SOLAR NEUTRINO PROBLEM, 1995 [1]

V. Berezinsky

INFN, Laboratori Nazionali del Gran Sasso, 67010 Assergi (AQ), Italy

Abstract

The status of the Solar Neutrino Problem (SNP), as it is seen in 1995, is reviewed. Basically, there are two principal solutions to the SNP: (i) with *standard neutrino* (neutrino of SM of electroweak interactions) and (ii) with *nonstandard neutrino* (neutrino beyond the SM). Actually, one can distinguish three solar-neutrino problems: the deficit of ^8B-neutrinos, the deficit of ^7Be-neutrinos and the Homestake/Kamiokande conflict. The first problem probably can be solved with small correlated changes of nuclear cross-sections and the change of central temperature of the Sun. The deficit of ^7Be- neutrinos looks like the key problem. The Homestake/Kamiokande conflict strongly disfavors or excludes the standard neutrino (nuclear/astrophysical solution to the SNP). MSW conversion gives most plausible explanation to the SNP.

[1] updated version of talk given at 30th Recontres de Moriond, 12 - 18 March, 1995

1 Introduction

The Solar Neutrino Problem (SNP) is a deficit of neutrino fluxes detected in all four solar-neutrino experiments [1],[2], [3],[4]. The data, as reported in 1995, are listed in Table 1 and compared with calculations of Bahcall and Pinnsoneault [5] for the Standard Solar Model (SSM).

Table 1: The solar-neutrino data of 1995 compared with the SSM prediction [5]

	DATA	SSM [5]	DATA/SSM
GALLEX (SNU)	$77.1 \pm 8.5^{+4.4}_{-5.4}$	137	0.563 ± 0.073
SAGE (SNU)	$69 \pm 10^{+5}_{-7}$	137	0.504 ± 0.085
KAMIOKANDE ($10^6\ cm^{-2}s^{-1}$)	$2.89^{+0.22}_{-0.21} \pm 0.35$	6.5	0.444 ± 0.062
HOMESTAKE (SNU)	$2.55 \pm 0.17 \pm 0.18$	9.3	0.274 ± 0.027

The solar neutrino spectrum is characterized by three most important components. (see Table 2).

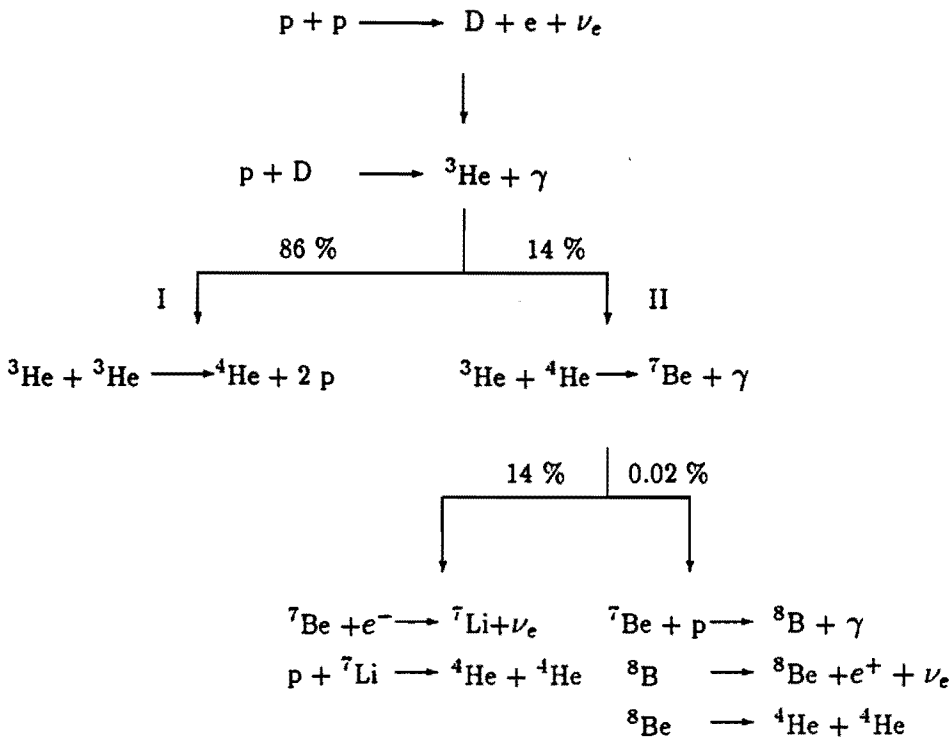
(i) The most energetic part of the spectrum is presented by boron neutrinos from ${}^8B \to {}^8Be + e^+ + \nu_e$ decay. The maximum energy of neutrinos in this spectrum is $E_{\nu,max} \approx 14\ MeV$. Kamiokande, which has the highest threshold of neutrino detection ($E_\nu^{th} \approx 7\ MeV$ since 1991) detects only boron neutrinos.

(ii) Beryllyum neutrinos (${}^7Be + e^- \to {}^7Li + \nu_e$) are monoenergetic ($E_\nu = 0.862\ MeV$). Predicted flux of Be-neutrinos depends weakly on the solar model and is $(4.2 - 4.9) \cdot 10^9\ cm^{-2}s^{-1}$. Homestake detects both boron and beryllium neutrinos: ${}^8B$-neutrinos provide about 80% of the total signal and ${}^7Be$-neutrinos - about 15%

(iii) The low-energy part of the solar-neutrino specrum is presented by pp- neutrinos ($p + p \to {}^2H + e^+ + \nu_e$) with maximum energy $E_\nu^{max} = 0.42\ MeV$. These neutrinos greatly overnumber the flux of other neutrinos ($6.1 \cdot 10^{10}\ cm^{-2}s^{-1}$). The flux is determined practically only by solar luminsity and therefore is very reliably predicted. GALLEX and SAGE measure mostly pp-neutrinos (about 60% of the total signal) with some contribution of ${}^7Be$ and ${}^8B$ neutrinos (about 25% and 10%, respectively).

From Table 1 one can see that the suppression factor, DATA/SSM, is ~ 0.5 within 1σ for the first three experiments, while for the Homestake detector it is ~ 0.3. It is easy to understand that it creates a problem for nuclear/astrophysical solution to SNP. Indeed, since the nuclear/astrophysical factors cannot change the shape of ${}^8B$-neutrino spectrum, the suppression factor for boron neutrino signal in Homestake should be the same (~ 0.5) as in Kamiokande.

Table 2: Nuclear reactions in the Sun (pp-chain)



Of course ^7Be-neutrinos can be suppressed more strongly, but their contribution to the total signal in the Homestake detector is small ($\sim$ 15%). The incompatibility of the Homestake and Kamiokande results was first recognized Bahcall and Bethe [6].

Neutrino oscillations, e.g. $\nu_e \to \nu_\mu$, easily solves the Homestake/Kamiokande conflict. Each case of $\nu_e \to \nu_\mu$ conversion results in full disappearance of a signal in the Homestake detector, while in the Kamiokande detector it still exists due to $\nu_\mu + e \to \nu_\mu + e$ scattering. As a result the signal in Kamiokande should be stronger than in Homestake, as observed.

