2} \text{s}^{-1}$), this means that the fusion chain is shifted towards the pp-I termination.

Theoretically, this shift can be attained in several ways, by varying the parameters of solar models beyond the range of the observational uncertainties. One can enhance the pp-I termination by using larger (smaller) values of the ${}^3\text{He}+{}^3\text{He}$ (${}^3\text{He}+{}^4\text{He}$) cross section, without altering the inner solar structure (e.g. central temperature, density...). Alternatively, one can play on parameters which reduce the central temperature (opacity, age, S_{pp} ...). We will present a series of non-standard solar models which can account for the Gallex result. It is worth observing that all these *ad-hoc* models require huge variations of the parameters.

Next we investigate what can be learnt from future experiments aimed at the detection of the ${}^7\text{Be}$ and pep lines, in order to distinguish non-standard solar models from non-standard neutrinos.

Since the rate of fusion reactions (one half the rate of neutrino emission) is essentially fixed by solar energetics, one can derive an upper bound on the ${}^7\text{Be}$ -neutrino flux. A measurement of the Berillium line intensity in excess of this limit will be a clear signal of non-standard neutrinos.

The pep and pp reactions are strongly connected with each other [9], so that one expects eq (1.1) can be translated into a strict prediction on Φ_{pep} . In order to analyze the relevance of an experiment on pep neutrinos,

we will compare the predictions on Φ_{pep} arising from (non-standard) solar models with those from MSW [10] oscillation models.

2. The relevant variables and the relevant equations

For standard neutrinos, the measurement of the solar constant ($K = L_{\odot}/4\pi a^2 = (0.849 \pm 0.002) \cdot 10^{12} \text{ MeV cm}^{-2} \text{ sec}^{-1}$) and the signals in the various neutrino experiments can be expressed as a set of linear equations, where the unknown variables are the energy integrated neutrino fluxes on Earth Φ_i . The solar constant can be written as:

$$(2.1) \quad K = \sum_i (Q/2 - \langle E \rangle_i) \Phi_i$$

where Q is the energy released in the fusion reaction ,

$$Q = 4m_p + 2m_e - m_{\alpha} = 26.73 \text{ MeV}$$

and $\langle E \rangle_i$ is the average neutrino energy. Note that, if the difference among the $\langle E \rangle_i$ is neglected, eq. (2.1) actually fixes the total neutrino flux.

The signal S_x of any experiment can be represented as:

$$(2.2) \quad S_x = \sum_i X_i \Phi_i$$

where the weighting factors X_i are cross sections for the detection reaction, averaged over the spectrum of the i -th component of the neutrino flux.

These averages do not depend on solar physics, the shape of each component of the spectrum being determined by nuclear physics alone. Note also that the X_i are ordered according to the neutrino energy (larger $\langle E \rangle_i$ correspond to bigger X_i) as typical of low energy weak interaction processes, see table II for the numerical values.

As mentioned above, in order to manage the discussion, let us refer only to the main components Φ_p , Φ_{Be} , Φ_B and $\Phi_{\text{CNO}} = \Phi_N + \Phi_O$ (we neglect the very small contribution of ^{17}F -neutrinos). For the moment we take the ratio $\xi = \Phi_{\text{pep}}/\Phi_p$ from the SSM ($\xi = 2.38 \cdot 10^{-3}$) and similarly the ratio $\eta = \Phi_N/\Phi_{\text{CNO}} = 0.54$. A reader, willing to avoid these assumptions, could take $\Phi_{\text{pep}} = 0$ (actually the pep-neutrinos are a very small fraction of the pp-I) and $\eta = 1/2$, as would be in the case of a fully operational CN cycle. He will get anyhow similar results.

