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THE SOLAR NEUTRINO PROBLEM: PRESENT STATUS AND POSSIBLE NEUTRINO PHYSICS SOLUTIONS

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Abstract

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The Solar Neutrino Problem: Present Status and Possible Neutrino Physics Solutions

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1. INTRODUCTION

It has been realized as early as in 1967 [1] that the measurements of the flux of electron neutrinos emitted by the Sun can provide unique information not only about the physical conditions and the nuclear reactions taking place in the central part of the Sun, but also about the neutrino intrinsic properties. The solar neutrino problem emerged in the 70'ies as a discrepancy between the results of the first experiment aimed at detection of the solar ν_e flux – the epic Davis et al. experiment [2], and the theoretical predictions for the signal in this experiment [3], based on detailed solar model calculations. The hypothesis of unconventional behaviour of the solar ν_e on their way to the Earth (vacuum oscillations [4] $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ and/or $\nu_e \leftrightarrow \nu_s$, ν_s being a sterile neutrino, MSW transitions [5] $\nu_e \rightarrow \nu_{\mu(\tau)}$ and/or $\nu_e \rightarrow \nu_s$, etc.) provided a natural explanation of the deficiency of solar neutrinos reported by Davis et al. However, as the fraction of the solar ν_e flux to which the experiment of Davis et al. is sensitive (neutrinos with energy $E \geq 0.814$ MeV) was known [3] i) to be produced in a chain of nuclear reactions (representing a branch of the pp cycle) which play a minor role in the physics of the Sun and whose cross-sections cannot all be measured directly in the relevant energy range on Earth, and ii) to be extremely sensitive to the predicted value of the central temperature, T_c , in the Sun (scaling as T_c^{18}), the possibility of an alternative (astrophysics, nuclear physics) explanation of the Davis et al. results could not be excluded.

In 1986 an independent measurement of the

high energy part ($E \geq 7.5$ MeV) of the flux of solar ν_e was successfully undertaken by the Kamiokande II collaboration using a completely different experimental technique; in 1990 the measurements were continued (they are still going on) by the Kamiokande III group with an improved version of the Kamiokande II detector [6]. At the beginning of the 90'ies two new experiments, SAGE [7] and GALLEX [8], sensitive to the low energy part ($E \geq 0.233$ MeV) of the solar neutrino flux, began to operate and to provide qualitatively new data. At the same time considerable efforts were also made to understand better the potential sources and the possible magnitude of the uncertainties in the theoretical predictions for the signals in the indicated solar neutrino detectors, and to develop improved, physically more precise solar models on the basis of which the predictions are obtained [9–14]. With the accumulation of more data and the developments in the theory certain aspects of the solar neutrino problem changed and new aspects appeared.

In the present article we shall review the present day status of the solar neutrino problem. We shall review also the status of the neutrino physics solutions of the problem based on the hypotheses of vacuum oscillations or of MSW transitions of solar neutrinos.

2. THE DATA AND THE SOLAR MODEL PREDICTIONS

We begin with a brief summary of the solar model predictions and of the solar neutrino data. According to the existing models of the Sun [3,9–

14], the solar ν_e flux consists of several components, six of which are relevant to our discussion: i) the least energetic pp neutrinos ($E \leq 0.420$ MeV, average energy $\bar{E} = 0.265$ MeV), ii) the intermediate energy monoenergetic ${}^7\text{Be}$ neutrinos ($E=0.862$ MeV (89.7% of the flux), 0.384 MeV (10.3% of the flux)), iii) the higher energy ${}^8\text{B}$ neutrinos ($E \leq 14.40$ MeV, $\bar{E} = 6.71$ MeV), and three additional intermediate energy components, namely, iv) the monoenergetic pep neutrinos ($E=1.442$ MeV), and the continuous spectrum CNO neutrinos produced in the β^+ -decays v) of ${}^{13}\text{N}$ ($E \leq 1.199$ MeV, $\bar{E} = 0.707$ MeV), and vi) of ${}^{15}\text{O}$ ($E \leq 1.732$ MeV, $\bar{E} = 0.997$ MeV).

Three different methods of solar neutrino detection have been and are being used in the five solar neutrino experiments [2,6,7,8] that have provided data so far: the radiochemical Cl-Ar method proposed by Pontecorvo in 1946 [15] - in the experiment of Davis et al. [2], the $\nu - e^-$ elastic scattering reaction - in the Kamiokande experiments [6], and the radiochemical Ga-Ge method - in SAGE [7] and GALLEX [8] experiments. The threshold energy of the reaction $\nu_e + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$ on which the Cl-Ar method is based, is $E_{\text{th}} = 0.814$ MeV. Consequently, the pp neutrinos do not give a contribution in the signal in the Davis et al. detector. Inspecting the predictions of all presently discussed in the literature solar models one finds that the major contribution to the signal in the Cl-Ar experiment, between 66% and 77%, should be due to the ${}^8\text{B}$ neutrinos; the ${}^7\text{Be}$ neutrinos are predicted to generate between 22% and 14% of the total signal, and the pep and the CNO neutrinos - between 13% and 9%. With a threshold neutrino energy, $E_{\text{th}}(\text{K})$, first of 9.5 MeV and subsequently reduced to 7.5 MeV and further to 7.3 MeV, the Kamiokande experiments can detect only the higher energy ${}^8\text{B}$ component of the solar ν_e flux. Having the lowest threshold energy $E_{\text{th}}(\text{Ga}) = 0.233$ MeV, the Ga-Ge detectors GALLEX and SAGE are sensitive to all six components of the flux indicated above. Moreover, the major part of the signal in these detectors, between 54% and 60%, is predicted to be produced by the pp neutrinos; the ${}^7\text{Be}$ neutrinos are expected to generate between 27% and 24% of the

total signal, the ${}^8\text{B}$ neutrinos - between 10% and 6%, and the CNO neutrinos - between 8% and 12%. The above analysis implies that the Cl-Ar and Kamiokande experiments on one side, and the Ga-Ge experiments on the other, are most sensitive to very different components of the solar neutrino flux: the former - to the ${}^8\text{B}$ neutrinos, and the latter - to the pp neutrinos. The ${}^7\text{Be}$ neutrinos are predicted to give the second largest (and non-negligible) contributions to the signals in both Cl-Ar and Ga-Ge experiments.

