SOLAR NEUTRINO OSCILLATIONS

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ABSTRACT

The current status of oscillation solutions to the Solar Neutrino Problem is reviewed. Four oscillation solutions are discussed in the light of 708d Superkamiokande data: MSW, Just-So VO, VO with Energy-Independent Suppression (EIS) and Resonant-Spin-Flavor-Precession (RSFP). Only EIS VO is strongly disfavoured by the global rates, mostly due to the Homestake data. Vacuum oscillations give an interesting solution which explains high-energy excess of events observed by Superkamiokande and predicts *semi-annual* seasonal variation of Be-neutrino flux. There are indications to these variations in the GALLEX and Homestake data. No direct evidence for oscillation is found yet.

1. Introduction

With Superkamiokande in operation and SNO in preparation the study of solar neutrinos has entered a decisive stage, when neutrino oscillations can be directly discovered. At present we know almost certainly that something happens to neutrinos either inside the Sun or on the way between the Sun and Earth. This knowledge has been provided mainly by solar-neutrino experiments, by helioseismic observations and by theoretical analysis.

1. *Helioseismic data* confirm the Standard Solar Models (SSM's) with precision sufficient for reliable prediction of solar-neutrino fluxes. The seismic data (in agreement within a fraction of percent with the SSM predictions) are valid down to radial distance $0.05R_\odot$, where production of B- and Be - neutrinos has maximum, while the other neutrinos are mostly produced at larger distances. For the smaller radial distances, where production of neutrinos falls down due to decreasing of volume, the seismic data still exist, though with worse precision.

Acoustic frequencies comprise the set of seismic data. Nothing in physics is measured with greater precision than frequencies. This is why seismic measurements give the super-precise data on density and sound speed inside the Sun. Within fraction of percent seismically measured density and sound speed are different from the SSM predictions (especially at distance $0.7R_\odot$) and this difference is statisticlally significant. It might imply that some physical processes are not included in SSM's, and they are of great interest for physics of the Sun. But not for solar neutrinos! This statistically significant difference, *e.g.* in measured and predicted sound speed, produces negligible difference in neutrino fluxes, which is out of interest for any present (and most probably for any future) solar-neutrino experiment.

Almost for half century we thought that solar neutrinos with their tremendous penetrating power give us the best way to look inside the Sun. We see now that seismic observations do it with higher precision, while solar neutrinos provide us with the unique information about neutrino properties.

2. *Nuclear cross-sections* is now the dominat source of uncertainties in the calculated solar-neutrino fluxes. The impressive progress exists here too. In the LUNA experiment at Gran Sasso the cross-section of one of the most intriguing reaction,$^3He +^3 He \to^4 He + 2p$, was measured at energy corresponding to maximum of the Gamow peak in the Sun. The famous speculations about solving or ameliorating the SNP due to increase of this cross-section at very low energy, have been now honorably buried. In the nearest future most of cross-sections relevant to SNP will be measured in the LUNA experiment at very low energy. There is also considerable progress in calculations of cross-sections and screening of nuclear reactions in the solar plasma. A rather exceptional case is cross-section of Hep reaction $p +^3He \to^4He + e^+ + \nu$, in which neutrinos with the highest energies are produced. Uncertainties in calculation of this cross-section are very large.

3. *Solar Neutrino Problem (SNP)* is a deficit of neutrino fluxes (as compared to the SSM prediction) detected in all solar-neutrino experiments (Homestake, SAGE, GALLEX, Kamiokande and Superkamiokande). This deficit is described by factor ~ 3 for Homestake and by factor ~ 2 for all other experiments.

4. *Astrophysical solution* to SNP is strongly disfavoured by combination of any two solar-neutrino experiments, *e.g.* the boron and chlorine experiments (Superkamiokande and Homestake) or the gallium and boron experiments (GALLEX/SAGE and Superkamiokande). The ratio of Be to B neutrino fluxes, extracted from each pair of experiments mentioned above, is negative (or too small). This is the essence of failure of astrophysical solution. The arbitrary variation of temperature and unknown cross-sections do not solve a problem of Be/B ratio.

Solar neutrino experiments have a status of disappearance oscillation experiment.

But solar-neutrino oscillations are not proved yet. In this paper I will discuss the status of different oscillation solutions to SNP.

2. Status of Astrophysical Solution to SNP

The global rates of four solar-neutrino experiments [1,2,3,4], as reported up to 1999, are listed in Table 1 and compared with calculations of Bahcall and Pinsonneault [5].

