A few comments after the charged current measurement at the Sudbury Neutrino Observatory

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ABSTRACT

The comparison of the SNO charged current result with the solar neutrino signal measured by Super-Kamiokande has provided, for the first time, the evidence of a non electron flavour active neutrino component in the solar flux. We remark here that this evidence can be obtained in a model independent way, i.e. without any assumption about solar models, about the energy dependence of the neutrino oscillation probability and about the presence of sterile neutrinos. Furthermore, from the $^8$B neutrino flux obtained by combining SNO and Super-Kamiokande, one can determine the central solar temperature, $T = 1.57 \cdot (1 \pm 1\%) \cdot 10^7$ K, and provide an estimate of the beryllium neutrino flux, $\Phi_{Be} = 4.9 \cdot (1 \pm 11\%) \cdot 10^9$ cm$^{-2}$s$^{-1}$.

1. Introduction

All solar neutrino experiments performed over the past thirty years and probing different portions of the solar neutrino spectrum have reported a deficit with respect to the Standard Solar Model (SSM), see Table 1. Furthermore, by combining the various experimental results, it has been possible to obtain indications in favour of non standard neutrinos even independently of SSM, see e.g. 6). All this evidence, however is not a proof, and the focus is now on the search of real footprints of neutrino oscillations.

In this respect, SNO has recently produced an important result, i.e., when combined with Super-Kamiokande data, SNO provides evidence of a non electron flavour active neutrino component in the solar flux. Briefly, as it was suggested in ref. 8), one can use the charged currents (CC) at SNO to tell neutral currents at Super-Kamiokande (SK).

The suggestion of ref. 8) was based on the following points:

- If $\nu_e$ oscillate into active neutrinos of different flavour – say $\nu_\mu$ – these too contribute to the Super-Kamiokande solar neutrino signal $S$;

- The contribution $S_\mu$ of muon neutrinos to SK signal is expected to be much larger than the experimental error $\Delta S$;

- By a suitable choice of the energy threshold, the CC signal of SNO can be used to determine the $\nu_e$ component $S_e$ of the SK signal;
- The accuracy of SNO should be sufficient for extracting the $\nu_\mu$ contribution to the SK signal, from $S_\mu = S - S_e$.

All this means that by combining the results of SK with CC data from SNO, one can have a signature of oscillations among active neutrinos.

*An important point is that this signature is independent of assumptions about the solar model and the neutrino spectrum.*

In the first part of this paper, following 8) we shall present a general derivation of this result, which has been used in 7,9,10 in order to perform a model independent analysis of experimental data. The method, outlined here for the energy integrated rates, has been extended in ref. 12 for the comparison of the SK and SNO energy spectra.

As also suggested in 8), by combining the CC results of SNO and SK it is possible to determine experimentally the total active flux of $^8$B neutrinos produced in the sun. This too has been successfully accomplished by SNO 7), which has thus provided a refined test of the SSM and has opened the possibility of using neutrinos as probes of the sun.

In the final part of this paper we shall comment on the accuracy of neutrinos as thermometer of the solar interior. Furthermore, we shall provide a determination of the $^7$Be neutrino flux, which is essentially independent of the solar model.

Table 1: Experimental results of solar neutrinos experiments, compared with theoretical predictions.