Let us turn next to the data. The average rate of ${}^{37}\text{Ar}$ production by solar neutrinos, $\bar{R}(\text{Ar})$, observed in the experiment of Davis et al. in the period 1971-1993 (altogether ~ 800 solar ν_e induced events registered, the experiment continues to collect data) is [2]

$$\bar{R}(\text{Ar}) = (2.55 \pm 0.25) \text{ SNU}. \quad (1)$$

Here (and in the experimental results we quote further) the error represents the added in quadratures statistical (1 s.d.) and systematical errors. The flux of ${}^8\text{B}$ neutrinos, Φ_B , measured by the Kamiokande experiments reads [3]

$$\Phi_B = (2.89 \pm 0.42) \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1}. \quad (2)$$

The result is based on a statistics of 439 events accumulated by the two experiments in 1557 days of measurements in the period 1986-1993.

The GALLEX and SAGE experiments began to collect data in 1991 and 1990, respectively. So far the GALLEX group has registered 136, and the SAGE group about 76 solar neutrino induced events. The average rates of ${}^{71}\text{Ge}$ production by solar neutrinos, $\bar{R}(\text{Ge})$, measured by the two collaborations are [8,7]

$$\bar{R}_{\text{GALLEX}}(\text{Ge}) = (79 \pm 12) \text{ SNU}, \quad (3)$$

$$\bar{R}_{\text{SAGE}}(\text{Ge}) = (69 \pm 13) \text{ SNU}. \quad (4)$$

Obviously, the results of the two experiments are compatible. Combining them (i.e., taking the weighted average) one finds

$$\bar{R}_{\text{exp}}(\text{Ge}) = (76 \pm 9) \text{ SNU}. \quad (5)$$

Recently the GALLEX collaboration has successfully completed a very important (and rather

spectacular) calibration experiment with an artificially prepared powerful ^{51}Cr source of monoenergetic ν_e (four lines: $E = 746$ keV (81%), 751 keV (9%), 426 keV (9%) and 431 keV (1%)) of known intensity [16]. At the beginning of the exposure the signal due to the ^{51}Cr neutrinos was approximately 12 times bigger than the signal due to the solar neutrinos. The results of the experiment showed, in particular, that the efficiency of extraction of the ^{71}Ge , produced by neutrinos, from the tank of the detector coincides (within the 10% error) with the calculated one. They demonstrated that the GALLEX detector is capable of detecting both the low energy pp and the intermediate energy ^7Be neutrinos with a high efficiency and represent a solid proof that the data on the solar neutrinos provided by the GALLEX experiment are correct. They also represent the first real proof of the feasibility of the radiochemical method invented by Pontecorvo [15] for detection and quantitative study of solar neutrinos. Let us add that at present GALLEX is the only calibrated solar neutrino detector.

The results of the solar neutrino experiments have to be compared with the corresponding theoretical predictions. Many authors have worked (and many continue to work) in the field of solar modelling and have produced predictions for the values of the pp, ^7Be , ^8B , pep and CNO neutrino fluxes, and for the signals in the solar neutrino detectors: a rather detailed review of the results obtained by different authors prior 1992 and the corresponding references can be found in ref. [9]. Most persistently solar models with increasing sophistication and precision, aiming to account for and/or reproduce with sufficient accuracy the physical conditions and the possible processes taking place in the inner parts of the Sun have been developed starting from 1964 by Bahcall and his collaborators.

We shall present here the results obtained in four models [9–12] which can be characterized by their predictions for the total flux of ^8B neutrinos as "high flux" [9,11], "intermediate flux" [10] and "low flux" [12] models. The predictions for the ^8B neutrino flux and for the signals in the solar neutrino detectors in these models determine the corresponding intervals in which the results of all

currently discussed in the literature solar models lie (see, e.g., refs. [13–14]). Thus, they give an idea about the dispersion and the possible uncertainties in the predictions. Let us note also that the four models as models of the solar interior differ, in particular, in one important aspect, namely, in the way the possible diffusion of the light and heavy elements in the Sun is accounted for: the model [10] is without diffusion, in [9] for the first time the ^4He diffusion was taken into account, while in the more recent models [11] and [12] the diffusion of the elements heavier than ^4He was also included in the calculations.

In Table I we have collected the results of the models of Bahcall–Pinsonneault (BP) [9], Turck-Chièze and Lopez (TL) [10], Proffitt [11] and of Dar and Shaviv (DS) [12] for the values of the fluxes of the pp, ^7Be , ^8B , pep and CNO neutrinos at the Earth surface. We have included also the estimated 1 s.d. uncertainties in the predictions for the fluxes made by Bahcall and Pinsonneault, and for some of the fluxes – by Dar and Shaviv, for their respective models. In Tables II and III we give the predictions for the contributions of each of the indicated six fluxes to the signals in the Cl–Ar [2] and the Ga–Ge [7,8] experiments, respectively, and quote the predictions for the total signals in these experiments (including the estimated 1 s.d. uncertainty in the predictions whenever it is given by the authors).

A comparison between the experimental results (1)–(5) and the corresponding predictions given in Tables II and III leads to the conclusion that none of the solar models proposed so far provides a satisfactory description of the solar neutrino data: the predictions typically exceed the observations. This is one of the current aspects of the solar neutrino problem.

Taking into account the estimated uncertainties in the theoretical predictions and the experimental errors in (1)–(5) one finds that the differences between the predictions and the observations are largest for the "high flux" models: the measured values of $\bar{R}(\text{Ar})$, $\bar{\Phi}(\text{B})$ and $\bar{R}(\text{Ge})$ in the Cl–Ar, Kamiokande and Ga–Ge experiments are at least by (3.5–4.0) s.d. smaller than the predicted ones in [9,11]. The "low flux" model of Dar and Shaviv reproduces the result of the Kamio–

Table 1
Solar neutrino fluxes at the Earth surface (in units of $\text{cm}^{-2}\text{sec}^{-1}$) predicted by the solar models [9–12].

Flux	BP	Proffitt	TL	DS
$\Phi_{pp} \times 10^{-10}$	6.00 ± 0.04	5.91	6.03	6.03
$\Phi_{pep} \times 10^{-8}$	1.43 ± 0.02	1.39	1.39	1.38
$\Phi_{Be} \times 10^{-9}$	4.89 ± 0.29	5.18	4.34	4.31 ± 0.55
$\Phi_B \times 10^{-6}$	5.69 ± 0.82	6.48	4.43 ± 1.1	2.87 ± 0.72
$\Phi_N \times 10^{-8}$	4.92 ± 0.84	6.40	3.83	4.15
$\Phi_O \times 10^{-8}$	4.26 ± 0.82	5.57	3.18	4.13

Table 2
Signals (in SNU) in Cl–Ar detectors due to the solar neutrinos, predicted by the solar models [9–12].