The deficit of detected neutrino fluxes seen in the last column of Table 1 is impossible to explain by astrophysics or/and nuclear physics. This conclusion is based on the following.

(i) Compatibility of the boron (Superkamiokande) and chlorine (Homestake) signals or boron and gallium (GALLEX/SAGE) signals results in unphysically small ratio

Table 1. The solar-neutrino data of 1998 compared with the SSM prediction , Bahcall and Pinnsoneault 1998 [5]. The data of Superkamiokande are given in units $10^6\ cm^{-2}s^{-1}$.

	DATA	SSM [5]	DATA/SSM
SUPERK	2.42 ± 0.08	5.15	0.47 ± 0.02
GALLEX (SNU)	77.5 ± 7.7	129	0.60 ± 0.06
SAGE (SNU)	66.6 ± 8.0	129	0.52 ± 0.06
HOMEST (SNU)	2.56 ± 0.23	7.7	0.33 ± 0.03

$\Phi_\nu(Be)/\Phi_\nu(B)$ [6)-15)]. The best fit value of this ratio is negative. The statement above is model-independent.

(ii) The arbitrary variation of unknown nuclear cross-sections and the central temperature cannot bring $\Phi_\nu(Be)/\Phi_\nu(B)$ ratio in agreement with observations [16].

(iii) Seismic observations of the density and sound speed radial profiles confirm SSM at distances down to $0.05R_\odot$ with accuracy better than fraction of percent [17)-20)] and at the center with accuracy better than 4% for sound speed [21].

(iv) As minimum, SSM is a good approximation to realistic model of the Sun. In this case there must be a track, when changing the parameters of SSM and/or introducing the new physical phenomena, one arrives from SSM neutrino fluxes to the observed ones. Such a track does not exist [15].

We shall analyze the last item at some details. But two comments are in order now.

There are two other, more model-dependent arguments against astrophysical solution to SNP.

If one takes three major components of neutrino fluxes (pp, Be and B) as independent and positive, and the CNO neutrino flux (which gives much smaller contribution) - according to SSM, then arbitrary variation of those three fluxes do not give acceptable fit to the observational data at 99.99%CL [22].

The deficit of B neutrinos seen in the Superkamiokande data (Table 1) is another problem for astrophysical solution. Some time ago many people thought that with extreme and correlated uncertainties in pBe-cross-section and in the central temperature T_c this discrepancy can be eliminated. Now the situation looks like follows. In the helioseismically constrained solar models (HCSM) [23] the central temperature $T_c = 1.58 \cdot 10^7\ K$ within maximum uncertainty $\Delta T_c/T_c = 1.4\%$. Taking T_c 1.4% lower and S_{17} 40% lower we obtain the minimum B-neutrino flux $3.0 \cdot 10^6\ cm^{-2}s^{-1}$, *i.e.* 7.4σ higher than the measured one. The most recent attempt [24,25,26] to reconcile the astrophysical solution with measured neutrino fluxes involves an old idea of ^3He-mixing in the solar core. In SSM's ^3He-abundance is very low in the Be, B-neutrino production zone. ^3He is accumulated at much larger distance $r \sim 0.3R_\odot$. It is assumed that due to some process (it could be gravity wave induced diffusion [25]) or non-linear instability [24]) the "fresh" ^3He is brought into solar core. It could happen as the short repeating episodes. Then neutrinoless channel in nuclear reactions, $^3He +^3He \to ^4He + 2p$, is enhanced and the central temperature T_c decreases too.