| Reaction | Experiment       | SSM prediction  | Experimental result          |
|----------|------------------|-----------------|------------------------------|
| $\nu_e + ^{71}$Ga$\rightarrow ^{71}$Ge$+e^-$ | GALLEX+GNO, SAGE | $128_{-7}^{+9}$ SNU | $74.1_{-6.8}^{+6.7}$ SNU, $67.2_{-7.6}^{+8.0}$ SNU |
| $\nu_e + ^{37}$Cl$\rightarrow ^{37}$Ar$+e^-$ | Homestake | $7.6_{-1.1}^{+1.3}$ SNU | $2.56 \pm 0.22$ SNU |
| $\nu + e^- \rightarrow \nu + e^-$ | Kamiokande, Super-Kamiokande, SNO | $5.05(1_{-0.16}^{+0.20}) \cdot 10^6$ cm$^{-2}$s$^{-1}$ | $(2.80 \pm 0.38) \cdot 10^6$ cm$^{-2}$s$^{-1}$, $(2.32 \pm 0.08) \cdot 10^6$ cm$^{-2}$s$^{-1}$, $(2.39 \pm 0.37) \cdot 10^6$ cm$^{-2}$s$^{-1}$ |
| $\nu_e + d \rightarrow p + p + e^-$ | SNO | $5.05(1_{-0.16}^{+0.20}) \cdot 10^6$ cm$^{-2}$s$^{-1}$ | $(1.75 \pm 0.14) \cdot 10^6$ cm$^{-2}$s$^{-1}$ |

*For a different approach to the analysis of SK and SNO combined data see also 11*
2. The SNO-Super-Kamiokande connection

The goal of this section is to show that one can extract from the Super-Kamiokande data the contribution of active neutrinos different from $\nu_e$ by using the CC result of SNO, without assumptions about the solar model and the neutrino spectrum.

In order that the argument can be presented in a very simple way, first we assume that the solar neutrino spectrum is not distorted, i.e. the survival (transition) probability $P_{ee}$ ($P_{e\mu}$) is energy independent. Next we shall prove that our results hold generally, i.e. independently of the functional form of $P_{ee}(E_\nu)$ and $P_{e\mu}(E_\nu)$.

2.1. The case of energy independent oscillations

Super-Kamiokande detects electrons from the reaction

$$\nu_l + e^- \rightarrow \nu_l + e^- \quad l = e, \mu, \tau$$

with kinetic energy $T \geq T_{SK} = 4.5$ MeV.

After 1258 days of operations, the signal is $S = (0.459 \pm 0.016) S^{(SSM)}$, where $S^{(SSM)}$ is the prediction of the Standard Solar Model of ref.\textsuperscript{[3]}, corresponding to a $^8$B neutrino flux $\Phi_{B}^{(SSM)} = 5.05 \cdot 10^6$ cm$^{-2}$ s$^{-1}$. Statistical (1$\sigma$) and systematical errors, here and in the following, are added in quadrature.

If the neutrino spectrum is undistorted, the contribution of $\nu_e$ and $\nu_\mu$ to the SK signal (here and in the following we use the index $\mu$ for any active neutrino species different from $\nu_e$),

$$S = S_e + S_\mu$$

are simply given by

$$S_e = \Phi_B \sigma_e P_{ee}; \quad S_\mu = \Phi_B \sigma_\mu P_{e\mu}$$

where $\Phi_B$ is the flux of boron neutrinos produced in the sun, $\sigma_e$ and $\sigma_\mu$ are the effective cross sections for $\nu_e$ and $\nu_\mu$ detection (see the next subsection for a precise definition) and all signal rates, here and in the following, are normalized to unit target. The ratio,

$$\beta = \frac{\sigma_\mu}{\sigma_e}$$

in the energy range of interest to us is $\beta \simeq 0.152$.

Clearly SK determines only the sum of $S_e$ and $S_\mu$ and cannot discriminate between the two contributions.

\textsuperscript{[3]}Super-Kamiokande generally quotes the “visible energy” $E_{vis}$ of the detected electron, which corresponds to the total electron energy ($E_{vis} = T + m_e$).
SNO has recently reported results on the rate of solar neutrino events from the charged current reaction:

$$\nu_e + d \rightarrow p + p + e^- .$$

The observed rate is $C = (0.347 \pm 0.029) \ C^{(SSM)}$ where $C^{(SSM)}$ is the SSM-predicted signal.