The discrepancy between predicted and observed neutrino fluxes, as given in Table 1, is a severe problem for an astrophysical solution. The SSM is the most elaborated stellar model. The modern status of the SSM is described in ref's [7],[8]. The calculations use input parameters such as the solar mass, solar radius, surface chemical composition and nuclear reaction rates, and are normalized by the value of luminosity, $L_\odot$. The SSM is confirmed by helioseismological data for distances $r > 0.1 R_\odot$ from the center.

There are at least 11 recently published calculations [5,9-20] for the SSM as it is described above. In all these works the physics included is the same. The slight difference in the results is caused by the different input parameters, most notably by the opacity of the Sun. The calculated parameter which is most important for the solar neutrino fluxes is the central temperature. It varies by $\pm 1\%$ in the above cited calculations. The results are summarized in ref.[20] as $T_c = (15.55 \pm 0.15) \cdot 10^6 K$.

The numerial predictions of the SSM are questioned by uncertainties most notably in the rate of nuclear reactions [7],[10] and in the opacity coefficients [7],[8]. They can be also influenced by collective effects in plasma [21].

There are actually three solar-neutrino problems.

The Homestake/Kamiokande conflict, mentioned above, will be described in some detail in Section 2. This is the most serious problem for the case of the standard neutrino (the nuclear/astrophysical solution to the SNP). If both experiments are correct and $\nu^{37}Cl$-cross-section is not overestimated, neutrino is not standard. The Homestake/Kamiokande problem is analyzed in refs.[6], [10], [22], [23]. An interesting discussion of the adjacent problem, the ratio of beryllium and boron neutrino fluxes, is given in ref.[24].

Boron-neutrino deficit is a second solar-neutrino problem. For the last 25 years the Homestake results were interpreted as deficit of ^8B-neutrinos. As described in Section 3, it could be that ^8B- neutrino problem will be solved by the small correlated changes in the nuclear cross-sections combined with very small ($\sim 1 - 2\%$) reduction of the central temperature of the Sun. It must be emphasized that the boron- neutrino flux could be brought into agreement with with the direct measurements by the *Kamiokande detector*, while the Homestake result remains unexplained.

The third solar-neutrino problem, the *deficit of* ^7Be*-neutrinos*, is discussed in Section 4. At present it looks like the essence of the solar-neutrino problem. The significant contribution to understanding of this problem is given in refs.[25]-[28]. The direct detection of ^7Be-neutrinos will be performed by BOREXINO [29] at Gran Sasso.

The three solar-neutrino problems, as they discussed above, were recently reviewed in refs. [23], [30].

It is worth to emphasize the role of gallium experiments in understanding of Be-neutrino problem. In fact, the gallium results alone limit the beryllium neutrino flux below the prediction of the SSM [31], [32]: $\phi(Be)/\phi_{SSM}(Be) < 0.76$ at $95\% CL$. However, if to subtract from the gallium counting rate the contribution due to ^8B- neutrinos (taken, for example, from the Kamiokande data) and the contribution due to pp-neutrinos (from the solar-luminosity sum rule) then no place is left for ^7Be-neutrino flux [33]. For more detailed analysis see ref.[27].

One can conclude therefore that the case of the standard neutrino (the astrophysical solution to the SNP) is strongly disfavored.

The other solution is given by the nonstandard neutrino: MSW conversion [34], vacuum oscillations [35](for the state-of-the-art description see [36]), resonant spin-flavor precession [38], and matter enhanced transition induced by flavor-chaging neutral currents [39]. The most accurate description of all solar-neutrino data is given by the small-mixing angle MSW conversion.

We shall not touch here the description of the experiments. A reader can find it in the recent review [40].

2 Homestake/Kamiokande conflict or a problem of Be/B neutrino ratio

It can be rigorously proved that the case of the standard neutrinos (a nuclear/astrophysical solution) is excluded or strongly disfavored if the Homestake and Kamiokande results are correct within the cited the statistical and systematic errors.

The point is that the suppression of SSM flux for the Homestake detector (data/SSM = 0.27) is stronger than for Kamiokande (data/SSM = 0.44). However, Homestake detects the same boron neutrinos as Kamiokande, and additionally Be-neutrinos. This argument was first considered quantitatively by Bahcall and Bethe [6]. Using the known relative efficiencies of the two detectors, they found that the counting rate due to boron neutrinos in the Homestake detector calculated from the Kamiokande date to be 3.0 ± 0.49 SNU. It has to be compared with the total counting rate, 2.55 ± 0.25 SNU, which includes Be-neutrinos, *pep*-neutrinos etc. For this latter contribution the authors suggested to use the SSM calculations, since SSM uncertainties for Be- and *pep*-neutrinos are considerably smaller than for B-neutrinos. The two above-mentioned sources give 1.4 SNU and therefore the total counting rate should be 4.40 ± 0.49 SNU, to be compared with 2.55 ± 0.25 SNU observed. Note that we updated here the data used in ref.[6].

In refs.[10],[22] the Homestake/Kamiokande problem was analyzed using the graph $\phi_\nu(^7Be) - \phi_\nu(^8B)$, where ϕ_ν is the neutrino flux at the Earth. It is demonstrated that two regions allowed by Kamiokande and Homestake, respectively, do not intersect each other. The separation of two regions is the smallest at the zero ^7Be- neutrino flux, however, even here they do not intersect each other at $90\% CL$.

In ref.[23] the Homestake/Kamiokande problem is analyzed analytically in terms of two ratios: $R_{Be} \equiv \phi_\nu(Be)/\phi_\nu^{SSM}(Be)$ and $R_B \equiv \phi_\nu(B)/\phi_\nu^{SSM}(B)$. It is shown that independently of the choice of the SSM model

$$R_{Be}/R_B < -1.08 \pm 0.48$$

The uncertainties in nuclear cross-sections do not affect this proof. The temperature solution (low T_c) is strongly excluded.

The analysis described above implies that an astrophysical solution to the Homestake-Kamiokande conflict needs unphysically low Be-neutrino flux.

The only way to avoid the Homestake/Kamiokande contradiction is to assume that $\nu^{37}Cl$ cross-section is overestimated (however, according to ref.[7] it is clear that it is not the case) or that at least one of the two experiments (Homestake and Kamiokande) has uknown large systematic error.

3 Boron neutrino problem

This problem is clearly seen from Table 1 as neutrino deficit in the Kamiokande detector, which measures only boron neutrinos. The neutrino deficit in the Homestake detector also shows the suppression of the boron neutrino flux, because about 80% of the total signal in this detector is provided by the boron neutrinos. The boron neutrino problem was recognized during the last 25 years due to the Homestake results.

Two recently discussed effects, if combined, can resolve this problem.

The first one is the new measurements of $p + {}^7Be \rightarrow {}^8B + e^+ + \nu_e$ cross-section. As one can see from Table 2, the boron neutrino flux is proportional to this cross-section or to the astrophysical S-factor, $S_{17}(0)$, which conventionally characterizes [7] this cross-section. Recently this factor was found from the inverse process, the dissociation of ${}^8B$-nuclei in the Coulomb field of ${}^{208}Pb$: ${}^8B + {}^{208}Pb \rightarrow {}^{208}Pb + {}^7Be + p$. These measurements [41] result in the value of S-factor $S_{17}(0) = 16.7 \pm 2\ eV \cdot b$ to be compared with $S_{17}(0) = 22.4 \pm 2.1\ eV \cdot b$ used by Bahcall and Pinsonneault [5]. This value of $S_{17}(0)$ coincides with the lowest value from the previous measurements and, if true, can lower the predicted flux by a factor 1.3, which alone is still insufficient to resolve the boron neutrino problem (see Table 1).