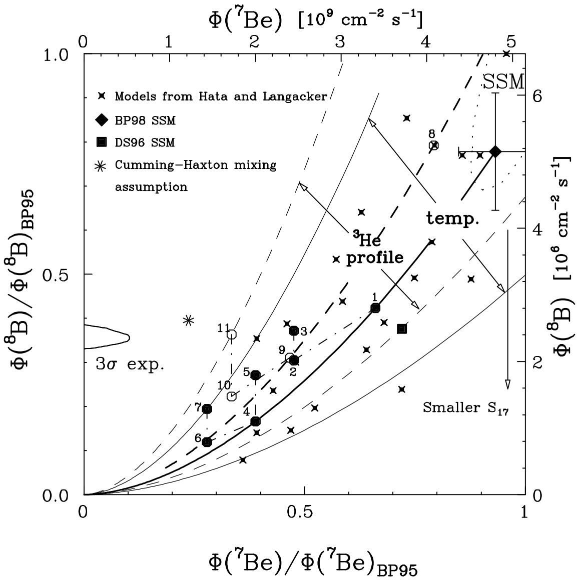

Fig. 1. *Neutrino fluxes allowed by arbitrary ^3He mixing accompanied by independent variations of temperature, S_{34} and S_{17}. The solid lines limit the allowed region in case ^3He radial profile is the same as in SSM, and the dashed lines limit the region when both, temperature and ^3He profiles are varying. Some trajectories from the SSM allowed regions are shown for illustration. The best fit is given by point 11, separated by more than 6σ from experimentally allowed region (shown as "3σ exp." in the figure).*

A general analysis of astrophysical solution, which includes arbitrary ^3He-mixing has been recently performed in ref.([27]). The ^3He-mixing was assumed not to be accompanied by mixing of other elements. Additionally all other relevant parameters in the neutrino production zone were varying within wide range: T_c - within $\pm 5\%$, S_{17} - within $\pm 40\%$ and S_{34} - in the range $(-20\% + 40\%)$. The temperature and ^3He radial profiles were also varying. The results are presented in Fig.1 as allowed regions between two limiting curves, thin solid ones ("temp.") and two broken ones ("^3He profile"). The best fit is at least 6σ away from observationally allowed region. It can be interpreted as well that there is no allowed track from the SSM's region ("SSM") to the observationally allowed region (see Fig.1). A trajectory with variation of temperature T_c is shown by thick solid line ("temp.")

3. Oscillation Solutions

Due to oscillations, electron neutrino emitted from the Sun can be found at the

Earth as neutrino with another flavor: muon, tau or sterile neutrino. These neutrinos either do not give a signal in the detector (*e.g.* muon neutrinos in gallium or chlorine detectors) or interact weaker due to NC (*e.g.* muon- or tau-neutrinos in Superkamiokande). I will not discuss in this review sterile neutrinos. Atmospheric neutrino oscillations imply that ν_μ and ν_τ neutrinos are maximally mixed. In this case solar ν_e neutrino oscillates with equal probability to each of those neutrinos.

The probability to find emitted electron neutrino in the same flavor state in the detector $P_{\nu_e\to\nu_e}$ is called survival probability or (less precisely) suppression factor. In general case survival probability depends on energy, $P_{\nu_e\to\nu_e}(E)$, *i.e.* solar neutrinos are suppressed in energy-dependent way and actually this property allows to solve SNP with help of oscillations.

Four oscillation solutions are currently discussed in the literature (see Table 2.)

Table 2. Oscillation Solutions to SNP.

	$\sin^2 2\theta$ best fit	Δm^2 (eV^2) best fit
MSW		
SMA	$6.0 \cdot 10^{-3}$	$5.4 \cdot 10^{-6}$
LMA	0.76	$1.8 \cdot 10^{-5}$
LOW	0.96	$7.9 \cdot 10^{-8}$
VO		
Just-so	0.75	$8.0 \cdot 10^{-11}$
EIS	~ 1	$10^{-9} - 10^{-3}$
RSFP		
	small	$10^{-8} - 10^{-7}$

1. *MSW solution* [28].

MSW effect in the Sun is a resonance conversion of ν_e into ν_μ or ν_τ. For neutrino energies at interest it occurs in the narrow layer, $\Delta R \sim 0.01 R_\odot$, at the distance $R \sim 0.1 R_\odot$ from the center of the Sun. There are three MSW solutions to SNP , which explain the global rates in all four solar-neutrino experiments: Small Mixing Angle (SMA) MSW, Large Mixing Angle (LMA) MSW and LOW solution with low probability (it appears only at $99\% CL$). The best fits of these solutions to the rates are reported in Table 2.

2. *Vacuum Oscillations (VO)*

The concept of vacuum oscillations was first put forward by B.Pontecorvo [29] (for a review see [30]). The survival probability for ν_e neutrino with energy E at distance r is given by

$$P_{\nu_e\to\nu_e} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} r\right), \tag{1}$$

where $l_v = 4\pi E/\Delta m^2$ is the vacuum oscillation length. At $\Delta m^2 = 8 \cdot 10^{-11}$ eV^2 (the best fit) the oscillation length of neutrino with energy $E_\nu \sim 3$ MeV is $l_\nu \sim 1 \cdot 10^{13}$ cm, *i.e.* of order of distance between the Sun and Earth. That is why this VO solution is called *just-so*. Since observational data need large suppression of neutrino flux, by factor ~ 2, $\sin^2 2\theta \sim 1$ is needed: see Eq.(1). Thus just-so VO solution must be large mixing angle solution. The best fit values are given in Table 2.