By deriving the Boron flux from the Kamiokande result [4] ,

$$(2.3) \quad \Phi_B^{\text{Ka}} = (2.9 \pm 0.4) 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

(1σ errors here and in the following, statistical and systematical errors being added quadratically) we are left with the three unknowns Φ_p , Φ_{Be} , Φ_{CNO} , constrained by the luminosity equation,

$$(2.4) \quad \chi = 2K/Q = \alpha_p \Phi_p + \alpha_{\text{Be}} \Phi_{\text{Be}} + \alpha_{\text{CNO}} \Phi_{\text{CNO}}$$

(where $\alpha_i = 1 - 2\langle E \rangle_i/Q$ and the very small contribution of ^8B -neutrinos is neglected) and by the Gallex result:

$$(2.5) \quad S_G = S_G(B) + G_p \Phi_p + G_{\text{Be}} \Phi_{\text{Be}} + G_{\text{CNO}} \Phi_{\text{CNO}} \quad .$$

We take [8] $S_G=87\pm16$ SNU and we derive the Boron contribution to the Gallium signal, $S_G(B)=G_B\Phi_B$, from Kamiokande, $S_G^{Ka}(B)=7\pm2$ SNU, where a 25% error ($\approx 1\sigma$) on G_B is assumed. The errors on the other G_i are taken to be a few percent, see table II, and thus can be neglected in comparison with the error of the Gallex result. The factor G_p is the average between G_{pp} and G_{pep} ($G_p=G_{pp}(1-\xi)+G_{pep}\xi$), and similarly $G_{CNO}=G_O(1-\eta)+G_N\eta$. Note that we use the SSM just for evaluating G_p , G_{CNO} and the corresponding α_p and α_{CNO} .

Alternatively, one could derive the Boron flux from the Chlorine experiment:

$$(2.6) \quad S_C = C_{pep}\Phi_{pep} + C_{Be}\Phi_{Be} + C_{CNO}\Phi_{CNO} + C_B\Phi_B,$$

where we take $S_C = 2.23\pm0.22$ [5] and the C coefficients are again shown in Table II. In this way the expression for the Gallex signal becomes:

$$(2.7) \quad S_G = D + G'_p\Phi_p + G'_{Be}\Phi_{Be} + G'_{CNO}\Phi_{CNO}$$

where $D = S_C (G_B/C_B)$ and $G'_{Be} = G_{Be} - C_{Be} (G_B/C_B)$, similarly for G'_{CNO} , whereas $G'_p = G_p - \xi C_p (G_B/C_B)$.

Eqs. (2.4) and (2.5), or alternatively (2.7), are at the basis of our discussion.

3. The solar luminosity, the Gallex result and the flux of pp-I neutrinos

The solar luminosity equation (2.4) provides a lower limit to the total neutrino flux, which is reached when all neutrinos are from pp-I :

$$(3.1) \quad \Phi_{tot} \geq \chi / \alpha_p = 64.8 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1},$$

This is due to the fact that pp-I neutrinos are the least energetic ones. Clearly, it also provides an upper bound to the flux of pp-I neutrinos, $\Phi_p \leq \Phi_p^{max} = \chi / \alpha_p$.

When used in conjunction with the Gallex result, the luminosity equation gives useful information on the way fusion reactions proceed in the Sun. For example, the CNO cycle, as the main source of solar energy [11,12], can immediately be rejected. The luminosity would require $\Phi_{CNO} = 67.8 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$, whereas from eq. (2.5) one immediately gets $\Phi_{CNO} \leq 11 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ (more stringent bounds can be derived from the following discussion).

In order to gain information about the pp-I neutrinos, we observe that the minimum signal in the Gallex experiment is obtained when all neutrinos (but the small 8B fraction) are from pp-I, since in this case Φ_{tot} is minimized and all neutrinos have the lowest energy. By adding the small contribution of 8B -neutrinos:

$$(3.2) \quad S_G \geq G_p \chi / \alpha_p + S_G^{Ka}(B) = 86.6 \text{ SNU}.$$

This value being very close to the experimental result, one understands that pp-I neutrinos must be a substantial component of the total flux. For a quantitative determination of this component, let us see what happens when other neutrinos (7Be and CNO) are present, i.e. for $\Phi_p < \Phi_p^{max}$. For a given value of Φ_p the minimum signal is obtained when all other neutrinos are from Berillium, so that the energy is as low as possible. This gives an expression of the minimum signal for Gallex as a function of Φ_p :

$$(3.3) \quad S_G^{min}(\Phi_p) = S_G^{Ka}(B) + G_{Be}\chi/\alpha_{Be} + (G_p - G_{Be}\alpha_p/\alpha_{Be})\Phi_p$$