If the neutrino spectrum is undeformed, the $\nu_e$ flux at earth ($\Phi_e = \Phi_B P_{ee}$) can be determined from:

$$C = \Phi_B \sigma_{CC} P_{ee} .$$

One can thus extract the muon signal in SK by combining the SK and SNO experimental results. From the previous equations one has:

$$S_\mu = S - \frac{\sigma_e}{\sigma_{CC}} C$$

Moreover, under the hypothesis of oscillation only among active neutrinos, one can also get the total flux of neutrinos produced in the sun. The foregoing equations give in fact

$$\Phi_B = \left( \frac{\beta - 1}{\beta} \frac{C}{\sigma_{CC}} + \frac{1}{\beta} \frac{S}{\sigma_e} \right)$$

We remark that $S_\mu$ and $\Phi_B$ are determined, by means of (7) and (8), only in terms of experimental data, independently of solar models, assuming however that the survival/transition probability is energy independent.

By using the available data from SK, the SSM prediction for $\Phi_B$ and a conservative ($\sim 10\%$) estimate of the uncertainty of $\sigma_{CC}$, in ref. it was concluded that:

- A muon signal $S_\mu = 0.10 \ S_{BP}$, should be evident at about $2\sigma$ by combining the SK results with the SNO data taken during one year.
- The total $^8$B flux should be measured with an accuracy of about $20\%$ during the same time.

The beautiful measurement of SNO has confirmed these predictions. In fact the comparison of the CC signal of SNO to the SK result has shown a $3.3\sigma$ difference, providing thus a significant evidence that there is a non-electron flavour active neutrino component in the solar flux.

The total flux of active $^8$B neutrinos has been determined by the SNO collaboration as:

$$\Phi_B = (5.44 \pm 0.99) \cdot 10^6 \text{cm}^{-2} \text{s}^{-1} ,$$

The $3.3\sigma$ significance instead of $2\sigma$ predicted in is due mainly to a more recent ($\sim 3\%$) estimate of the uncertainty of $\sigma_{CC}$, see and references therein.
in close agreement with the predictions of solar models, see Table 3.

2.2. The general case

In the general case the transition/survival probability depends on the neutrino energy and eqs. (3) and (6) do not hold. Nevertheless due to the fact that the SK and SNO response functions can be equalized the final relations (7) and (8) still hold.

Let us explain this statement in some detail. In the general case, eqs. (3) and (6) are replaced by:

\[ S_e = \Phi_B \sigma_e \langle P_{ee} \rangle_{SK} , \]  
\[ S_\mu = \Phi_B \sigma_\mu \langle P_{e\mu} \rangle_{SK} , \]  
\[ C = \Phi_B \sigma_{CC} \langle P_{ee} \rangle_{SNO} , \]

where the energy averaged oscillation probability are:

\[ \langle P_{ee} \rangle_{SK} = \int_0^\infty dE_\nu P_{ee}(E_\nu) \rho_e(E_\nu, T_{SK}) , \]  
\[ \langle P_{e\mu} \rangle_{SK} = \int_0^\infty dE_\nu P_{e\mu}(E_\nu) \rho_\mu(E_\nu, T_{SK}) , \]  
\[ \langle P_{ee} \rangle_{SNO} = \int_0^\infty dE_\nu P_{ee}(E_\nu) \rho_{CC}(E_\nu, T_{SNO}) . \]

The response functions (\( \rho_e, \rho_\mu \) and \( \rho_{CC} \)) summarize completely the SK and SNO detector properties. They are defined in terms of the standard \( ^8 \)B energy spectrum, \( \lambda_B(E_\nu) \) \(^4\), of the energy thresholds (\( T_{SK} \) and \( T_{SNO} \)) in the two experiments, of the differential cross sections for the detection processes (\( d\sigma_e/dT' \) and \( d\sigma_\mu/dT' \) for elastic scattering \(^3\) and \( d\sigma_{CC}/dT' \) for CC absorption \(^4\)) and of the detector resolution functions (\( r_{SK}(T, T') \) \(^5\) and \( r_{SNO}(T, T') \) \(^6\)):