3. *EIS VO solution*

VO with Energy Independent Suppression (EIS) occurs when $\Delta m^2 \gg 10^{-10}\ eV^2$. In this case the oscillation length is much smaller than distance between the Sun and Earth. Oscillatory function in Eq.(1) is averaged to factor 1/2 and hence suppression factor is energy independent and equals to $1 - \frac{1}{2}\sin^2 2\theta$. Since this suppression should be of order 0.5, $\sin^2 2\theta \sim 1$ is needed. On the other hand one must assume $\Delta m^2 \ll 10^{-3}\ eV^2$ because of non-observation of ν_e oscillation in the atmospheric neutrinos.

The energy independent suppression is excluded by observed rates at $99.8\% CL$ [22)]. However, the Homestake data give the dominant contribution to this conclusion. If these data are arbitrarily excluded from analysis, EIS VO survives. I will not give more attention to discussion of EIS VO solution. Further details a reader can find in references [31,32,33,34)].

4. *RSFP solution*

The Resonant Spin-Flavor Precession (RSFP) describes two physical effects working simultaneously: the spin-flavor precession, when neutrino spin (coupled to magnetic moment) precesses around magnetic field, changing simultaneously neutrino flavor, and the resonant, density-dependent effect, which produces difference in potential energy of neutrinos with different flavors (similar to the MSW effect). This complex transition occurs in the external magnetic field due to presence of non-diagonal (transition) neutrino magnetic moments. The RSFP was first recognized in ref.'s [35,36)]. For excellent review see [37)].

This theory had a predecessor. The precession of neutrino magnetic moment around magnetic field converts left-chiral electron neutrino ν_{eL} into sterile right component ν_{eR}, suppressing thus ν_e-flux[38)]. However, the suppression effect in this case is energy-independent and thus contradicts to the observed solar-neutrino rates. In ref's [38,39)] the matter effect was included and in [40)] spin-flavor precession was discovered. The observed rates in solar-neutrino experiments can be explained only by the RSFP, because only this type of precession give the energy-dependent suppression factor. Majorana neutrino can have only transition magnetic moment. RSFP induces the transition ν_{eL} to $\bar{\nu}_{\mu R}$, i.e. electron neutrino to muon antineutrino, which can scatter off the electron due to NC. The survival probability is similar to that of SMA MSW (see Fig.3 from [41)]). Neutrino mixing is not needed directly for RSFP effect, but it is needed indirectly to provide the transition magnetic moment of the Majorana neutrino. To be a solution to SNP, RSFP needs a transition magnetic moment $\mu \sim 10^{-11}\mu_B$, magnetic field in the resonance layer of the Sun, $B \sim 20 - 100\ kG$ and Δm^2 in the range $10^{-8} - 10^{-7}\ eV^2$ (see Section 6).

4. Signatures of Oscillation Solutions

A common signature of most neutrino oscillation solutions is distortion of B-neutrino spectrum. The survival probabilities for SMA MSW, LMA MSW and just-so VO are shown in Fig.2. The survival probabilities for RSFP are similar to SMA MSW and shown in Fig.3.

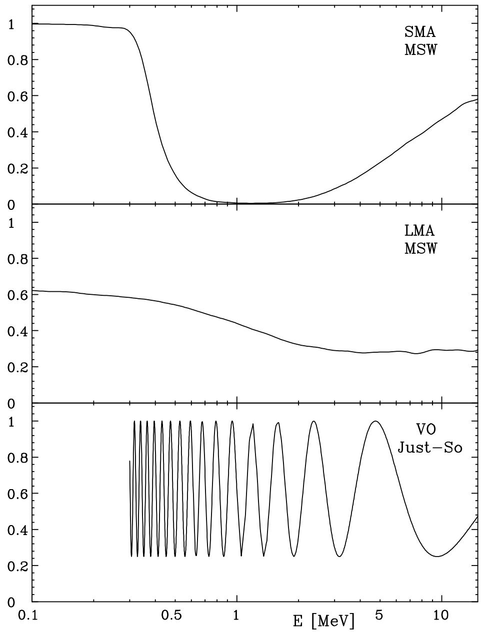

Fig. 2. *Electron neutrino survival probabilities as function of neutrino energy.*