In a similar way, the maximum signal $S_G^{max}(\Phi_p)$ is obtained when all other neutrinos are from the CNO cycle:

$$(3.4) \quad S_G^{\max}(\Phi_p) = S_G^{\text{Ka}}(B) + G_{\text{CNO}} \chi / \alpha_{\text{CNO}} + (G_p - G_{\text{CNO}} \alpha_p / \alpha_{\text{CNO}}) \Phi_p$$

The allowed region for conventional neutrinos is thus the small area within the two straight lines, $S_G^{\min}(\Phi_p)$ and $S_G^{\max}(\Phi_p)$, see Fig. 1. Taking into account the experimental value of S_G , one finds:

$$(3.5) \quad 62.3 \leq \Phi_p [10^9 \text{ cm}^{-2} \text{ s}^{-1}] \leq 64.8$$

where the upper bound is given by the luminosity constraint and the lower one from Gallex result, at 1σ .

By using the Chlorine result instead of Kamiokande, one gets a similar conclusion:

$$(3.6) \quad 61.6 \leq \Phi_p [10^9 \text{ cm}^{-2} \text{ s}^{-1}] \leq 64.8 .$$

It is worth observing that Gallex experiment, in spite of its error of about 20%, fixes the pp-I neutrino flux within 5%. The point is that neutrinos different from pp-I have a large weighting factor in the Gallium signal, so that even a small flux gives an appreciable contribution.

The result has to be compared with the SSM value, $\Phi_p^{\text{SSM}} = 60 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$, affected by an uncertainty ($\approx 1\sigma$) of about 0.7%, see ref. [13]. Although the SSM value may seem not too far from the above bounds, actually solar models which can account for the experimental value of Φ_p - eq. (1.1) - are extremely non-standard, in the sense that huge variations of the relevant parameters, well beyond the range of uncertainties, are to be introduced (for results of solar models close to the SSM see ref.[14]).

Note also that bringing Φ_p into the right range is a necessary condition but it is not sufficient to fully account for the Gallex result. In fact, even if Φ_p is right, there is generally a contribution from CNO-neutrinos, so that the signal can be larger than the minimum value given by eq. (3.3). The results of several models for the Gallium signal (we remind that the Boron contribution is anyhow directly taken from the Kamiokande experiment) are shown in Fig. 2, as some solar model parameter x is varied from its standard value x_{SSM} .

In order to enhance the pp-I branch of the fusion reaction chain we resorted to several manipulations:

i) a large $^3\text{He}+^3\text{He}$ cross section at low energy. This nuclear physics solution requires an astrophysical S-factor larger than the standard value by a factor at least fifteen, see Fig. 2 (we require that the Gallex value is reproduced at 1σ level). The possibility of a low energy resonance cannot be excluded [7,15,16] and is presently investigated experimentally [17]. Note that the internal solar structure is minimally changed, the central solar temperature T_c being reduced by just 5% with respect to T_c^{SSM} for $S_{33}/S_{33}^{\text{SSM}} = 50$. Alternatively one could diminish the cross section for the $^3\text{He}+^4\text{He}$ reaction, getting similar conclusions since all neutrino fluxes depend just on the ratio S_{33}/S_{34}^2 , see ref. [7].

ii) A large p-p cross section. Increasing S_{pp} implies a lower central temperature, since fusion gets easier while the solar luminosity has to be kept constant [18]. Clearly at lower temperatures the pp-II termination and the CNO cycle are disfavoured. Although S_{pp} is well determined, one can introduce an artificial variation just in order to get cooler Suns. One needs S_{pp} at least twice the standard value, corresponding to a central temperature $T_c \leq 1.44 \cdot 10^7 \text{ °K}$, about 8% smaller than in the SSM.

iii) A less opaque Sun is another way to get a cooler solar interior. This can be accomplished by lowering (by an overall multiplicative factor x_{opa}) the opacity tables or by decreasing the metal fraction Z/X . We have lowered the opacity tables down to $x_{\text{opa}} = 0.6$. We did not proceed any further because otherwise we cannot produce stable solar models. Also for $x_{\text{opa}} = 0.6$ the calculated Gallium signal exceeds the experimental result. The value of Z/X needed to reproduce the Gallex result at 1σ is $Z/X \leq 0.3 \cdot (Z/X)_{\text{SSM}}$, the central temperature being decreased by about 6%.

iv) A younger Sun is another way to get a cooler Sun. Agreement with Gallex cannot be reached even for a Sun $5 \cdot 10^8$ y old!