The second phenomenon is the collective processes in the dense plasma [21].

Collective effects imply the influence of plasma on the elementary processes (e.g. on scattering). The major effect is the change of opacity. According to ref.[21] there are three main effects: the Doppler effect in the Raman resonance, the collective effects in the bremsstrahlung and degeneration of electrons. All these effects can diminish the local opacity in solar core by 18%. In principle it should result in decreasing of T_c. However, at present we have only the indication of the new plasma effects, which must be incorporated in the calculations of solar opacity and the solar models. Note that helioseismological data confirm the existing SSM models at $r \geq 0.1 R_\odot$. Therefore, these effects should operate only at very small distances and disappear at $r \geq 0.1 R_\odot$. Production of boron neutrinos has maximum at $r \sim 0.04 R_\odot$, not far away from the distance given above.

To bring the Kamiokande flux into agreement with theoretical prediction one needs, beyond the factor 1.3 due to the low value of $S_{17}(0)$, to diminish the central temperature T_c only by 2.5%. It can be achieved by lowering the opacity in the solar core due to e.g. the collective plasma effects or due to slight increase of the heavy element abundancies. The increase of ${}^3He + {}^3He$ cross-section, S_{33}, or decrease of ${}^3He + {}^4He$ -cross-section, S_{34}, (see Table 2) can also facilate this task.

We therefore conclude that the prediction for boron neutrino flux can be brought into agreement with the Kamiokande observations by the price of small correlated changes of the cross-sections and the central temperature. At present this possibility should be still considered as the speculative one.

4 Beryllium-neutrino problem

We have at least a realistic hope that the boron-neutrino problem can be solved within the nuclear/astrophysical solution.

In several works [25]-[28] it was recently realized that the essence of the solar neutrino problem is a deficit of beryllium neutrinos.

We saw already this problem in Section 2: the Homestake/Kamiokande conflict demands too low Be/B neutrino ratio.

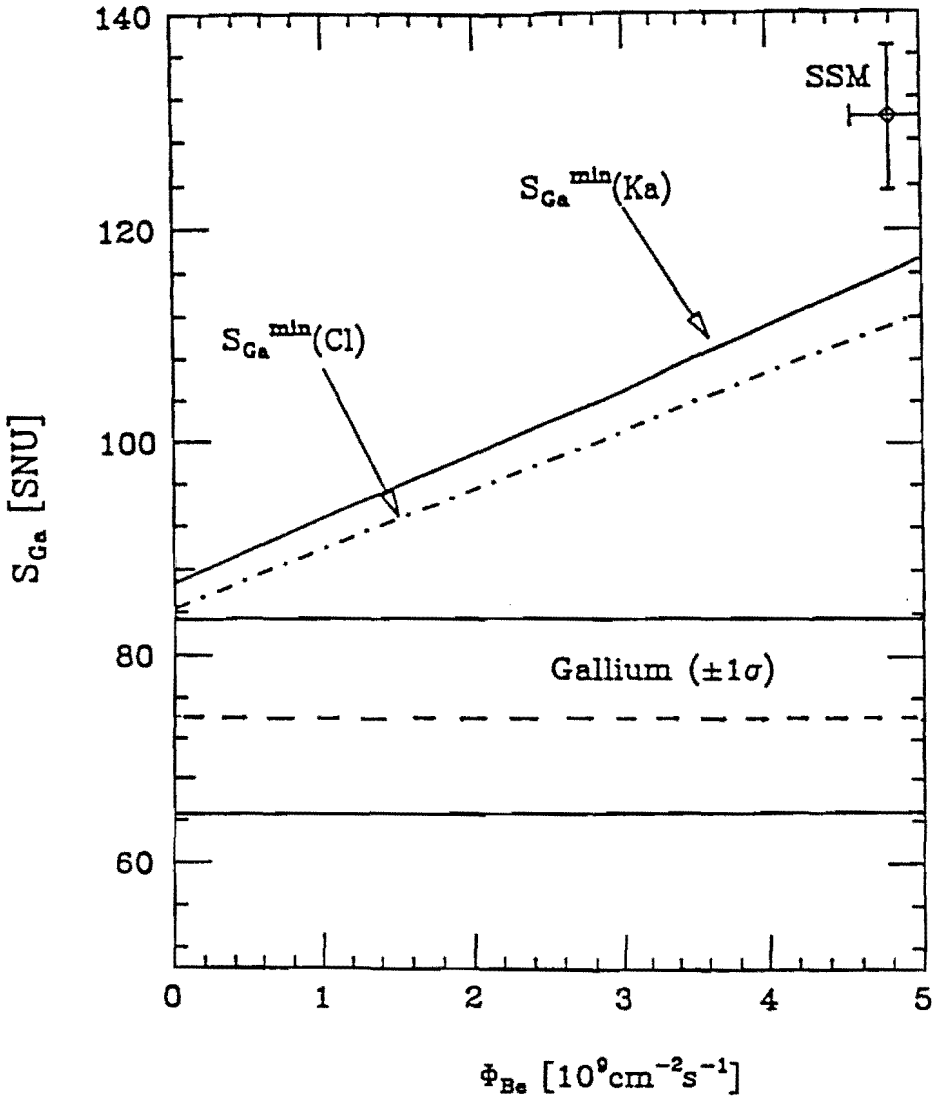


Fig.1 The gallium signal S_{Ga} as a function of ^7Be- neutrino flux (from [27]). Curves $S_{Ga}^{min}(Cl)$ and $S_{Ga}^{min}(Ka)$ give the gallium signal with the minimum boron neutrino contribution evaluated from the Homestake and Kamokande experiments, respectively. The predicted signal is above the observed one (73.1 ± 7.6 SNU) even when $\phi_\nu(Be) = 0$.

The model-independent lower limit for the gallium experiment gives another insight into the problem [33]. To obtain this limit let us assume zero beryllium neutrino flux $\phi_\nu(Be) = 0$. The flux of pp-neutrinos can be found from the solar luminosity sum rule. We obtain $\phi(pp) = 6.48 \cdot 10^{10}\ cm^{-2}s^{-1}$ or 76.5 SNU for a gallium detector. The flux of ^8B- neutrino as given by the Kamiokande experiment is $(2.89 \pm 0.40) \cdot 10^6\ cm^{-2}s^{-1}$. The 1σ lower limit (statistical error only) corresponds to $2.49 \cdot 10^6\ cm^{-2}s^{-1}$ or 6.0 SNU for the gallium experiments. If we neglect all other neutrino sources we obtain in sum 82.5 SNU. To compare this (unrealistically low) lower limit with observational data we use the latest data of GALLEX [1] ($77.1 \pm 8.5^{+4.4}_{-5.4}$ SNU) and SAGE [2] ($69 \pm 10 \pm {}^{5}_{7}$ SNU). If we take the average and sum the errors quadratically we obtain 73.1 ± 7.6 SNU, i.e. 1.2σ below the very stringent lower limit obtained above. We then conclude that the results of the gallium experiments combined with the lower limit of Kamiokande leaves no place for beryllium neutrinos.