One can see there that LMA MSW (and LOW too) predicts small distortion of B-neutrino spectrum spectrum in the region of observation $5-15\ MeV$. For EIS VO the distortion is absent. The strongest spectrum distortion one can expect for SMA MSW and just-so VO. However, spectrum of recoil electrons are distorted weaker than that of neutrinos, because of cross-section and averaging over energy bins in observations (*e.g.* see Fig.8). *The absence of distortion of neutrino or recoil-electron spectra is not a general argument against neutrino oscillations.*

Anomalous NC/CC ratio is another common signature of neutrino oscillations which can be observed in SNO. The NC events will be seen there by detection of neutrons produced in $\nu + D \to p + n + \nu$ reaction. Oscillation $\nu_e \to \nu_\mu(\nu_\tau)$ does not change NC interaction but changes CC interaction and thus the ratio of NC/CC rate. In case of oscillation to sterile neutrino the NC/CC ratio is not changed. Therefore, *the normal ratio NC/CC is not a general argument against neutrino oscillations.*

MSW solutions have very specific signatures which are unique. They are day/night effect, zenith angle dependence of solar-neutrino flux and difference in day/night

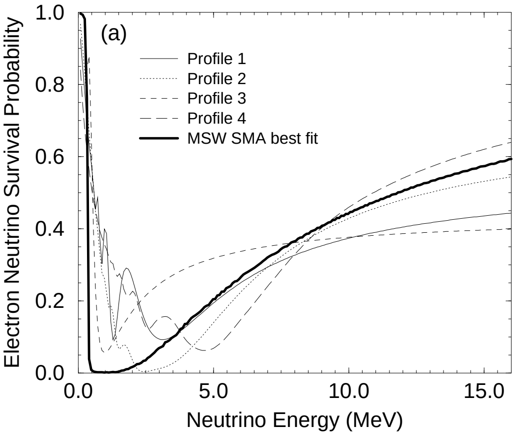

Fig. 3. *RSFP survival probabilities from* [41] *compared with SMA MSW (best fit) survival probability, shown by thick solid line. The four other curves correspond to different radial profiles of magnetic field.*

neutrino spectra. All these effects are caused by the MSW matter effect in the Earth. Another related effect is seasonal variation of neutrino flux caused by longer nights in the winter. This effect is smaller than integrated day/night effect. For recent calculations and references see [42].

The signature of *just-so VO* is anomalous seasonal variation of neutrino flux [43]. Due to ellipticity of the Earth's orbit, the distance between the Sun and Earth changes with time, causing the universal 7% variation of the flux due to r^{-2} effect ("geometrical" seasonal variation). As a result of just-so VO the flux of ν_e neutrinos changes additionally due to dependence of survival probability (1) on distance. This effect is absent for MSW solution, because vacuum oscillation length is too small. As follows from Eq.(1) neutrinos with different E have different phases and it weakens the observed effect, since finite energy interval ΔE is used in measurements. In case of monochromatic Be neutrinos the VO seasonal variations are strongest, in contrast to seasonal MSW variations, which are very small at this energy. For the detailed calculations of VO anomalous seasonal variations see [44] and for the recent calculations [45,46,47,48,49].

For *EIS VO solution* the anomalous seasonal variations are absent, because the oscillation length is too small. It results in a signature, which can be observed by BOREXINO: Be-neutrino flux is suppressed by a factor ~ 2, but does not show anomalous seasonal variations.

RSFP has two signatures:
As a result of RSFP electron neutrinos oscillate inside the Sun into muon/tau antineutrinos. Due to vacuum oscillations on the way to the Earth these neutrinos oscillate to electron antineutrinos. The latter oscillations are suppressed by mixing angle, which is small in case of RSFP. However, even small fluxes of electron antineutrino can be

reliably detected (*e.g.* by KamLand [50]).