Note that the common point of models ii), iii) and iv) is the reduction of the central temperature. Different models give similar results for the Gallium signal when the central temperature is the same, see Fig. 3.

Clearly all these models are desperate attempts in order to save the hypothesis of standard neutrinos. We will discuss in the next section how future experiments can distinguish non-standard solar models from non-standard neutrinos.

4. ^7Be and pep-neutrinos

If the fusion chain is shifted towards the pp-I termination, as shown in the previous section, the flux of ^7Be -neutrinos has to be reduced with respect to the SSM, since the total neutrino flux is fixed by the solar luminosity. We recall that the minimum Gallium signal occurs when the CNO flux is put equal to zero. By expressing Φ_p in terms of Φ_{Be} through the luminosity constraint, eq. (3.3) becomes:

$$(4.1) \quad S_G^{\text{min}}(\Phi_{\text{Be}}) = S_G^{\text{Ka}}(B) + G_p \chi / \alpha_p + (G_{\text{Be}} - G_p \alpha_{\text{Be}} / \alpha_p) \Phi_{\text{Be}}$$

In Fig. 4 the region of non-standard neutrinos lies below the full line. Assuming standard neutrinos, the Gallex result at 1σ then implies:

$$(4.2) \quad \Phi_{\text{Be}} \leq 2.7 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}.$$

If the Chlorine result is used, one gets $\Phi_{\text{Be}} \leq 3.3 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$. The skeptical reader of sect. 2 would get $\Phi_{\text{Be}} \leq 3.1 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ instead of (4.2), and by using the Chlorine results $\Phi_{\text{Be}} \leq 3.8 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$. Note that these limiting values are definitely smaller than $\Phi_{\text{Be}}^{\text{SSM}} = 4.8 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$.

A measurement of Φ_{Be} in excess of these bounds would be a clear signal of non-standard neutrinos.

It has to be observed that the MSW solution of the solar neutrino problem does not put any significant constraint on Φ_{Be} , the allowed range being $(1.1 + 3.6) \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ at 90% C.L. [19].

One can repeat the same discussion in order to obtain an upper bound for the CNO flux (in this case Φ_{Be} is taken equal to zero). One finds $\Phi_{\text{CNO}} \leq 2.2 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ if the Boron flux is taken from Kamiokande and $\Phi_{\text{CNO}} \leq 2.9 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ if one derives Φ_{B} from the Chlorine experiment. This means that in any case the CNO cycle does not contribute more than 5% to the solar energy production.

Pep neutrinos look very interesting since that the pep and pp reactions are strongly connected, the pep-rate being proportional to the pp one ($\lambda_{\text{pep}} \propto n_e \lambda_{\text{pp}}$, where λ_i are the rates and n_e is the electron density). One thus expects that the ratio $\xi = \Phi_{\text{pep}} / \Phi_p$ is rather stable as solar models are varied, so that a measurement of the pep line intensity is a direct test of the pp-I termination of the fusion chain.

In the SSM one has $\xi = 2.38 \cdot 10^{-3}$, with an estimated error of 0.8% at 1σ level, essentially due to the uncertainties on S_{pp} and on the metal fraction Z/X [13]. From the constraints on Φ_p found in the previous section, we derive that Φ_{pep} must lie in a very narrow range:

$$(4.3) \quad 0.147 \leq \Phi_{\text{pep}} [10^9 \text{ cm}^{-2} \text{ s}^{-1}] \leq 0.154$$

Bahcall [13] has shown that the factor ξ is rather stable against moderate variations around the SSM. Actually, in order to save standard neutrinos one must resort to very non-standard model, where the value of ξ may be somehow different. We have investigated the prediction of Φ_{pep} in a large class of non-standard model adjusted

so as to reproduce the Gallex result within 1σ (the Boron contribution anyhow being taken from the Kamiokande experiment). We find that Φ_{pep} stays within $(0.1 \div 0.2) \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ even for huge variations of the parameters, see Fig. 5.