\[ \rho_e = \frac{\lambda_B(E_\nu) \int_0^\infty dT \int_0^\infty dT' \frac{d\sigma_e(E_\nu, T')}{dT'} r_{SK}(T, T')}{\int_0^\infty dT' \frac{d\sigma_e(E_\nu, T')}{dT'} r_{SK}(T, T')} , \]  
\[ \rho_\mu = \frac{\lambda_B(E_\nu) \int_0^\infty dT \int_0^\infty dT' \frac{d\sigma_\mu(E_\nu, T')}{dT'} r_{SK}(T, T')}{\int_0^\infty dT' \frac{d\sigma_\mu(E_\nu, T')}{dT'} r_{SK}(T, T')} , \]  
\[ \rho_{CC} = \frac{\lambda_B(E_\nu) \int_0^\infty dT \int_0^\infty dT' \frac{d\sigma_{CC}(E_\nu, T')}{dT'} r_{SNO}(T, T')}{\int_0^\infty dT' \frac{d\sigma_{CC}(E_\nu, T')}{dT'} r_{SNO}(T, T')} \]

\(^d\)In this work we use the SNO resolution function described in \(^8\) and references therein. See \(^8\) for a more recent determination.
Figure 1: The normalized response functions of SK and SNO to $^8B$ neutrinos, for representative values of detector thresholds. See text for details.
The denominators $σ_e$ ($σ_µ$) and $σ_{CC}$ represent the total cross sections for electron (muon) neutrino detection in SK and SNO respectively, as obtained by integrating over $E_ν$ the corresponding numerators in Eqs. (16)–(18). The response functions are normalized to unity.

Figure 1 shows the response functions of SK and SNO as a function of the neutrino energy, for representative values of the detector thresholds. One sees that $ρ_e$ and $ρ_µ$ are almost coincident. This is not surprising since the cross sections for $ν_e e$ and $ν_µ e$ scattering have a similar shape in the range probed by SK, up to an overall factor $^{18}$. For any practical purpose, one can assume that

$$ρ_e(E_ν, T_{SK}) = ρ_µ(E_ν, T_{SK})$$

(19)

to a very good approximation.

It is intriguing to notice that the SK and SNO response functions in Fig. 1 also look very similar, provided that the SNO threshold is chosen 1-2 MeV below the SK threshold, despite the fact that the differential cross sections are very different. This feature can be understood, qualitatively, by means of the following considerations:

i) The high energy behaviour of the response functions is essentially determined by the shape of the $^8$B neutrino spectrum, and is almost unsensitive to the cross section. In particular, in the limit of infinite resolution, the fact that the $^8$B neutrino spectrum has an end-point at $E_ν \simeq 14$ MeV gives:

$$ρ_{e,µ}(E_ν, T_{SK}) = 0 \quad \text{for} \quad E_ν \geq 14 \text{ MeV}$$

$$ρ_{CC}(E_ν, T_{SNO}) = 0 \quad \text{for} \quad E_ν \geq 14 \text{ MeV}$$

ii) The low energy behaviour depends on the chosen threshold; i.e., in the limit of infinite resolution:

$$ρ_{e,µ}(E_ν, T_{SK}) = 0 \quad \text{for} \quad E_ν \leq T_{SK} + m_e/2$$

$$ρ_{CC}(E_ν, T_{SNO}) = 0 \quad \text{for} \quad E_ν \leq T_{SNO} + Q$$

where $Q = 2m_p + m_e - m_d = 1.442$ MeV.

iii) This implies that, by taking $T_{SK} - T_{SNO} \simeq Q - m_e/2 \simeq 1.2$ MeV, the response functions of SK and SNO are non vanishing in the same neutrino energy window. Since both are normalized to unit area, their heights have thus to be similar.

The presence of a finite resolution makes the picture more complicated. Numerically, the relative position of the two thresholds has been optimized so as to minimize the difference between the response functions.