The second signature is prediction of 11-year periodicity for Be-neutrino flux [37]. RSFP occurs in the resonant layers, which are located at different distances for neutrinos of different energies: for pp and B neutrinos the resonant layers are located near the solar center and at the periphery, respectively, where magnetic field is weak and RSFP too. The resonant layer for Be neutrinos is located at intermediate distance, where magnetic field is large and RSFP is strongest. 11-year variations of neutrino flux is caused by periodic variation of toroidal magnetic field at the bottom of convective zone. The magnetic activity of the sun exhibits quasi-periodic time variations with the mean period 11 yr. Taking into account changing of magnetic polarity, one can argue for 22 yr as a basic period for large-scale magnetic field. This periodicity is thought to be originated due to toroidal field, generated in so-called *overshoot layer* by dynamo mechanism and located near the bottom of convective zone. Theoretically, magnetic field there can reach 100 kG. This field rises through convective zone to the surface of the sun. The 11 yr periodicity should be observed most effectively by neutrino detectors sensitive to Be-neutrinos: Homestake, GALLEX and BOREXINO. In particular (see Fig.3) when toroidal magnetic field disappears (due to change of magnetic polarity) survival probability increases from ~ 0.1 to ~ 1. Since B-neutrino flux is also suppressed by factor $\sim 0.4 - 0.6$, 11 yr variations should be seen in the combined Kamiokande and Superkamiokande data.

5. 708-day Superkamiokande Data

The 708-day of Superkamokande data are presented by K.Inoue in these Proceedings. After 708 days of solar-neutrino observations Superkamiokande has not found direct evidences for neutrino oscillations. There are only some indications to the distortion of the spectrum of recoil electrons, which will be discussed in this Section.

The spectrum of the recoil electrons (708 d) is shown in Fig.4 [1,51] as the ratio to (undistorted) spectrum calculated in BP98 SSM [5]. The spectrum is suppressed by overall factor 0.47, but there is no distortion of the spectrum, except the high energy excess at $E_e \geq 13\ MeV$. In principle, this excess can be a result of low statistics or small systematic errors at the end of the boron neutrino spectrum. For example, due to very steep end of the electron spectrum, even small systematic error in electron energy (e.g. due to calibration) could enhance the number of events in the highest energy bins.

Another possible explanation of this excess [52] is that the Hep neutrino flux might be significantly larger (about a factor 10–20) than the SSM prediction. The Hep flux depends on solar properties, such as ^{3}He abundance and the temperature, and on S_{13}, the zero-energy astrophysical S-factor of the $p + {}^3He \to {}^4He + e^+ + \nu$ reaction. Both SSM based [52] and model-independent [53] approaches give a robust prediction for the ratio $\Phi_\nu(Hep)/S_{13}$. Therefore, this scenario implies a cross-section larger by a factor 10–20 than the present calculations. Such a large correction to the calculation does not seem likely, though is not excluded. The signature of Hep neutrinos, the presence of electrons above the maximum boron neutrino energy, can be tested by the SNO experiment.

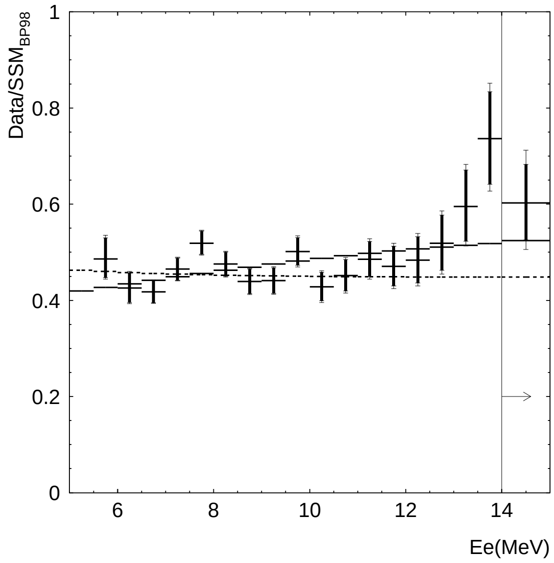

Fig. 4. *Energy spectrum of recoil electrons from 708d of Superkamiokande data* [1,51]. *Plotted is ratio of the observed spectrum to one predicted by BP SSM* [5]. *The long- and short- dash lines show SMA MSW and LMA MSW spectra, respectively, for best-fit rates (calculations by K.Inoue).*

The observed excess is difficult to explain by neutrino oscillations. The oscillation parameters $\sin^2 2\theta$ and Δm^2, which correspond to the allowed global rates in four neutrino experiments, result in the recoil electron spectra in bad agreement with the excess. The spectra for the best fit MSW solutions (LMA shown by short-dash lines and SMA – by long-dash lines) are displayed in Fig.4.