It is interesting to compare this range with that allowed for the MSW (non-adiabatic) solution at 90% C.L., see again Fig. 5 and for more details Fig. 6 and ref. [19] :

$$(4.4) \quad \Phi_{\text{pep}}^{\text{MSW}} \leq 3 \cdot 10^7 \text{ cm}^{-2} \text{ s}^{-1}$$

Note that a very low pep-neutrino flux is mandatory for MSW, since the Chlorine and Kamiokande result can be reconciled by the MSW effect when the low energy part of the Boron spectrum is strongly suppressed, and this overlies the pep energy. The same is generally true for any mechanism (resonant spin flip, neutrino decay...) which attempts to reconcile Chlorine and Kamiokande results.

In conclusion, the measurement of the pep line intensity will clearly distinguish non-standard solar models from non-standard neutrinos (as recently pointed out in ref.[3]). Furthermore, as shown in Fig. 5, the measurement of Φ_{pep} can also discriminate among different solar models.

5. Conclusions

We summarize the main points of our discussion:

i) The Gallex result together with the luminosity constraint implies that almost all neutrinos, if standard, are from the pp-I termination

$$62 \leq \Phi_{\text{pp+pep}} [10^9 \text{ cm}^{-2} \text{ s}^{-1}] \leq 65$$

The strict bound derives from the fact that even a small flux of other (=more energetic) neutrinos gives an appreciable contribution to the Gallium signal.

ii) A clear check of neutrino properties can be obtained by looking at ${}^7\text{Be}$ -neutrinos: $\Phi_{\text{Be}} \leq 3 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ or neutrinos are non-standard;

iii) (non-)standard solar models give always a large pep flux, $\Phi_{\text{pep}} \approx 1.5 \cdot 10^8 \text{ cm}^{-2} \text{ s}^{-1}$, whereas the MSW solution requires $\Phi_{\text{pep}}^{\text{MSW}} \leq 3 \cdot 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ (and even a smaller value for the best fit). The measurement of the pep line intensity will clearly distinguish non-standard solar models from non-standard neutrinos. Furthermore, it can also discriminate among different solar models.

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Acknowledgements

It is a pleasure to thank E. Fiorini, G. Mezzorani, M. Moretti and D. Vignaud for fruitful discussions.

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Table I

Our Standard Solar Model. We show the age, the central temperature (T_c), the Helium mass fraction (Y), the metal mass fraction (Z) and the neutrino fluxes, in units of $10^9 \text{ cm}^{-2}\text{s}^{-1}$. Also shown are the theoretical values for the Chlorine and Gallium signals.

Age [Gyr]	4.6
T_c [°K]	$1.564 \cdot 10^7$
Y	0.289
Z	0.0184
Φ_{pp}	60.05
Φ_{pep}	0.14
$\Phi_p = \Phi_{pp} + \Phi_{pep}$	60.19
Φ_{Be}	4.79
Φ_N	0.47
Φ_O	0.40
$\Phi_{CNO} = \Phi_N + \Phi_O$	0.87
Φ_B	$5.6 \cdot 10^{-3}$
Chlorine [SNU]	7.8
Gallium [SNU]	130

Table II

For the different components of the neutrino flux we show the average neutrino energy $\langle E \rangle$ and the averaged neutrino capture cross sections for Chlorine (C) and Gallium (G), with errors at 1σ level, from ref. [13] but for C_B taken from ref. [20]. When averaging the pp and pep components we use the relative weights of our SSM, see Table I; similarly for ^{13}N and ^{15}O .