Type of neutrinos	BP	Proffitt	TL	DS
pp	0.0	0.0	0.0	0.0
pep	0.23	0.22	0.22	0.20
${}^7\text{Be}$	1.17	1.26	1.10	1.06
${}^8\text{B}$	6.20	7.06	4.63	3.10
${}^{13}\text{N}$	0.10	0.12	0.06	0.08
${}^{15}\text{O}$	0.30	0.38	0.21	0.29
Total:	8.0 ± 0.1	9.0	6.4 ± 1.4	4.7 ± 1.0

kande experiments for $\bar{\Phi}(\text{B})$. However, the prediction of the model for $\bar{R}(\text{Ge})$ is by at least 2.5 s.d. higher than the GALLEX and SAGE results (3) and (4). The discrepancy between the solar model predictions and the Ga–Ge data is larger if one compares the predictions with the combined result (5) of the GALLEX and SAGE experiments. For the DS model, for instance, the difference is at the level of (3.0 – 3.5) s.d.

Let us discuss in somewhat greater detail the results of the four representative models [9–12] for the fluxes of the pp, pep, ${}^7\text{Be}$, ${}^8\text{B}$ and CNO neutrinos shown in Table 1. The predictions for the values of the pp and pep neutrino fluxes are remarkably coherent: they vary from model to model at most by 2% and 3.5%, respectively. Actually, the two fluxes are related [17]: Φ_{pep} is proportional to Φ_{pp} and the coefficient of proportionality is practically solar model independent, being determined by the ratio of the cross-sections of the reactions $p + e^- + p \rightarrow D + \nu_e$ and $p + p \rightarrow D + e^+ + \nu_e$ in which the pep and pp neutrinos are produced in the Sun. One has [17,

9–14]

$$\Phi_{pep} = (2.3 - 2.4) \times 10^{-3} \Phi_{pp}. \quad (6)$$

The value of the pp flux is constrained by the existing rather precise data on the solar luminosity, $L_\odot$. Indeed, the solar luminosity is determined by the thermal energy released in the Sun in the two well known cycles of nuclear reactions, the pp and the CNO cycles (see, e.g., ref. [17]), in which 4 protons are converted into ${}^4\text{He}$ with emission of 2 neutrinos. From the point of view of the energy effectively generated, the indicated hydrogen burning reactions can be written as

Depending on the cycle, the two emitted neutrinos can be both of the pp or pep type, or a pp (pep) and a ${}^7\text{Be}$, a pp (pep) and a ${}^8\text{B}$ (pp cycle), and a ${}^{15}\text{O}$ and/or ${}^{13}\text{N}$ (CNO cycle) neutrinos [17]. The thermal energy released per one produced pp, pep, ${}^7\text{Be}$ and ${}^8\text{B}$ neutrino is equal to $(Q/2 - \bar{E}_j)$, where $Q = 26.732 \text{ MeV}$ is the Q-value of the reaction (7), and $\bar{E}_j$ is the average energy of the neutrino of the type j ($j = \text{pp}, \dots$). The energy

Table 3

Signals (in SNU) in Ga-Ge detectors due to the solar neutrinos, predicted by the solar models [9–12].

Type of neutrinos	BP	Proffitt	TL	DS
pp	70.8	70.0	71.1	71.6
pep	3.1	3.0	3.0	3.0
^7Be	35.8	37.9	30.9	30.7
^8B	13.8	15.7	10.8	7.0
^{13}N	3.0	3.9	2.4	2.55
^{15}O	4.9	6.4	3.7	4.76
Total:	131.5^{+7}_{-6}	137	122.5 ± 7.0	119.6 ± 7.0

released per one ^{15}O and/or one ^{13}N neutrino, as can be shown (taking into account, in particular, the discussion of the rates of the different reactions of the CNO cycle given in [17]) is equal with a high precision to the difference $(Q/2 - (\bar{E}_N + \bar{E}_O)/2)$. Obviously, the values of Q and $\bar{E}_j$ are solar physics (and therefore solar model) independent. Given the average energies $\bar{E}_j$ carried away by the pp, pep, ^7Be , ^8B and CNO neutrinos (they are listed at the beginning of Section 2, $\bar{E}_{\text{Be}} = 0.813$ MeV), and knowing that the energy emission by the Sun is quasistationary (steady state), it is possible to relate $L_\odot$ with the pp, pep, ^7Be , ^8B and CNO neutrino luminosities of the Sun. One finds in this way the following constraint on the solar neutrino fluxes:

$$\begin{aligned} \Phi_{\text{pp}} + 0.958\Phi_{\text{Be}} + 0.955\Phi_{\text{CNO}} + 0.910\Phi_{\text{pep}} = \\ = (6.517 \pm 0.02) \times 10^{10} \text{ cm}^{-2}\text{sec}^{-1}, \end{aligned} \quad (8)$$

where $\Phi_{\text{CNO}} = \Phi_N + \Phi_O$, we have used $L_\odot = (3.846 \pm 0.010) \times 10^{33} \text{ erg sec}^{-1}$ [18] and have neglected the terms proportional to Φ_B and to $(\Phi_N - \Phi_O)$ in the left hand side of the equation, which are predicted to be smaller than $2 \times 10^8 \text{ cm}^{-2}\text{sec}^{-1}$. The fluxes Φ_B and $(\Phi_N - \Phi_O)$ have to be more than 60 and 3 times bigger than the largest ("high flux") model predictions [11] and [9], respectively, in order for these terms to exceed the indicated value. The coefficient multiplying the Φ_{Be} term in eq. (8) is just the ratio of the thermal energies produced per one ^7Be and one pp neutrino, $(Q/2 - \bar{E}_{\text{Be}})/(Q/2 - \bar{E}_{\text{pp}})$, etc. Since, as Table 1 shows, Φ_{Be} and Φ_{CNO} are smaller than Φ_{pp} at least by the factors 0.09 and

0.02, respectively, and Φ_{pep} is even smaller (see eq. (6)), eq. (8) limits primarily the pp neutrino flux.

Comparing the experimental results (3) – (5) with the solar model predictions given in Table 3 one notices, in particular, that the rate of ^{71}Ge production due only to the pp neutrinos, $R^{\text{pp}}(\text{Ge}) = (70 - 72)$ SNU, is very close to the rates observed in the GALLEX and SAGE experiments. This suggests that a large fraction of, or all pp (electron) neutrinos emitted by the Sun reach the Earth intact and are detected.