Night/Day excess is found to be small, consistent with zero within 1.7σ. The excess after 201.6, 504 and 708 days of observation, respectively, looks as follows:

$$\frac{N-D}{N+D} \times 100 = -0.4 \pm 3.1 \pm 1.7 \qquad (201.6d)$$

$$\frac{N-D}{N+D} \times 100 = +2.3 \pm 2.0 \pm 1.4 \qquad (504d)$$

$$\frac{N-D}{N+D} \times 100 = +2.9 \pm 1.7 \pm 0.39 \qquad (708d)$$

The observed (708 d) excess has the right sign, but is statistically insignificant (1.7σ). Note that systematic error is much smaller than observed effect. Statistics, if increased by factor 5, can make the effect statistically significant. For clear discussion see [54]. *The absence of day/night effect does not rule out MSW solution.*

The zenith-angle dependence is not seen in Superkamiokande data.

The Superkamiokande data have the great restriction power for the oscillation solutions.

6. Status of Oscillation Solutions

I will discuss here the status of MSW, VO and RSFP solutions in the light of 708d Superkamiokande data.

6.1. MSW solutions

The regions in oscillation parameter space allowed by global rates do not explain the high energy excess in the recoil-electron spectrum [55] (see Fig.4). MSW solutions need an alternative explanation of this excess, *e.g.* by Hep neutrinos (see Section 5).

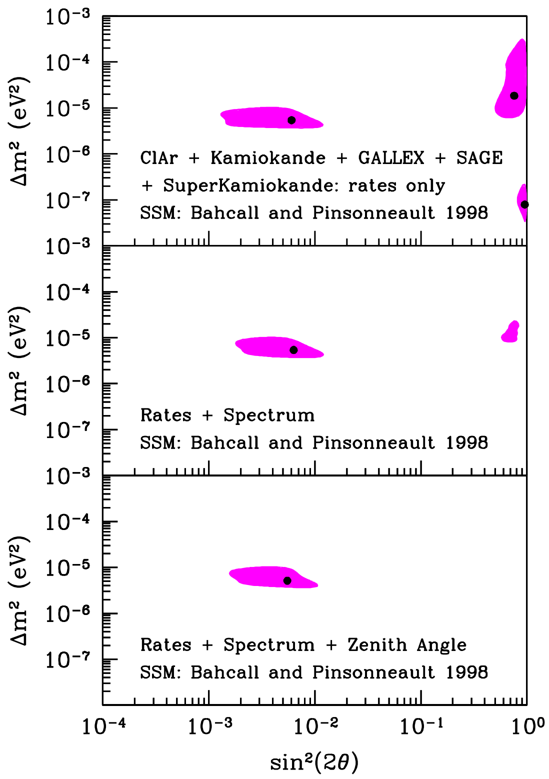

Fig. 5. *Status of MSW oscillation solutions after 504 days of Superkamiokande data* [22]*. Global rates+spectrum+zenith angle exclude LMA MSW.*

The status of MSW solutions is determined by *combined* restrictions due to global rates, day/night effect, zenith-angle flux dependence and the energy spectrum (with free Hep neutrino flux). According to Bahcall, Krastev and Smirnov [22] the 504d Superkamiokande data exclude LMA MSW solution. In Fig.5 the upper panel shows the regions allowed by the global rates. The middle panel includes additionally restrictions due to spectrum and the low one includes three restrictions (rates, spectrum and zenith-angle dependence). All regions are shown at 99% CL. One can see how LMA and LOW solutions disappear.

This result is in contradiction with the Superkamiokande analysis of 708d data (K.Inoue, these Proceedings): LMA MSW solution is more favorable than SMA MSW. The latter is not acceptable at 90% CL if day/night effect and spectrum (with free Hep flux) are included in the analysis simultaneously.

6.2. VO Solutions

If high energy excess in the spectrum is due to Hep neutrinos, just-so VO solution fits the rates and the spectrum. In case the excess is due to oscillations, the regions in oscillation parameter space allowed by the rates (Fig.6, upper panel) are excluded by energy spectrum (low panel).