The upper limits for beryllium neutrino fluxes were obtained in ref's [25] and [26] from gallium experiments and Kamiokande. In terms of the signal in the gallium detectors they are found to be 19 SNU at 95% CL [25] and 5.1 SNU at 68% CL [26]. These figures are to be compared with $31 - 36$ SNU predicted by the most SSM. If one takes the Homestake data instead of Kamiokande, almost the same cotradiction arises [27]. This result is illustrated by Fig.1 from the work [27]. We updated this graph averaging the fluxes of GALLEX and SAGE.

5 Low neutrino-flux models.

Reducing the $S_{17}(0)$ and slightly changing the other cross-sections or the temperature, one can bring the prediction for the ^8B- neutrino flux into agreement with observations (the Kamiokande data). Two models with low ^8B-neutrino flux have been recently elaborated.

Let us start with the Shi and Schramm (SS) model [42]. This is the SSM model with two input parameters modified as $S_{17} = 20.2\ eV$ and heavy element abundance $Z = 0.015$. The low Z provides the lower central temperature T_c. Actually, this aim can be accomlished due to the collective plasma effects. The ^8B-neutrino flux is predicted to be $3 \cdot 10^6\ cm^{-2}s^{-1}$, in a good agreement with the Kamiokande data $(2.75 \pm 0.45) \cdot 10^6\ cm^{-2}s^{-1}$.

Dar and Shaviv [43] introduced in their model (DS) the following new elements: (i) they calculated $S_{17}(0)$ from the Filippone et al data and found this value as low as $17\ eV \cdot b$, (ii) they evaluated also $S_{34}(0)$ for $^3He(\alpha,\gamma)^7Be$ reaction and found it to be $0.45\ keV \cdot b$, which is considerably lower than the Bahcall-Pinsonneault value $0.533\ keV \cdot b$, (iii) they used the updated value of the solar luminosity, $L_\odot = 3.826(8) \cdot 10^{33}\ erg/s$, (iv)they reconsidered the screening effects for the nuclear reactions and (v) they included into stellar evolution code the diffusion of *all* chemical elements and started the evolution calculations from the pre-main sequence stage. Actually, only items (i) - (iii) are relevant to neutrino fluxes. In fact, the item (v) was already included in the Kovetz-Shaviv [9] model and did not give much difference in comparison with the other SM calculations. The item (iv), as the authors mentioned, give the minor effect. The same is true for the

item (iii),which was already taken into account in some other calculations. Therefore, the main impact on the neutrino fluxes is caused by diminishing of S_{17} and S_{34}.

The comparison of the low neutrino-flux models (SS and DS) with the two standard models (BP [5] and TL [11]) and with the observational data is given in Table 3.

Table 3: Comparison of the low neutrino-flux models with the Standard Solar models and experimental data.

	BP	TL	SS(93)	DS(94)	experim. data
pp(E10)	6.00	6.02	6.1	6.04	
$^7Be(E9)$	4.89	4.33	3.9	4.30	$< 2.1(95\%CL)$
$^8B(E6)$	5.69	4.43	3.0	2.77	2.75 ± 0.45 (Kamiokande)
$^{13}N(ES)$	4.92	3.83	—	0.747	
$^{15}O(ES)$	4.26	3.15	—	0.217	
Homestake (SNU)	8.0 ± 3.0	6.4 ± 1.4	4.5	4.2	2.55 ± 0.25
GALLEX (SNU)	132^{+21}_{-17}	127 ± 7	114	109	$79 \pm 10 \pm 6$
SAGE (SNU)	132^{+21}_{-17}	127 ± 7	114	109	$69 \pm 10 \pm 6$
$T_c(10^7\ K)$	1.559	1.549	1.545	1.571	
$S_{17}\ eV \cdot b$	24	21	20.2	17	
$S_{34}\ keV \cdot b$	0.533	—	—	0.45	
$S_{33}\ MeV \cdot b$	5.0	—	5.6	5.6	

The first column in Table 3 gives the list of physical quantities and of experiments, the second column gives the predictions of the Bahcall and Pinsonneault model [5], the third column refers to the Turck-Chiese and Lopes model [11], in the fourth and fifth columns the predictions of the low-flux models (Shi and Schramm [42] and Dar and Shaviv [43]) are listed and the last column gives the experimental data. The neutrino fluxes (pp, Be etc) are given in units $cm^{-2}s^{-1}$ with the orders of magnitude indicated in the first column.

One can see that in both low neutrino-flux models the predicted ^8B- neutrino flux is in good agreement with the observations (Kamiokande). In accordance with the general demonstration given in Section 2, both models contradict the Homestake data. As we already know from Section 2 the only way to avoid this confict in the framework of an astrophysical solution is to assume that one of the two experiments (or both) has the large systematic error. This point is clearly recognized by Shi and Schramm [42]. Dar and Shaviv [43] claim that the discrepancy of their model with the Homestake data is not significant, if one takes the Homestake data after 1986. But actually even in this case

their predicted flux (4.2 SNU) is 4.1σ higher than the the flux 2.78 ± 0.35 SNU measured for the same period [4]. For the case of the flux, averaged over 1970 - 1993, it is 6.6σ higher.

We conclude therefore that both low neutrino-flux models are in contradiction with the Homestake observations as they must be according to the general demonstration given in Sections 2 and 4.

The second neutrino problem, i.e. the deficit of ^7Be-neutrinos, is also present in the low-flux models. It can be seen from the comparison of the predicted ^7Be-neutrino flux ($3.9 \cdot 10^9$ $cm^{-2}s^{-1}$ and $4.30 \cdot 10^9$ $cm^{-2}s^{-1}$ for the SS and DS models, respectively) with the model-independent upper limits$2.4 \cdot 10^9$ $cm^{-2}s^{-1}(95\%CL)$ and $2.1 \cdot 10^9$ $cm^{-2}s^{-1}(95\%CL)$ according to refs. [25] and [26], respectively). The deficit of ^7Be-neutrinos is also reflected by too high prediction for the counting rate in the gallium experiments (114 SNU and 109 SNU for the SS and DS models, respectively).

Thus the models confirm the model-independent conclusions of the Sections 2 - 4:
(i) Boron-neutrino problem can be solved by the price of the small correlated changes of the input parameters.
(ii) The Homestake/Kamiokande conflict and the deficit of ^7Be neutrinos are not solved by these models, in accordance with the model-independent analysis.

6 The last hope

One might hope to save an astrophysical solution in the following way.
(i) First increase strongly S_{33} motivated by a hypothetical low-energy resonance in the $^3He +^3 He$ channel until $\phi_\nu(Be)$ decreases below the obtained upper limit. It results also in the undesired effect of equally strong suppression of the boron flux $\phi_\nu(B)$ (see Table 2). To boost $\phi_\nu(B)$ back to the observed level one can either increase S_{17} (the boron flux is proportional to this factor) or increase the central temperature T_c ($\phi_\nu(B)$ grows with T_c much faster than $\phi_\nu(Be)$). This possibility was recently studied in ref.[44]. The CNO neutrinos play an important role to exclude this possibility. Fig.2 illustrates well the game.