The relative spread in the predictions for the ^7Be neutrino flux Φ_{Be} and for the signals due to the ^7Be neutrinos in the Cl-Ar and Ga-Ge experiments, as it follows from Tables 1–3, do not exceed 21%. The largest (1 s.d.) uncertainty in the prediction for Φ_{Be} is quoted by Dar and Shaviv and is 13%.

3. THE ^8B NEUTRINO PROBLEM

A further inspection of the results collected in Table 1 reveals that the differences (and the estimated uncertainties) in the predictions of the solar models for the total flux of ^8B neutrinos is the largest: the value of Φ_B in the "high flux" model [11] is by more than a factor of 2 larger than the value obtained in the "low flux" model [12]. The ^8B neutrinos are born in the Sun in the β^+ decay, $^8\text{B} \rightarrow ^8\text{Be}^* + e^+ + \nu_e$, of the ^8B nucleus which is produced in the reaction

initiated by ~ 20 keV protons. Obviously, Φ_B is

proportional to the rate of the process (9) taking place in the solar plasma environment, which in turn is to large extent determined by the cross-section of (9), $\sigma_{17}(E_p)$. The latter is usually represented in the form [17]

$$\sigma_{17}(E_p) = \frac{S_{17}(E_p)}{E_p} \exp(-8\pi e^2/v), \quad (10)$$

where E_p and v are the $p - {}^7\text{Be}$ c.m. kinetic energy and relative velocity, and $\exp(-8\pi e^2/v)$ is the Gamow penetration factor. The largely different values of the astrophysical factor S_{17} , $S_{17} \equiv S_{17}(E_p \sim 20\text{keV})$, adopted by the authors of refs. [9,11] and of ref. [12] is the major source of the large spread in the predictions for Φ_B .

Because of background problems it is impossible to measure the cross-section $\sigma_{17}(E_p)$ directly at the low energies of the incident protons, which are of astrophysical interest. The experimental studies of the process (9) were performed at energies $110\text{ keV} \leq E_p \leq 2000\text{ keV}$. They are technically rather difficult because of the instability of the ${}^7\text{Be}$ serving as a target. The results obtained in the indicated higher energy domain are extrapolated to $E_p \sim 20\text{ keV}$ using a theoretical model describing the data (and the process (9) in the entire energy range $20\text{ keV} \leq E_p \leq 2000\text{ keV}$) and taking into account the possible solar plasma screening effects. Obviously, there are at least two major sources of uncertainties in the determination of S_{17} inherent to the indicated approach: the uncertainties associated with the data at $E_p \geq 110\text{ keV}$, and those associated with the extrapolation procedure exploited. Altogether six experiments have provided data on the the $p - {}^7\text{Be}$ cross-section $\sigma_{17}(E_p)$ so far. The results of the four most accurate of them [19,20] can be grouped in two distinct pairs, [19] and [20], which agree on the energy dependence of $S_{17}(E_p)$, but disagree systematically by $\sim (20-25)\%$ ($\sim (2-3)$ s.d.) on the absolute values of $S_{17}(E_p)$. The authors of refs. [9] and [11] used in their calculations the value $S_{17} = (22.4 \pm 2.1)\text{ eV-b}$ derived by extrapolation in ref. [21] on the basis of the data from all six experiments.

A new method of experimental determination of S_{17} was proposed recently in ref. [22]. It is based on the idea of measuring the cross-section

of the inverse reaction, $\gamma + {}^8\text{B} \rightarrow {}^7\text{Be} + p$, by studying the dissociation of ${}^8\text{B}$ into $p + {}^7\text{Be}$ in the Coulomb field of a heavy nucleus, chosen to be ${}^{208}\text{Pb}$. The time-reversal symmetry guarantees that the cross-sections of (9) and of the inverse reaction should be equal. The extraction of the values of $\sigma_{17}(E_p)$ (and of $S_{17}(E_p)$) from the data on the process ${}^8\text{B} + {}^{208}\text{Pb} \rightarrow p + {}^7\text{Be} + {}^{208}\text{Pb}$ is not straightforward and is associated with certain subtleties (see, e.g., ref. [23]).

Using the first results of the experiment of Motobayashi et al. [22] on the reaction ${}^8\text{B} + {}^{208}\text{Pb} \rightarrow p + {}^7\text{Be} + {}^{208}\text{Pb}$ to determine $\sigma_{17}(E_p)$ for E_p in the interval $500\text{ keV} \lesssim E_p \lesssim 2000\text{ keV}$, the results of the most recent of the experiments on (9) of Filippone et al. [20] in the interval $(110 - 500)\text{ keV}$, and a new extrapolation model developed by them, the authors of ref. [12] obtain $S_{17} = 17 \pm 2\text{ eV-b}$.

Let us add that in ref. [10] the value of S_{17} derived in [21] and adopted in refs. [9,11] was also used, but with a larger systematical error, $S_{17} = (22.4 \pm 1.3 \pm 3.0)\text{ eV-b}$, introduced to account for the (systematic) difference between the data on $\sigma_{17}(E_p)$ from the experiments [19] and [20]. The results of ref. [10], apart from minor differences, are in a good agreement with the results of the version of the BP model [9] without ${}^4\text{He}$ diffusion.

The theoretical predictions for Φ_B can be affected by a change in the solar opacities used in the respective solar model calculations in [9-14] due to possible unaccounted for delicate collective plasma effects [24]. The latter can lead to a somewhat lower (by 1%-3%) value of the central temperature T_c in the Sun (in comparison with the values obtained in the current solar model calculations), and thus to a lower ${}^8\text{B}$ neutrino flux as $\Phi_B \sim T_c^{18}$ [17].