	$\langle E \rangle$ [MeV]	C [$10^{-9}\text{SNUcm}^2\text{s}$]	G [$10^{-9}\text{SNUcm}^2\text{s}$]
pp	0.265	0.	1.18(1 $\pm$ 0.02)
pep	1.442	1.6(1 $\pm$ 0.02)	21.5(1 $\pm$ 0.07)
p=pp+pep	0.268		1.23(1 $\pm$ 0.02)
^7Be	0.814	0.24(1 $\pm$ 0.02)	7.32(1 $\pm$ 0.03)
^{13}N	0.707	0.17(1 $\pm$ 0.02)	6.18(1 $\pm$ 0.03)
^{15}O	0.996	0.68(1 $\pm$ 0.02)	11.6(1 $\pm$ 0.06)
$\text{CNO}=\text{}^{13}\text{N}+\text{}^{15}\text{O}$	0.840	0.40(1 $\pm$ 0.02)	8.67(1 $\pm$ 0.05)
^8B	6.71	1.09 $\cdot 10^3$ (1 $\pm$ 0.01)	2.43 $\cdot 10^3$ (1 $\pm$ 0.25)

Figure captions

Fig.1. The Gallium signal S_G as a function of the neutrino flux Φ_p from the pp-I termination. The Gallex result $\pm 1\sigma$ is shown. For standard neutrinos, the allowed area is within the two straight lines $S_G^{\min}$ and $S_G^{\max}$ (we derived the Boron contribution from the Kamiokande experiment). The region consistent with the Gallex result and standard neutrinos is the shaded area. The lower limit for the pp-I flux is thus $\Phi_p^{\min} = 62.3 \cdot 10^9 \text{ cm}^{-2}\text{s}^{-1}$ and the upper limit, given by the luminosity constraint, is $\Phi_p^{\max} = 64.8 \cdot 10^9 \text{ cm}^{-2}\text{s}^{-1}$. The upper scale represents the pep-neutrino flux Φ_{pep} , for a ratio $\xi = \Phi_{\text{pep}}/\Phi_p = 2.38 \cdot 10^{-3}$ as in the SSM. For reference, the result of our SSM is also shown ($\diamond$).

Fig. 2. The Gallium S_G signal given by various non-standard solar models when some parameter x is varied from the standard value x_{SSM} : we consider variations of S_{33} ($\times$), S_{pp} ($\square$), opacity ($\bowtie$), Z/X ($\frac{1}{2}$) and age ($\dagger$). The region consistent with the Gallex result at 1σ level lies within the dashed lines. The Boron contribution is taken from the Kamiokande experiment for the standard model ("SSM") as well as for the other models.

Fig. 3. The Gallium signal as a function of central solar temperature T_c , in units of T_c^{SSM} , same notation as in Fig. 2.

Fig. 4. The Gallium signal S_G as a function of the ^7Be -neutrino flux Φ_{Be} . The Gallex result $\pm 1\sigma$ is also shown (dashed lines). For standard neutrinos, the allowed area is above the straight line $S_G^{\min}(\Phi_{\text{Be}})$, if the Boron contribution is derived from the Kamiokande experiment. The region consistent with the Gallex result and standard neutrinos is the shaded area. The allowed flux has to be smaller than $\Phi_{\text{Be}}^{\max} = 2.7 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}$. The result of our SSM is also shown ($\diamond$).

Fig. 5. The pep-neutrino flux (Φ_{pep}) vs. the ^7Be -neutrino one (Φ_{Be}):

-for the standard solar model ($\diamond$).

-For several non standard solar models adjusted so as to reproduce the Gallex result within 1σ (the Boron contribution anyhow being taken from Kamiokande experiment). Same notation as in Fig.2. The numbers close to each point represent the corresponding value of x/x_{SSM} .

-The values for the MSW solution, for the best fit ($\times$) and for the 90% C.L. region (dots), see also ref [16].

Fig. 6. Iso-signal curves in the MSW model for the pep line, normalized to the SSM value. Labels refer to solid curves and the dashed curves are half-way the solid ones. The 90% C.L. region (long-dashed curves) and the best fit to the present experimental data (Chlorine, Kamiokande and Gallex) are also shown ($\bullet$). The best fit [19] is obtained for $\Delta m^2 = 6.9 \cdot 10^{-6} \text{ eV}^2$, $\sin^2 2\theta = 5.8 \cdot 10^{-3}$ and it corresponds to $\Phi_{\text{pep}}/\Phi_{\text{pep}}^{\text{SSM}} = 3.5\%$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6