Let us start with the SSM prediction (point SSM in Fig.2) and follow the track shown by solid line. Increasing S_{33} we can diminish $\phi_\nu(Be)$ below the model-independent lower limit $2.4 \cdot 10^9$ $cm^{-2}s^{-1}$ $(95\%CL)$. In Fig.2 point 1 corresponds to $\phi(Be) + \phi(CNO) = 1.6 \cdot 10^9$ $cm^{-2}s^{-1}$. Increasing the temperature t_c we move away from the region allowed by the four solar-neutrino experiments (shown in Fig.2 by the solid ellipse). Increase of S_{17} does the better job (solid line 1-2),but still we do not reach the allowed region. If we arbitrarily neglect CNO neutrinos (dashed line in Fig.2) we can reach the allowed region (point 5), but the price for this agreement is unrealistically high: S_{33} should be increased by a factor ~ 200 and S_{17} – by a factor of 3.

Thus the last hope turned out to be a no-hope case.

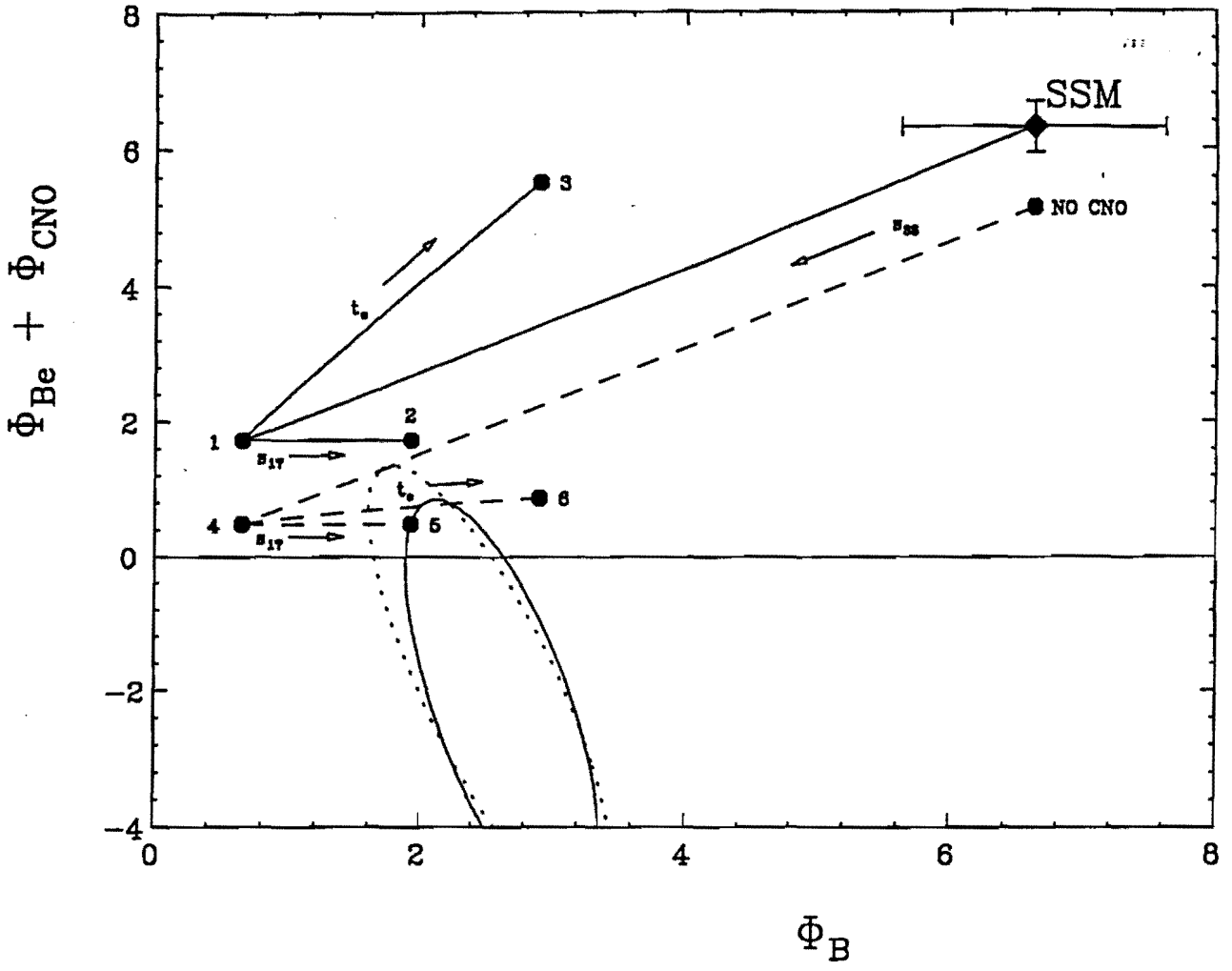


Fig.2. The last hope.
$\phi(Be)+\phi(CNO)$ and $\phi(B)$ are given in units $10^9\ cm^{-2}s^{-1}$ and $10^6\ cm^{-2}s^{-1}$. respectively. The solid ellipse confines the region allowed at $95\% CL$ by the Homestake. Kamiokande. GALLEX and SAGE experiments. The dotted region corresponds to the limits from the chlorine and and gallium experiments. The solid lines give evolutionary track from the SSM to point 1 (increase of S_{33}) and further – to point 3 (increase of central temperature) or to point 2 (increase of S_{17}). Dashed lines correspond to the case when CNO neutrinos are arbitarily excluded.

7 MSW solution for the models with low ^8B-neutrino flux

Assuming the SSM for neutrino production, the MSW conversion describes well all solar neutrino experiments. Howevere, it seems plausible that the SSM will be modified as described above, with the boron neutrino flux reduced.

Does MSW solution exist for such the models?

What are parameters of this solution (Δm^2 and $sin^2 2\theta$) for the models with low ^8B-neutrino flux?

The refs.[45] and [46] address these questions. Fig.3 (from ref.[46]) illustrates how the allowed regions in $\Delta m^2 - \sin^2 2\theta$-plot transform with variation of ^8B-neutrino flux.

The numbers in Fig.3 give the ratio ζ of ^8B neutrino flux to that in the SSM [5].