4. THE MISSING ${}^7\text{Be}$ NEUTRINOS

Even if one accepts that that Φ_B has the low value suggested in [12] (a view not shared by all experts in the field of solar modelling, see, e.g., the polemic in refs. [25] and [26]), or that there are large uncertainties in the predictions for the flux of ${}^8\text{B}$ neutrinos and in all analyses one should rather use for Φ_B the value implied by the Kami-

Figure 1. The normalized to one E-distributions of the signals due to the ^8B neutrinos in the Cl-Ar, Kamiokande and Ga-Ge detectors (from ref. [30]).

okande data, eq. (2), another problem arises: the predictions of all current solar models for the flux of ^7Be neutrinos, Φ_{Be} , are considerably larger than the value of suggested by the existing solar neutrino data. This was first noticed in refs. [27] and confirmed in several subsequent more detailed analyses [28–31] utilizing a variety of different methods. We shall present here an updated and somewhat modified version of the study performed in ref. [30]. It is based on the observation [30,32] that the normalized to one neutrino energy distributions of the signals due to the ^8B neutrinos in the Cl-Ar, Kamiokande and the Ga-Ge detectors, $dN_i^{\text{B}}(E)/dE$, $i = \text{Cl}, \text{K}, \text{Ga}$, are very similar (see Fig. 1). One has, in particular,

$$\frac{dN_{\text{Cl}}^{\text{B}}(E)}{dE} = \alpha \frac{dN_{\text{K}}^{\text{B}}(E)}{dE} + \beta(E), \quad (11)$$

where α is a positive constant close to 1 and $\beta(E)$ is a "small" (real) function of E . Searching for a maximal value of α under the condition $\beta(E) \geq 0$, the authors of ref. [30] find: $\max \alpha = 0.93$. This

implies

$$\frac{\Phi_{\text{B}}^{\text{SM}} n(E) \sigma_{\text{Cl}}(E)}{R_{\text{SM}}^{\text{B}}(\text{Cl})} \geq 0.93 \frac{\Phi_{\text{B}}^{\text{SM}} n(E) \sigma_{\text{K}}(E)}{R_{\text{SM}}(\text{K})}, \quad (12)$$

where $\Phi_{\text{B}}^{\text{SM}}$ is the total flux of ^8B neutrinos in a given reference solar model, $n(E)$ is the normalized to 1 spectrum of ^8B neutrinos, $\int_{14.4 \text{ MeV}} n(E) dE = 1$, $\sigma_{\text{Cl}}(E)$ is the cross-section

of the Pontecorvo–Davis reaction $\nu_e + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$, $\sigma_{\text{K}}(E)$ is the $\nu_e - e^-$ elastic scattering cross-section for ^8B neutrinos with energy E , in which the recoil e^- detection efficiency and energy resolution functions of the Kamiokande detector should be included (the authors of ref. [30] did not include in $\sigma_{\text{K}}(E)$ the detector's recoil e^- detection efficiency which, however, makes more conservative the conclusions we are going to reach), and

$$R_{\text{SM}}^{\text{B}}(\text{Cl}) = \Phi_{\text{B}}^{\text{SM}} \int_{E_{\text{th}}(\text{Cl})}^{14.4 \text{ MeV}} n(E) \sigma_{\text{Cl}}(E) dE, \quad (13)$$

and

$$R_{\text{SM}}(\text{K}) = \Phi_{\text{B}}^{\text{SM}} \int_{14.4 \text{ MeV}} n(E) \sigma_{\text{K}}(E) dE, \quad (14)$$

are the rate of ${}^{37}\text{Ar}$ production due to the ^8B neutrinos in the Cl-Ar experiment and the event rate in the Kamiokande detectors, respectively, predicted in the reference solar model. We have just used the explicit expressions for $dN_{\text{Cl},\text{K}}^{\text{B}}(E)/dE$ in terms of the ^8B neutrino flux, spectrum $n(E)$ and the corresponding cross-sections in writing (12). Note that eq. (11) and inequality (12), as it follows from (13) and (14), do not depend on $\Phi_{\text{B}}^{\text{SM}}$, and therefore are solar model independent.

Suppose that the ^8B neutrino flux predicted in the reference solar model (chosen by us to describe the data) differs due to unaccounted for astrophysical, and/or nuclear physics (and/or other) effects from the actual flux reaching the surface of the Earth. In all cases of practical interest the indicated effects can be parameterized by a real function $F(E) \geq 0$, such

that $\int_{E_{th}(Cl)} \Phi_B^{SM} n(E) \sigma_{Cl}(E) F(E) dE \equiv R^B(Ar)$ is the real contribution of 8B neutrinos in $R(Ar)$, and $\int_{14.4 \text{ MeV}} \Phi_B^{SM} n(E) \sigma_K(E) F(E) dE \equiv R_{obs}(K)$ is the event rate observed in the Kamiokande experiments. Multiplying both sides of inequality (12) by $F(E)$ and integrating them over E we get: $R^B(Ar)/R_{SM}^B(Ar) \geq 0.93 R_{obs}(K)/R_{SM}(K)$. Choosing for concreteness as a reference model the BP model [9] in which $\Phi_B^{BP} = 5.69 \times 10^6 \nu_e/\text{cm}^2/\text{sec}$ and $R_{BP}^B(Ar) = 6.2 \text{ SNU}$, and using the experimental result of the Kamiokande collaborations, eq. (2), we get:

$$R^B(Ar) \geq (2.94 \pm 0.40) \text{ SNU}. \quad (15)$$

The above inequality provides a lower bound on the contribution of 8B neutrinos to the signal in the Davis et al. experiment following from the Kamiokande data. Subtracting the minimal value of $R^B(Ar)$, determined by (15), from the total rate of ^{37}Ar production (1) observed by Davis et al., one finds for the contribution due to the ($^7Be + pep + CNO$) neutrinos to the signal in the Cl-Ar experiment:

$$R^{Be+pep+CNO}(Ar) \leq (-0.39 \pm 0.47) \text{ SNU}. \quad (16)$$

Given the solar model independent relation (6) between Φ_{pep} and Φ_{pp} , and that Φ_{pp} is rather tightly constrained by the data on the solar luminosity, we can consider as rather reliable (and weakly model dependent) the solar model predictions for $R_{SM}^{pep}(Ar) = (0.20 - 0.23) \text{ SNU}$. Taking $R^{pep}(Ar) = 0.20 \text{ SNU}$ one obtains from (16)

$$R^{Be}(Ar) \leq (-0.59 \pm 0.47) \text{ SNU}. \quad (17)$$

At 99.73% C.L. (3 s.d.) this implies $R^{Be}(Ar) \leq 0.82 \text{ SNU}$, which is smaller than the predictions of all current solar models, $R_{SM}^{Be}(Ar) = (1.1 - 1.3) \text{ SNU}$ [9-14].