The results are shown in Fig. 2 for some representative values of the thresholds. One sees that the two response functions $ρ_e$ and $ρ_{CC}$ can be equalized to a good approximation. Details can be found in ref. $^8$. Briefly, in the calculations of the electron rates $S$ and $C$ one can assume that the SK and SNO response functions are equal

$$ρ_µ(E_ν, T_{SK}) = ρ_e(E_ν, T_{SK}) = ρ_{CC}(E_ν, T_{SNO})$$

(20)
Figure 2: Examples of the approximate equality of the SK and SNO response functions for selected values of the detector thresholds $T_{SK}$ and $T_{SNO}$. Such values obey approximately the relation $T_{SNO} = 0.995T_{SK} - 1.71(\text{MeV})$. 
within an accuracy of a few percent or less, provided that the SK and SNO thresholds are chosen according to the empirical relation.

\[ T_{\text{SNO}} = 0.995 T_{\text{SK}} - 1.71 \ \text{(MeV)} \]  

(21)

The equality (20) allows a generalization of the results obtained in the previous section. From equations (14) and (15), independently of the functional form of \( P_{ee}(E_\nu) \), one has:

\[ \langle P_{ee}\rangle_{\text{SK}} = \langle P_{ee}\rangle_{\text{SNO}} . \]  

(22)

This shows that the \( \nu_e \) contribution to SK signal can be determined from the CC rate at SNO:

\[ \frac{S_e(T_{\text{SK}})}{\sigma_e(T_{\text{SK}})} = \frac{C(T_{\text{SNO}})}{\sigma_{\text{CC}}(T_{\text{SNO}})} . \]  

(23)

As a consequence, the muon contribution can be extracted by combining data of the two experiments:

\[ S_\mu(T_{\text{SK}}) = S(T_{\text{SK}}) - \frac{\sigma_e(T_{\text{SK}})}{\sigma_{\text{CC}}(T_{\text{SNO}})} C(T_{\text{SNO}}) . \]  

(24)

Moreover, under the assumption of oscillations only among active neutrinos, \( P_{ee}(E_\nu) + P_{e\mu}(E_\nu) = 1 \), one obtains from eqs. (13) and (14):

\[ \langle P_{ee}\rangle_{\text{SK}} = 1 - \langle P_{e\mu}\rangle_{\text{SK}} . \]  

(25)

This relation, together with eqs. (10), (11), (3) and (23) gives the following expression for the total flux \( \Phi_B \):

\[ \Phi_B = \left[ \frac{\beta(T_{\text{SK}}) - 1}{\beta(T_{\text{SK}})} \frac{C(T_{\text{SNO}})}{\sigma_{\text{CC}}(T_{\text{SNO}})} + \frac{1}{\beta(T_{\text{SK}})} \frac{S(T_{\text{SK}})}{\sigma_e(T_{\text{SK}})} \right] \]  

(26)

We conclude thus that the basic equations (7) and (8) can be recovered in the general case, provided only that the SK and SNO thresholds are chosen accordingly to the empirical relation (21).

The model independent approach described above was used in ref. [7,9,10] to determine the contribution \( S_\mu \) of non electron active neutrino flavour components to SK signal. It was concluded that \( S_\mu > 0 \), with a significance greater than 3\( \sigma \). We remark that this conclusion is independent of any assumption about the solar models, about the energy dependence of oscillation probability, and about the presence of sterile neutrinos.

Finally, under the additional assumption of oscillations only among active neutrinos, by using eq. (23) it was found in ref. [10] that

\[ \Phi_B = 5.20 \cdot (1^{+0.20}_{-0.16}) \cdot 10^6 \ \text{cm}^{-2} \text{ s}^{-1} . \]  

(27)
This determination is more accurate, in principle than that of ref.\textsuperscript{7}, eq. (9), since it has been obtained by matching the SK and SNO response function.

3. Neutrinos as probes of the solar interior

The central temperature $T$ of the sun is a nice example of a physical quantity which can be determined by means of solar neutrino detection, provided that the relevant nuclear physics is known. SSM calculations predict $T$ with an accuracy of 1% or even better, see e.g.\textsuperscript{19}. However, this is a theoretical prediction which, as any result in physics, demands observational evidence.