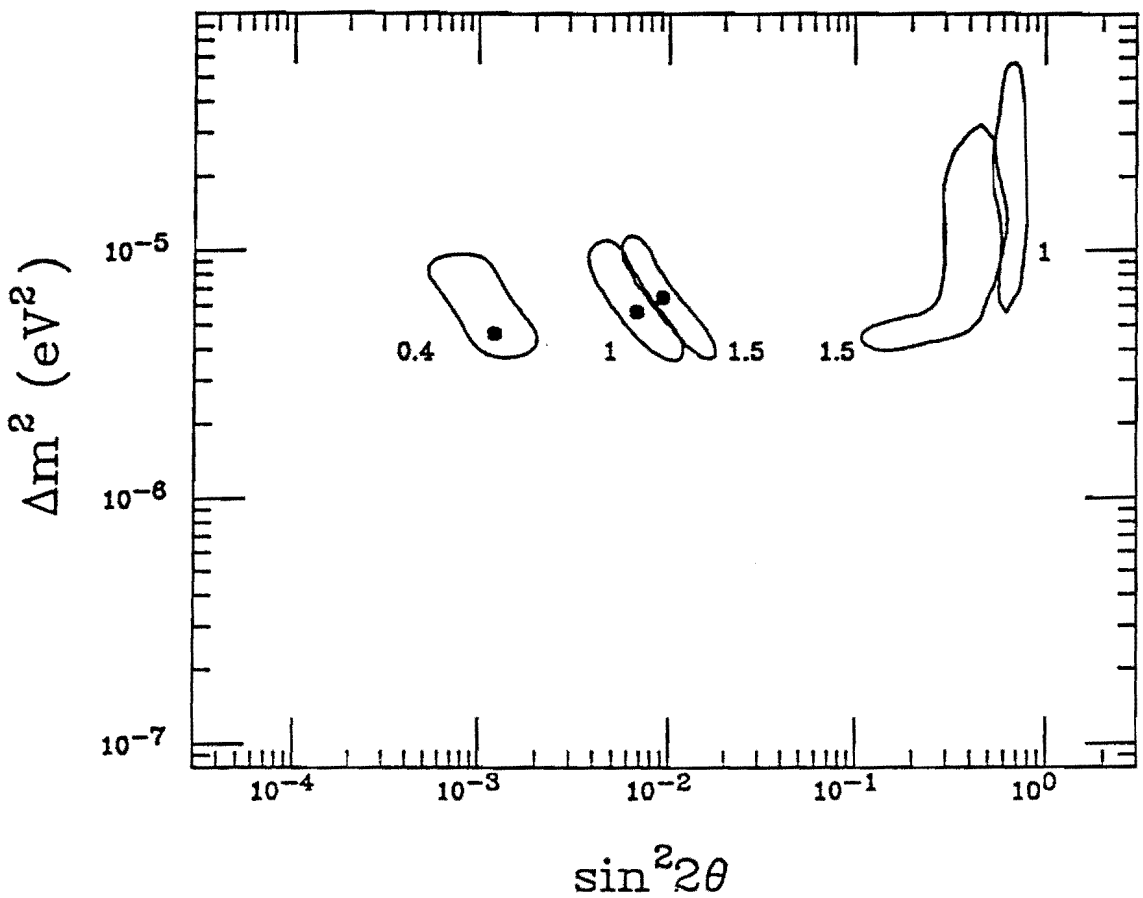


Fig.3 The $\Delta m^2 - \sin^2 2\theta$ plot for SSM [5] with the boron neutrino flux varied (from [46]). The original boron neutrino flux in this model corresponds to the ratio $\zeta = 1$. The flux reduced by factor $\zeta = 0.4$ is marked in Fig.3 by number 0.4. The region marked by number 1.5 corresponds to the boron flux increased by factor $\zeta = 1.5$. The confidence regions are defined as $\chi^2 = 7.82$.

The following conclusions can be derived from this picture.

(i) MSW solution exists for a large range of ratios ζ.

(ii) The *small angle* MSW solution shifts to the smaller mixing angles when the boron-neutrino flux becomes smaller (ζ decreases).

(iii) Increasing the boron neutrino flux results in appearance of large allowed region for the *large-angle* MSW solution, while the decreasing results in disappearance of this solution.

(iv) Δm^2 remains practically unchanged with the variation of the boron neutrino flux.

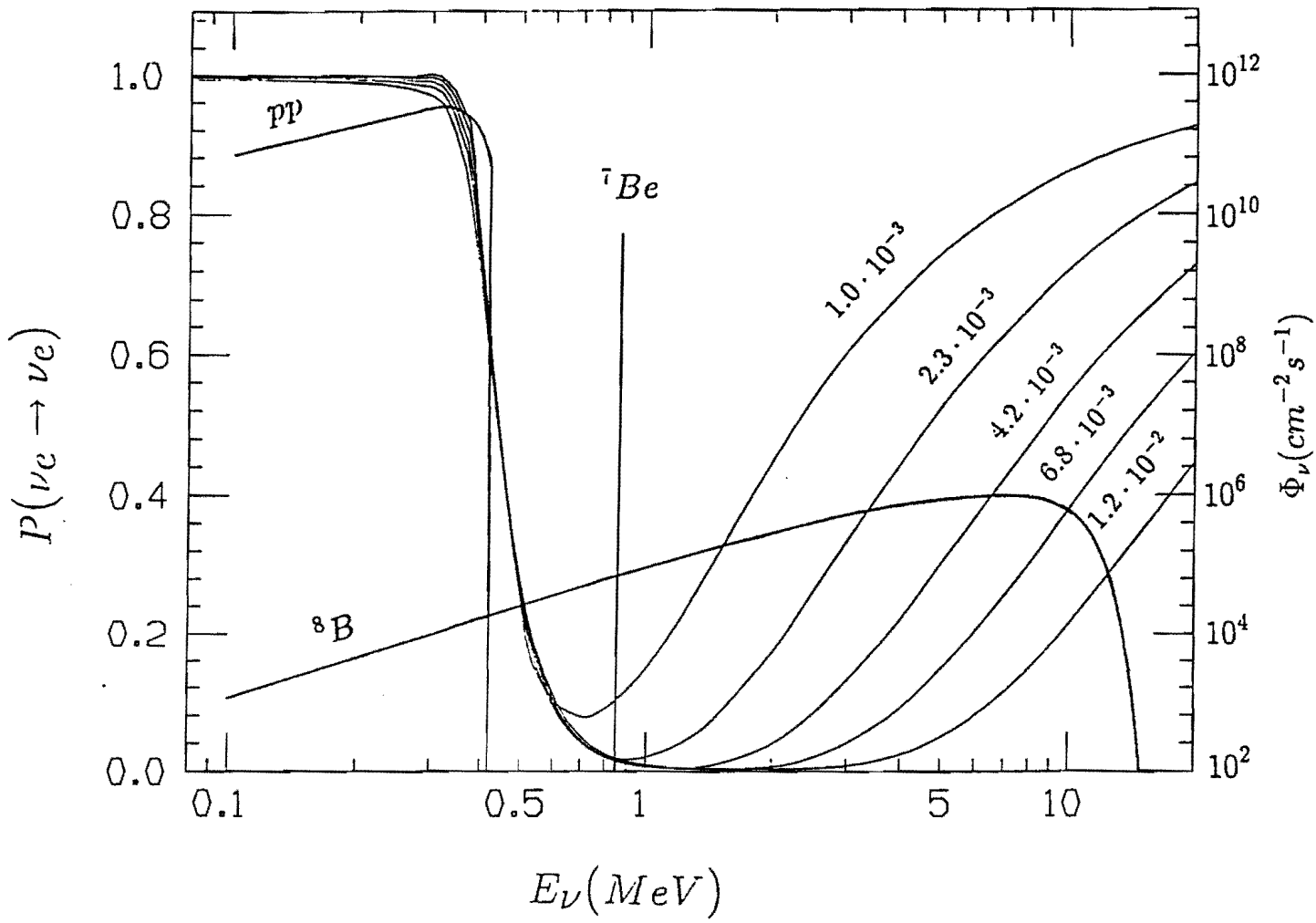


Fig.4 Neutrino spectra and the MSW suppression factors for different mixing angles (figures on the curves give values of $sin^2 2\theta$). For large mixing angles, $sin^2 2\theta \sim 10^{-2}$, the suppression of boron neutrino flux at $E_\nu \geq 5\ MeV$ is strong and therefore both Kamiokande and SNO can observe the distortion of spectrum. For small mixing angles $sin^2 2\theta \sim 10^{-3}$ the suppression factors at $E_\nu \geq 5\ MeV$ are close to 1 and the effects in Kamiokande and SNO are weak.