Relation similar to (11) can be written also for $dN_{Ga}^B(E)/dE$ and $dN_K^B(E)/dE$ (see Fig. 1), introducing another real constant α' (the analog of α) and "small" (real) function $\beta'(E)$ (the analog of $\beta(E)$). In this case imposing the condition $\beta'(E) \geq 0$ the authors of ref. [30] find $\max \alpha' =$

0.81. Starting from this result and performing an analysis analogous to the one described above, we can utilize the Kamiokande data (2) to derive a solar model independent lower bound on the contribution of 8B neutrinos to the signal in the Ga-Ge experiments, $R^B(Ge)$. We find: $R^B(Ge) \geq (5.7 \pm_{-3.5}^{+7.0}) \text{ SNU}$, where the errors are determined by the uncertainties in the cross-section of the Ga-Ge reaction $\nu_e + ^{71}Ga \rightarrow e^- + ^{71}Ge$ induced by the 8B neutrinos [31]. Taking into account the predictions of the solar models for the contribution in $R(Ge)$ generated by the ($pp + pep$) neutrinos, $R^{pp+pep}(Ge) = (73 - 75) \text{ SNU}$, and the data from, e.g., the GALLEX collaboration (3), we get the following upper limit on the contribution of the 7Be neutrinos to $R(Ge)$:

$$R^{Be}(Ge) \leq (0.3 \pm_{-12.5}^{+14.0}) \text{ SNU}. \quad (18)$$

Thus, at 95% C.L. (2 s.d.) we have $R^{Be}(Ge) \leq 28.3 \text{ SNU}$, while all solar model predictions lie in the interval (31 - 38) SNU. The discrepancy is larger (at least 3 s.d.) if one utilizes the SAGE data (4), or the combined GALLEX - SAGE value (5) for $R(Ge)$.

Similar results have been obtained in refs. [28]. Quantitatively stronger conclusions about the incompatibility of the solar model predictions and the data on Φ_{Be} have been reached in ref. [31] using a somewhat different approach (as a starting point of the analysis the Kamiokande data on Φ_B and the relevant Cl-Ar and Ga-Ge reaction cross-sections are utilized to determine the 8B neutrino contribution in $R(Ar)$ and $R(Ge)$), and in ref. [29] on the basis of a χ^2 -analysis of the solar model description of the data, in which the total pp , pep , 7Be , 8B and CNO neutrino fluxes are treated as free parameters subject only to the luminosity constraint (8), while the spectra of solar neutrinos were assumed to coincide with the predicted ones in the absence of unconventional neutrino behaviour (as oscillations in vacuum, etc.).

Thus, there are very strong indications from the already existing solar neutrino data that the flux of 7Be (electron) neutrinos is considerably smaller than the flux obtained in the current solar models. Given the results of the GALLEX calibration experiment, we can conclude that both

the Davis et al. and the Kamiokande data (2) and (3) have to be incorrect in order for the above conclusion to be not valid. The discrepancy between the value of Φ_{Be} suggested by the analyses of the existing solar neutrino data and the solar model predictions for Φ_{Be} represents the major new aspect of the solar neutrino problem. No astrophysical and/or nuclear physics explanation of this discrepancy has been proposed so far.

5. 8B AND 7Be NEUTRINO FLUXES AND THE VACUUM OSCILLATION AND MSW SOLUTIONS

We have seen that there can be large uncertainties in the solar model predictions for the total flux of 8B neutrinos and that the predictions for the 7Be neutrino flux vary by $\sim 20\%$. The next question we would like to discuss briefly is how stable are the well known vacuum oscillation and MSW solutions of the solar neutrino problem (see Figs. 2 and 3 and, e.g., refs. [33] and [34]) with respect to Φ_B and Φ_{Be} variations. A rather comprehensive answer to this question for the MSW solution with solar ν_e transitions into an active neutrino, $\nu_e \rightarrow \nu_{\mu(\tau)}$, was given in ref. [35] (see also refs. [36]), and for the vacuum oscillation solution (for both cases of $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ and $\nu_e \leftrightarrow \nu_s$ oscillations), as well as for the MSW solution with ν_e transitions into a sterile neutrino, $\nu_e \rightarrow \nu_s$, in ref. [37]. The behaviour of the solution based on the $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ oscillation hypothesis with respect to changes of Φ_B and Φ_{Be} in certain intervals around the values in the reference model [9] was studied also in ref. [38].

It is convenient to introduce the parameters

$$f_B \equiv \frac{\Phi_B}{\Phi_B^{BP}} \geq 0, \quad f_{Be} \equiv \frac{\Phi_{Be}}{\Phi_{Be}^{BP}} \geq 0, \quad (19)$$

in terms of which we shall describe the possible variations of Φ_B and Φ_{Be} , where Φ_B^{BP} and Φ_{Be}^{BP} are the two fluxes in the reference BP model [9].

The Kamiokande data, evidently, imposes limits on the values Φ_B (and f_B) can possibly have. The expression for the predicted event rate in the Kamiokande detector if the 8B (electron) neutri-

Figure 2. Regions of values of the parameters Δm^2 and $\sin^2 2\theta$ for which the MSW $\nu_e \rightarrow \nu_{\mu(\tau)}$ (a) and $\nu_e \rightarrow \nu_s$ (b) transitions of solar ν_e describe at 90% (dashed lines) and 95% (solid lines) C.L. the solar neutrino data (from ref. [39]). The results are obtained using the predictions (including their estimated uncertainties) of ref. [9].

nos undergo two-neutrino transitions into an active neutrino $\nu_{\mu(\tau)}$ (due to vacuum oscillations $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ or MSW transitions $\nu_e \rightarrow \nu_{\mu(\tau)}$), or $\bar{\nu}_{\mu(\tau)}$ (due to spin-flavour conversion $\nu_e \rightarrow \bar{\nu}_{\mu(\tau)}$) on their way to the Earth has the form:

$$R(K) = f_B \Phi_B^{BP} \int_{14.4 \text{ MeV}}^{\infty} n(E) \sigma_K(E) [P(E) + 0.16(1 - P(E))] dE, \quad (20)$$

where $P(E)$ is the probability of survival of the ^8B ν_e having energy E , $0 \leq P(E) \leq 1$, $((1 - P(E)))$ is the probability of the $\nu_e \rightarrow \nu_{\mu(\tau)}$ transition due to vacuum oscillations or the MSW effect, or of the $\nu_e \rightarrow \bar{\nu}_{\mu(\tau)}$ conversion), and we have used the fact that $\sigma_{\nu_{\mu(\tau)}e}(E)/\sigma_{\nu_e e}(E) \cong \sigma_{\bar{\nu}_{\mu(\tau)}e}(E)/\sigma_{\nu_e e}(E) \cong 0.16$ in the energy range of interest, $\sigma_{\nu_l e}(E)$ and $\sigma_{\bar{\nu}_l e}(E)$, $l=e, \mu, \tau$, being the $\nu_l - e^-$ and $\bar{\nu}_l - e^-$ elastic scattering cross-sections. In the case of $\nu_e \leftrightarrow \nu_s$ oscillations or $\nu_e \rightarrow \nu_s$ transitions the term with the coefficient 0.16 is absent from the expression in the right hand side of eq. (20).