The fluxes of $^8$B and $^7$Be neutrinos are given by, see\textsuperscript{6}:

$$
\Phi_B = c_B S_{17} \frac{S_{34}}{\sqrt{S_{33}}} T^{20} \quad (28)
$$

$$
\Phi_{Be} = c_{Be} S_{34} \frac{T^{10}}{\sqrt{S_{33}}} \quad (29)
$$

where $S_{ij}$ are the low energy astrophysical factors for nuclear reactions between nuclei with atomic mass numbers $i$ and $j$. These quantities have been subject of intense experimental study in the last few years. The present knowledge is summarized in Table 2. Each factor is known with an accuracy of 10% or better.

|        | a)            | b)            | c)            |
|--------|---------------|---------------|---------------|
| $S_{17}$ [$eVb$] | $19^{+4}_{-2}$ | $21 \pm 2$   | $18.8 \pm 1.7$ |
|         |               |               | $17.8^{+1.4}_{-1.2}$ |
| $S_{33}$ [$MeVb$] | $5.40 \pm 0.40$ | $5.40 \pm 0.40$ | $5.32 \pm 0.40$ |
| $S_{34}$ [$KeVb$] | $0.53 \pm 0.05$ | $0.54 \pm 0.09$ |               |

The constants $c_B$ and $c_{Be}$ are well determined. With convenient units, the above equations become:

$$
\Phi_B (cm^{-2}s^{-1}) = 1.443 \cdot 10^{-18} \left( \frac{S_{17}}{eVb} \right) \left( \frac{S_{34}}{KeVb} \right) \left( \frac{S_{33}}{MeVb} \right)^{-1/2} T_6^{20} \quad (30)
$$

$$
\Phi_{Be} (cm^{-2}s^{-1}) = 2.328 \cdot 10^{-2} \left( \frac{S_{34}}{KeVb} \right) \left( \frac{S_{33}}{MeVb} \right)^{-1/2} T_6^{10} \quad (31)
$$

where $T_6$ is the temperature in units of $10^6$K.

The high powers of $T$ in the above equations imply that the measured neutrino fluxes are strongly sensitive to $T$, i.e. $^7$Be and $^8$B neutrinos in principle are good thermometers for the innermost part of the sun.
Table 3: Predictions of some Solar Model calculations:

|       | BP2000 [13] | FRANEC97 [21] | RCVD96 [24] | JCD96 [20] | GARSOM2 [25] |
|-------|-------------|---------------|-------------|------------|--------------|
| $T_c$ [$10^6$ K] | 15.696      | 15.69         | 15.67       | 15.668     | 15.7         |
| $\Phi_B$ [$10^9$ cm$^{-2}$s$^{-1}$] | 5.05        | 5.16          | 6.33        | 5.87       | 5.30         |
| $\Phi_{Be}$ [$10^9$ cm$^{-2}$s$^{-1}$] | 4.77        | 4.49          | 4.8         | 4.94       | 4.93         |

As we have seen in the previous section, ignoring the possibility of sterile neutrinos, by combining the results of SK and SNO one can determine the total $^8$B neutrino flux, see eq. (27). This can be used together with eq. (30) to determine the central solar temperature:

$$T = 15.7 \cdot (1 \pm 1\%) \cdot 10^6 \text{ K}$$

(32)

where the error gets comparable contributions from the uncertainty on $\Phi_B$ and on nuclear physics.

This experimental result is in excellent agreement with the prediction of recent SSMs, see Table 3.

We add that, if sterile neutrinos are allowed, eq. (27) provides a lower limit on the total neutrino flux, and correspondingly, eq. (32) represents a lower limit to the central solar temperature.

Finally, one can use the above equations for getting an estimate of the $^7$Be neutrino flux in terms of experimental quantities. From eqs. (28) and (29) one has:

$$\Phi_{Be} = c_{Be} \frac{1}{c_B} \left( \Phi_B \frac{S_{34}}{S_{17} \sqrt{2} S_{33}} \right)^{1/2}.$$  

(33)

This gives:

$$\Phi_{Be} = 4.9 (1 \pm 11\%) \cdot 10^9 \text{ cm}^{-2}\text{s}^{-1}$$

(34)

where again the uncertainty on the $^8$B neutrino flux and on nuclear physics give comparable contribution to the error.