These models can have rather pessimistic predictions for the nearest-future solar neutrino experiments, SNO and Superkamiokande. In the models with the small mixing angles, $sin^2 2\theta \leq 1 \cdot 10^{-3}$, the MSW conversion of ν_e-neutrinos occurs most effectively at energy $E_\nu < 5\ MeV$, (see Fig.4) i.e. below the threshold energy for SNO and Superkamiokande. Therefore, the distortion of the boron-neutrino spectrum, as well as anomalous NC/CC-ratio, are the small effects for these detectors.

8 Time variation of solar neutrino flux

The data of the Homestake detector show the time variation of neutrino flux in anticorrelation with solar activity (e.g. sunspot number) during a period from 1970 to 1990. Most notably this effect was established in ref.[47], where the pronounced anticorrelation of the ^{37}Ar production with the product $s \mid z \mid$ (where s is sunspot number and z is the latitude of the line of sight) was found at the confidence level 0.9993 (for the other results see ref's [48, 49, 50] and references therein).

This anticorrelation was explained in terms of neutrino spin precession [37] or spin-flavor precession [38] in the toroidal magnetic field in the convective zone of the sun.

For these models the large magnetic magnetic moment of neutrino ($\mu \sim 10^{-11}\mu_B$) and strong magnetic field in the convective and radiation zones of the sun is needed.

A recent analysis of Stanev [52] has demonstrated that runs 106 - 126 in the Homestake experiment reveal no correlation with the sunspot number at all. Inclusion of the last 16 runs after 1990 in the analisis of ref.[47] has decreased the confidence level of the correlation from 0.9993 to 0.99. Simultaneously the data of the Kamiokande detector for 1987 - 1994 reveals no correlation, being consistent with time-independent flux. The GALLEX data are also consistent with constant flux.

A natural question arises. whether the time variation of the spot number reflects well the variation of perpendicular component of the toroidal magnetic field which is responsible for neutrino spin precession.

Recently there were the attempts to find the correlation between variations of neutrino flux and magnetic field on the surface of the sun, measured by the Zeeman effect. Obridko and Rivin [53] have searched for correlation of neutrino flux with different components of magnetic field on the surface of the sun. The strongest correlation was found with the perpendicular component of the surface magnetic field along a neutrino trajectory. The authors analyzed the data (Homestake and Kamiokande) up to 1992. The statistical significance of the correlation is not presented.

More accurate analysis was performed by Oakley et al [54]. These authors also found statistically significant correlation between the Homestake counting rate and the surface magnetic field along the line of neutrino propagation. The significance level decreases with increasing the latitude band, over which the magnetic field was averaged. It gives an additional signature for neutrino propagation effect.

One can observe that the Kamiokande data contradict the results of both analyses. In ref.[53] the Kamionkande data are displayed in the way different from the original

presentation of the Kamiokande group (e.g. [55, 56]). The authors of ref.[54] hope that the absence of time variation in the Kamiokande data are connected with the limited time of reported observations (January 1987 - April 1990) which coincides with the beginning of the solar cycle. Now the Kamiokande data [55, 56] are available up to 1994 and they are consistent with time-independent neutrino flux.

The interesting attempts to reconcile the variability of the Homestake data and the apparent constancy of the Kamiokande flux are made in ref's [52, 51].

My personal opinion is that at present we do not have neither convincing proof of neutrino flux variability, nor strong evidences for correlation with the solar activity. The data we have can be considered just as indication for the existence of these phenomena and only future experiments can shed light on this problem, exciting but controversial at present.

9 Conclusions

The low p^7Be- cross-section and reduced core opacity (due to collective plasma effects) can diminish the flux of ^8B- neutrinos to the level of the Kamiokande observations. Thus, the 25 year-old problem of the ^8B- neutrino deficit can disappear. Instead we face now the problem of low $\phi_\nu(Be)/\phi_\nu(B)$- ratio or Be- neutrino deficit. This problem is mainly created by the ratio of the Homestake to Kamiokande counting rates and is supported by the deficit of the ^7Be- neutrinos in the gallium experiments. If the Homestake and Kamiokande data are correct within the given statistical and systematic errors and if the $\nu_e + ^{37}Cl \rightarrow ^{37}Ar + e$- cross-section is not overestimated, a nuclear/astrophysical solution to the $\phi_\nu(Be)/\phi_\nu(B)$ problem is excluded. It means the existence of the *nonstandard* neutrino, i.e. with properties outside the SM of electroweak interactions.

If one belives that one of these experiments is wrong, we are still left with the conflict (though statistically less significant) between the gallium experiments and the remaining experiment. This comparison results in very small lower limit for ^7Be-neutrinos: $\phi_\nu(Be) < 2.6 \cdot 10^9\ cm^{-2}s^{-1}(95\%CL)$ [25] and $\phi_\nu(Be) < 2.1 \cdot 10^9\ cm^{-2}s^{-1}(95\%CL)$ [26]. These limits are to be compared with the SSM prediction $4.89 \cdot 10^9\ cm^{-2}s^{-1}$.

The deficit of the beryllium neutrinos looks now as the essence of the solar neutrino problem. SNO and Superkamiokande have too high energy threshold (5 MeV) for detection of beryllium neutrinos. BOREXINO [29], recently approved at Gran Sasso, will detect the beryllium neutrinos even in the case of the full conversion of electron neutrinos into muon or tau neutrinos. This is possible due to NC scattering of these neutrinos off the electrons. From the future projects HELLAZ [57] is extremely efficient detector of ^7Be neutrinos. Like BOREXINO it will exploit νe-scattering. The signature of ^7Be-neutrinos in this project is their energy, which is supposed to be known due to precise measurements of the energy of the recoil electron and its scattering angle.

In conclusion, a nuclear/astrophysical solution to the Solar Neutrino Problem is strongly disfavored, while the MSW solution can explain the results of all four neutrino experiments, even if the prediction for ^8B neutrino flux is considerably changed.

10 Acknowledgements

I am grateful to my collaborators G.Fiorentini and M.Lissia for many helpful discussions.

References

[1] P.Anselman et al (GALLEX collaboration), preprint LNGS 95/37, to be published in Phys.Lett. 1995.

[2] V.N.Gavrin (SAGE collaboration), Talk at Int. Workshop TAUP-95 (Toledo) 1995.

[3] K.Inoue, Talk at XXX Rencontres de Moriond. March 12-18, 1995.

[4] B.T.Cleveland et al (Homestake), Nuclear Phys.B (Proc.Suppl.) **39**, 47, (1995).

[5] J.N. Bahcall and M. Pinsonneault, preprint IASSNS-AST 95/ 24 to be published in Rev. Mod. Phys.1995.

[6] J.N. Bahcall and H.A. Bethe, Phys. Rev. Lett. **65**, 2233, (1990).

[7] J.N. Bahcall, Neutrino Astrophysics, Cambridge Univ. Press, Cambridge, 1989.