Given $R(K)$, Φ_B^{BP} , $n(E)$ and $\sigma_K(E)$, the minimal allowed value of f_B , as it follows from (20), is determined by the maximal possible value of $[P(E) + 0.16(1 - P(E))]$, which is 1 and is reached when $P(E) = 1$. Thus, we have $f_B \geq R(K)/R_{\text{BP}}(K) = (0.51 \pm 0.07)$, where $R_{\text{BP}}(K)$ is the event rate predicted in the BP model [9], and we have used the result of the Kamiokande experiment. At 99.73% (95%) C.L. this implies

$$f_B \geq 0.30 \text{ (0.37)}. \quad (21)$$

It is trivial to convince oneself that the above lower limit on f_B holds also in the case of solar ν_e two-neutrino oscillations or transitions into sterile neutrino ν_s , as well as for oscillations or transitions involving more than two neutrinos (sterile and/or active). The limit (21) is universal: it does not depend on the type of possible transitions, and on the specific mechanism responsible for them.

Similarly, the maximal allowed value of f_B by the Kamiokande data corresponds to $\min [P(E) + 0.16(1 - P(E))] = 0.16$. We have then: $f_B \leq R(K)/(0.16 R_{\text{BP}}(K)) = (3.2 \pm 0.44)$, which gives at 99.73% (95%) C.L.

$$f_B \leq 4.5 \text{ (4.1)}. \quad (22)$$

Note that inequality (22) is universal for two-neutrino solar ν_e transitions into active neutrino $\nu_{\mu(\tau)}$ or $\bar{\nu}_{\mu(\tau)}$: it does not depend on the transition mechanism.

Contrary to the lower limit (21), the upper limit (22) is not valid for two-neutrino $\nu_e \leftrightarrow \nu_s$ ($\nu_e \rightarrow \nu_s$) oscillations (transitions) or ν_e oscillations (transitions) involving more than two neu-

trinos. In the first case, for instance, the maximal value of f_B would correspond to the $\min P(E)$, and the use of the general property of the probability $P(E)$, $\min P(E) = 0$, does not allow one to derive a useful upper limit on f_B from the Kamiokande data.

Owing to the specific dependence of the MSW two-neutrino transition probability on the neutrino energy E , however, which for certain interval of values of E (in the case of adiabatic solar ν_e transitions) satisfies [5] $\min P_{\text{MSW}}(E) \cong \sin^2 \theta$, where θ is the neutrino mixing angle in vacuum (one of the two parameters characterizing the two-neutrino vacuum oscillations and MSW transitions, see refs. [4,5,33,34]), it is possible to derive a somewhat constraining upper bound on f_B in the case of $\nu_e \rightarrow \nu_s$ MSW transitions [37]:

$$\text{MSW, } \nu_e \rightarrow \nu_s : f_B \leq 90 \text{ (80)}. \quad (23)$$

It corresponds to $\min P(E) \cong \sin^2 \theta \cong 8.1 \times 10^{-3}$, and represents the 99.73% (95%) C.L. limit. For values of $\sin^2 \theta$ different from the indicated one the suppression (due to $P_{\text{MSW}}(E)$) of the integral entering into the expression for $R(K)$, as can be shown, is weaker and the upper bound on f_B one gets is not an absolute upper bound.

Obviously, the minimal value of f_B for which a given solar ν_e transition mechanism provides a description of the solar neutrino data at 99.73% (95%) C.L. may be larger than the absolute minimum value in (21). Similar remark is valid for the maximal value of f_B in the relevant cases of neutrino physics solutions and the absolute maxima in eqs. (22) and (23).

Let us add that the fluxes Φ_B and Φ_{B_e} in the models [9]–[12] correspond, respectively, to $f_B = 1.0; 0.78; 1.14; 0.50$, and $f_{B_e} = 1.0; 0.89; 1.06; 0.88$.

The studies performed in refs. [34,40] have shown that the MSW solution of the solar neutrino problem exists for each of the four specific models [9–12] discussed by us. Analyses based on the models [9] and [10] demonstrated that the solar ν_e oscillations $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ also provide a solution (in the framework of the indicated solar models) [33], while the $\nu_e \leftrightarrow \nu_s$ oscillations were shown to be excluded (at 99% C.L.) as a possible solution of the solar neutrino problem by the

Figure 3. Regions of values of the parameters Δm^2 and $\sin^2 2\theta$ for which the solar neutrino data can be described at 95% C.L. in terms of $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ oscillations of solar ν_e for $f_{Be} = 1.0$ (from ref. [37]).

(mean event rate) solar neutrino data (1) – (4) (see the last two articles quoted in ref. [33]).

In the studies of the stability of the vacuum oscillation and the MSW solutions with respect to Φ_B and Φ_{Be} variations performed in refs. [35,37] the following approach was adopted. The fluxes of the pp, pep and the CNO neutrinos were kept fixed and their values were taken from ref. [9]. The fluxes of the 8B and 7Be neutrinos, and correspondingly, f_B and f_{Be} , were treated as fixed parameters, which, however, were allowed to take any values within certain intervals. In the case of Φ_{Be} the interval chosen corresponds to $0.7 \leq f_{Be} \leq 1.3$, while for Φ_B values in intervals slightly narrower than those determined (depending on the case) by the inequalities (21) and (22), or (21) and (23), were considered. The searches for a

$\nu_e \leftrightarrow \nu_s$ oscillation solution were performed for $0.3 \leq f_B \leq 4.0$. The indicated choices were motivated by the fact that the contributions of the CNO neutrinos to the signals in all three types of detectors [2,6–8] are relatively small, and that the spreads in the predictions for the fluxes Φ_B and Φ_{Be} are the largest. Some of the values of Φ_{Be} used in the analyses, as those corresponding to $f_{Be} = 0.7$ and 1.3 , for instance, are obviously incompatible with the luminosity constraint (8). However, a 20% – 30% change in Φ_{Be} with respect to Φ_{Be}^{BP} is required by (8) to be balanced by only a few percent change of the pp neutrino flux, and the latter will have a small effect on the predictions for the signal in the Ga-Ge experiments. Besides, the aim of the studies was, in particular, to determine the ranges of values of Φ_B and Φ_{Be} for which the possibilities of vacuum oscillations and MSW transitions of solar neutrinos cannot be excluded by the existing solar neutrino data.