This estimate is as accurate as the SSM prediction and relies mainly on observational data.

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5. References

1) B. Cleveland et al., Ap. J. 496, 505 (1998).
2) GNO collaboration Phys. Lett. B 490 (2000) 16-26.
3) SAGE collaboration, Phys.Rev.Lett. 83 (1999) 4686-4689
4) K.S. Hirata et al. (Kamiokande coll.), Phys. Rev. Lett. 77, 1683 (1996).
5) S. Fukuda et al. (Super-Kamiokande coll.), Phys. Rev. Lett. 86, 5651 (2001).
6) V. Castellani, S. Degl’Innocenti, G. Fiorentini and B.Ricci Phys. Rep. 281, 309, (1997).
7) G. Aardsma et al. (SNO coll.), Phys. Lett. B 194, 321 (1987); Q.R. Ahmad et al. (SNO coll.) [nucl-ex/0106013]
8) F.L. Villante, G. Fiorentini, E. Lisi, Phys. Rev. D 59, 013006 (1999).
   F.L. Villante, PhD thesis, Università di Ferrara (2000).
9) G.L. Fogli, E. Lisi, D. Montanino, A. Palazzo, [hep-ph/0106247]
10) C. Giunti, [astro-ph/0107310]
11) V. Berezinsky, [astro-ph/0108166]
12) G.L. Fogli, E. Lisi, A. Palazzo, F.L. Villante, Phys. Rev. D 63, 113016 (1999).
13) J.N. Bahcall, M. Pinsonneault and S. Basu, Astrophys.J. 555 (2001) 990-1012
14) J.N. Bahcall, E.Lisi, D.E. Alburger, L. De Braeckeleer, S.J. Freedman and J. Napolitano, Phys. Rev, C 54, 411 (1996).
15) J.N. Bahcall, M. Kamionkowsky and A. Sirlin, Phys. Rev. D 51, 6146 (1995).
16) K. Kubodera and S. Nozawa, Int. J. Mod. Phys. E 3, 101 (1994). We use the computer programs described in J. N. Bahcall and E. Lisi, Phys. Rev. D 54, 5417 (1996) and available at the URL [http://www.sns.ias.edu/~jnb/SNdata]
17) Y. Suzuki, in Neutrino ’98, Proceedings of the XVIII International Conference on Neutrino Physics and Astrophysics, Takayama, Japan.
18) S. Hiroi, H. Sakuma, T. Yanagida, and M. Yoshimura, Phys. Lett. B 198, 403 (1987)
19) J.N. Bahcall, M.H. Pinsonneault, S. Basu and J. Christensen-Dalsgaard, Phys. Rev. Lett. 78, 171 (1997).
20) E. G. Adelberger et al., Rev. Mod. Phys. 70, 1265 (1998)
21) C. Angulo et al. (Nacre coll.), Nucl. Phys. A 656, 3 (1999).
22) F. Hammache et al., Phys. Rev. Lett. 86 3985 (2001)
23) B. Davids et al., [nucl-ex/0101010] (2001)
24) R. Bonetti et al. (LUNA coll.) Phys. Rev. Lett. 82 5205 (1999);/ M.Junker et al. (LUNA coll.) Phys. Rev. C 57 2700 (1998).
25) F. Ciocio, S. Degl’Innocenti and B. Ricci, Astron. Astroph. Suppl. 123, 449 (1997).
26) O. Richard, S. VAuclair, C. Charbonnel and W. A. Dziembowski Astron. Astrphys. 312 1000 (1996)
27) J. Christensen-Dalsgaard et al., Science 272 1286 (1996).
28) H. Schlattl, A. Weiss and H.G. Ludwig, Astron. Astrophys. 322, 646 (1997).