[8] S. Turck-Chieze, W. Däppen, E. Fossat, J. Provost, E. Schatzmann and D. Vignaud, Phys. Rep. **230**, 57, (1993).

[9] A.Kovetz and G.Shaviv Ap.J. **426**, 787, (1994).

[10] V.Castellani, S.Degl'Innocenti, F.Fiorentini, Astron. Astrophys. **271**, 601, 1993.

[11] S.Turck-Chiese and I.Lopes, Ap.J. **408**, 347 (1993).

[12] G.Berthomieu et al, Astron.Astroph.**268**, 775 (1993).

[13] D.B.Günter et al, Ap.J. **387**, 372 (1992).

[14] J.Christiansen-Dalsgaard, Geophys. Astrophys. Fluid.Dyn. **62**, 123 (1992).

[15] B.Ahrens, M.Stix and M.Thorn, Astron.Astroph. **264**, 673 (1992)

[16] J.A.Guzik and A.N.Cox, Ap.J.Lett. **381**, 331 (1991).

[17] C.R.Proffitt and A.N.Cox, Ap.J.**380**, 238 (1991).

[18] I.J.Sackman, A.I.Boothroyd and W.A.Fowler, Ap.J.**360**, 727 (1990).

[19] Y.Lebreton and W.Däppen, *in* Seismology of the Sun and the Sun-like Stars (ed. V.Domingo and E.J.Rolfe), European Space Agency, Noordwijk, 1988.

[20] J.N.Bahcall, Phys.Rev.Lett. **71**, 2369 (1993).

[21] V. Tsytovich, in "*Solar Neutrino Problem*", eds V.Berezinsky and E.Fiorini, vol.1, p.238, (1994).

[22] N.Hata, S.Bludman and P.Langacker, Phys.Rev.**D 49**, 3622, (1994).

[23] V.Berezinsky, Comm.Nucl.Part.Phys.**21**, 249, (1994).

[24] R.S.Raghavan, Science **267**, 45, (1995).

[25] J.Bahcall, Phys.Lett **338 B**, 276, (1994).

[26] S.Degl'Innocenti, G.Fiorentini ans M.Lissia, Preprint INFNFE-10-94,(1994)

[27] V.Castellani, S.Degl'Innocenti, G.Fiorentini, M.Lissia, B.Ricci, Phys. Rev.D **50**, 4749, (1994).

[28] W.Kwong and S.P.Rosen, Phys.Rev.Lett **73**, 369, (1994)

[29] C.Arpesella et al, "Borexino at Gran Sasso"(Proposal), ed. by G.Bellini and R.Raghavan, INFN, Univ.of Milan, 1991;
E.Bellotti, Nucl.Phys. B (Proc. Suppl)**38**, 90, (1995).

[30] T.Kirsten, Invited talk at 17th TEXAS Symposium on Relativistic Astrophysics, Munich, 1994, to be published in Ann. N.Y. Academy of Sciences (1995).

[31] T.Kirsten, Invited talk at Int. Conf. "Neutrino-95", Nucl.Phys.B(Proc.Suppl) **38**, 68, (1995).

[32] W.Hampel, Talk at the Topical Session "Berrylium Neutrinos: Problem and Detection", Gran Sasso, 1995.

[33] V.Berezinsky, Int. Workshop "Neutrino Telescopes" ed. M.Baldo Ceolin, Venice, Febr. 22-24 1994, p.239, (1994).

[34] S.P.Mikheyev and A.Yu.Smirnov, Yadern. Fiz., **42**, 1441, (1985);
L.Wolfenstein, Phys.Rev. **D17**, 2369, (1978).

[35] B.Pontecorvo, Zh.Eksp.Theor.Fiz. **33**, 549, (1953).

[36] P.I.Krastev and S.T.Petcov, Preprint SISSA 4/94/EP,
S.T.Petcov, Talk at Recontres de Physique de la Vallee d'Aoste, 1995.

[37] M.B.Voloshin, M.I.Vysotsky, L.B.Okun, Sov. Phys. JETP **64**, 446, (1988).

[38] E.Kh.Akhmedov, Phys.Lett.**213B**, 64, (1988);
C.S.Lim and W.Marciano, Phys.Rev.**D37**, 1368, (1988).

[39] S.P.Mikheyev and A.Yu.Smirnov, Proc. of Weak and Electromagnetic Interactions in Nuclei (Heidelberg 1986), ed. H.V.Klapdor, 710, (1987),
M.Guzzo. A.Masiero and S.T.Petcov, Phys.Lett. **260 B**, 154, (1991);
E.Roulet, Phys.Rev. **D 44**, R935, (1991).

[40] T.J.Bowles and V.N.Gavrin, Annu.Rev.Nucl.Part.Sci. **43**, 117, (1993).

[41] T.Motobayashi et al, Phys.Rev.Lett.**73**, 2680, (1994)

[42] X.Shi and D.N.Schramm, Part World **3**, 149, (1993)
D.N.Schramm and X.Shi, Nucl.Phys. B (Proc.Suppl.) **35**, 321, (1994)
X.Shi, D.N.Schramm and D.S.Dearborn, Phys.Rev. D**50**, 2414, (1994)

[43] A.Dar and G.Shaviv, Preprint Technion. Ph-94-5, (1994)
G.Shaviv Nucl.Phys. B (Proc.Suppl.) **38**, 81, (1995).

[44] V.Berezinsky, G.Fiorentini. M.Lissia, preprint LNGS 95/56, August 1995.

[45] P.I.Krastev and A.Yu.Smirnov, Phys.Lett.**338 B**, 282, (1994).

[46] V.Berezinsky, G.Fiorentini. M.Lissia, Phys.Lett. **341 B**, 38, (1994).

[47] J.W.Bieber, D.Seckel, T.Stanev, G.Steigman. Nature **348**, 407, (1990).

[48] B.W.Filippone and P.Vogel, Phys.Lett. **246 B**. 546, (1990)

[49] J.N.Bahcall and W.H.Press. Astroph.J..**370**, 730, (1991).

[50] V.Gavryusev and E.Gavryuseva, Proc. of 6th Int. Workshop "Neutrino Telescopes"(ed. M. Baldo Ceolin), p.319 (1994).

[51] E.Kh.Akhmedov. Proc. of 6th Int. Workshop "Neutrino Telescopes" (ed. M.Baldo Ceolin) p.285, (1994).

[52] T.Stanev. Proc. Int. Workshop "Solar-Neutrino Problem: Astrophysics or Oscillations?" (ed's V.Berezinsky and E.Fiorini), v.2. p.51, (1994).

[53] V.N.Obridko and Yu.R.Rivin, to be published in Izv. of Russian Academy of Sciences. ser. phys., **9**, (1995).

[54] D.S.Oakley et al., Astroph.J. **L63**, 437,(1994).

[55] Y.Suzuki, Proc. of 6th Int. Workshop "Neutrino Telescopes" (ed. M. Baldo Ceolin). 191, (1994).

[56] Y.Totsuka, Talk at Int. Workshop TAUP-95, (1995).

[57] T.Ypsilantis et al Preprint LPC-92-31
G.Bonvicini, Nucl.Phys.B (Proc.Suppl.) **35**. 438, 1994.