In the analyses performed in refs. [35,37] the χ^2 -method was utilized. It was found that at 95% C.L. the two-neutrino vacuum oscillations $\nu_e \leftrightarrow \nu_{\mu(\tau)}$, or the MSW transitions $\nu_e \rightarrow \nu_{\mu(\tau)}$ or $\nu_e \rightarrow \nu_s$, of the solar ν_e allow one to describe the solar neutrino data for rather large intervals of values of f_B for $0.7 \leq f_{Be} \leq 1.3$. These intervals depend somewhat on the value of f_{Be} chosen. Below we list only the overlapping parts of the intervals of the allowed values of f_B corresponding to the all different values of f_{Be} considered:

$$\nu_e \leftrightarrow \nu_{\mu(\tau)} : \quad 0.60 \leq f_B \leq 3.3 \quad [37], \quad (24)$$

$$\nu_e \leftrightarrow \nu_s : f_{Be} \cong 1.0, \quad 0.35 \leq f_B \leq 0.40, \quad [37] \quad (25)$$

$$\nu_e \rightarrow \nu_{\mu(\tau)} : \quad 0.38 \leq f_B \leq 3.3 \quad [35], \quad (26)$$

$$\nu_e \rightarrow \nu_s : \quad 0.38 \leq f_B \leq 60 \quad [37]. \quad (27)$$

In the case of $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ oscillations, for instance, a description of the data exists for $0.43 \leq f_B \leq 3.3$ if $f_{Be} \cong 0.7$ (to be compared with eq. (24)). The regions of values of the two parameters Δm^2 and $\sin^2 2\theta$ characterizing the $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ ($\nu_e \leftrightarrow \nu_s$) oscillations and the $\nu_e \rightarrow \nu_{\mu(\tau)}$ ($\nu_e \rightarrow \nu_s$) MSW transitions, corresponding to the values of f_B and f_{Be} for which one finds a description of the solar neutrino data, were also determined. Some examples of these regions corresponding to the

Figure 4. Regions of values of the parameters Δm^2 and $\sin^2 2\theta$ for which the solar neutrino data can be described at 95% C.L. in terms of $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ oscillations of solar ν_e for $f_{Be} = 0.7$ (from ref. [37]).

case of $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ oscillations are shown in Fig. 3 ($f_{Be} = 1.0$) and Fig. 4 ($f_{Be} = 0.7$).

It follows from the above results, in particular, that [37] new vacuum oscillation solutions of the solar neutrino problem appear at 95% C.L. for $f_{Be} \cong 1.0$ and $0.35 \leq f_B \leq 0.40$ in both cases of $\nu_e \leftrightarrow \nu_{\mu(\tau)}$ and $\nu_e \leftrightarrow \nu_s$ oscillations. They correspond respectively to $5 \times 10^{-12} \text{ eV}^2 \lesssim \Delta m^2 \lesssim 6 \times 10^{-12} \text{ eV}^2$ and $0.9 \lesssim \sin^2 2\theta \leq 1.0$, and to $4.3 \times 10^{-12} \text{ eV}^2 \lesssim \Delta m^2 \lesssim 7 \times 10^{-12} \text{ eV}^2$ and $0.65 \lesssim \sin^2 2\theta \leq 1.0$. Not also that the MSW solution with solar ν_e transitions into a sterile neutrino exists even for very large values of f_B , for instance, for $f_B \cong 60$.

The general conclusion the results (24) – (27) lead to is that the vacuum oscillation and the MSW solutions of the solar neutrino problem are

remarkably stable with respect to changes of the predictions for the ^8B and ^7Be neutrino fluxes.

6. OUTLOOK

After being with us for ~ 20 years the solar neutrino problem still remains unsolved. With the accumulation of the quantitatively new data provided by the Ga-Ge experiments the problem acquired a novel aspect: the constraints on the ^7Be neutrino flux following from the data imply a considerably smaller value of Φ_{Be} than is predicted by the solar models. The data of both Davis et al. and Kamiokande experiments have to be incorrect in order for the indicated conclusion to be not valid. The vacuum oscillations and MSW transitions of the solar neutrinos continue to be viable and very attractive solutions of the problem.

Our hopes for finding the cause of the solar neutrino problem are associated at present with the future second generation solar neutrino experiments: SNO [41], Super Kamiokande [42], BOREXINO [43], ICARUS [44], HELLAZ [45] and other. Two of these detectors – SNO and Super Kamiokande, are under construction and are planned to begin to take data in 1996; BOREXINO and ICARUS are at the stage of prototype construction and/or testing, and the possibilities to build HELLAZ are being studied. All these are planned to be high statistics, i.e., high precision, experiments (typically ~ 3000 events/year) with real time event detection. The SNO and Super Kamiokande detectors will be sensitive to the ^8B component of the solar neutrino flux. In the SNO experiment the ^8B neutrinos will be detected via the charged current and the neutral current reactions on deuterium: $\nu_e + D \rightarrow e^- + p + p$, and $\nu + D \rightarrow \nu + p + n$; the measurement of the kinetic energy of the electron in the first reaction will permit to reconstruct the energy of the ν_e and thus to measure the spectrum of ^8B neutrinos for $E \geq 6.44$ MeV. Information about the spectrum of ^8B neutrinos at $E \geq 5$ MeV will be obtained also in the Super Kamiokande experiment in which the energy of the recoil electron from the $\nu - e^-$ elastic scattering reaction will be measured with a rather high accuracy. Ap-

proximately 90% of the signal induced by the solar neutrinos in the BOREXINO detector (~ 50 events/day according to the reference model [9]) is predicted to be due to the ^7Be -neutrinos. The HELLAZ detector would be sensitive to the pp and the ^7Be ($E = 0.86$ MeV) components of the solar neutrino flux. The HELLAZ apparatus is envisaged to have the technical capabilities to measure the spectrum of the pp neutrinos at $E \gtrsim 100$ keV. The high statistics these experiments will accumulate, the measurement of the spectrum of the ^8B neutrinos with the SNO and Super Kamiokande detectors, and of the ratio of the charged current and the neutral current reaction rates with the SNO detector, will make it possible to perform crucial tests of the vacuum oscillation and the MSW [39], as well as of the other possible neutrino physics solutions [46,47] of the solar neutrino problem. We are at the dawn of a major breakthrough in the studies of the solar neutrinos.

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