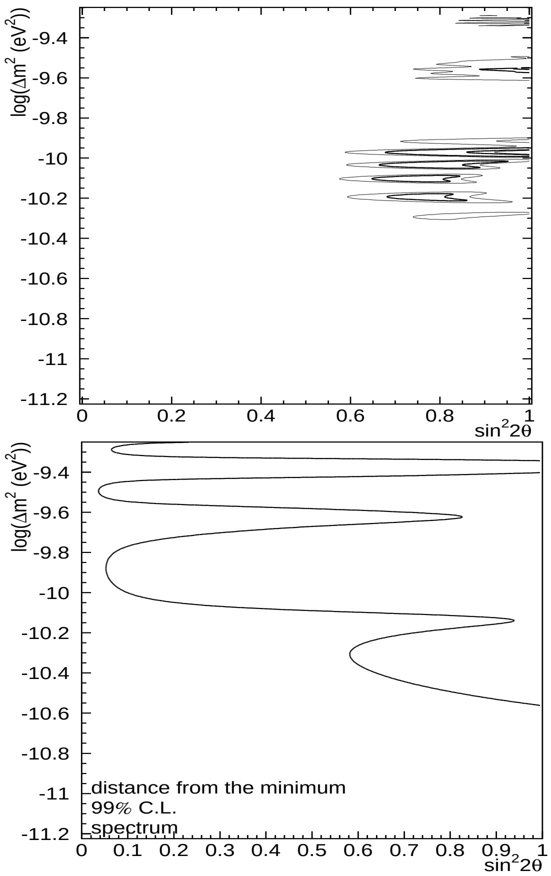

Fig. 6. *Just-so VO solution: regions allowed by rates (upper panel) and excluded by spectrum (low panel)– courtesy of Y.Totsuka.*

The spectrum is well fitted by vacuum oscillations with $\Delta m^2 = 4.2 \cdot 10^{-10}\ eV^2$ and $sin^2 2\theta = 0.93$ [55], but this point is located outside the regions allowed by the rates (Fig.6), *i.e.* it does not represent the SNP solution.

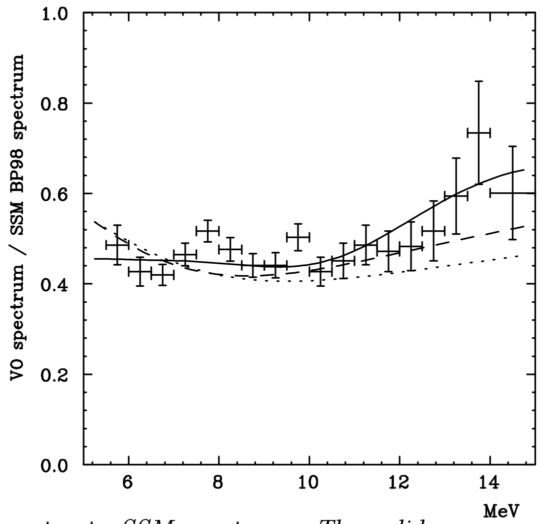

Fig. 7. *Ratio of the VO spectra to SSM spectrum. The solid curve corresponds to the* HEE VO *solution with* $\Delta m^2 = 4.2 \cdot 10^{-10}\ eV^2$ *and* $\sin^2 2\theta = 0.93$. *The dashed and dotted curves correspond to the VO solutions of Refs.* [15] *and* [22], *respectively.*

The status of this point has been further analysed in [56]. To explain both the excess and the rates it was assumed that boron neutrino flux is 15–20% smaller than the SSM prediction, and that the chlorine signal is about 30% larger than the Homestake observation. This assumed 3.4σ increase of the chlorine signal could have a combined statistical and systematic origin. The SSM boron neutrino flux and the Homestake signal were rescaled with help of parameters f_B and f_{Cl}, as $\Phi_B = f_B \Phi_B^{SSM}$ and $R_{Cl} = 2.56 f_{Cl}$ SNU, where 2.56 SNU is the Homestake signal. For each pair f_B and f_{Cl} there were found the parameters $(\Delta m^2, \sin^2 2\theta)$, that explain the observed rates. In particular, for $f_B = 0.8$ and $f_{Cl} = 1.3$ the oscillation parameters $(\Delta m^2 = 4.2 \cdot 10^{-10}\ \mathrm{eV}^2, \sin^2 2\theta = 0.93)$ give a good fit to all rates ($\chi^2/\mathrm{d.o.f.} = 3.0/3$) and to the spectrum with the excess (see Fig.7).

These VO solutions will be referred to as HEE VO (with HEE for High Energy Excess) to distinguish them from ordinary just-so VO solutions. The anomalous seasonal variations are rather unusual in the HEE VO solution. They are described by time dependence of survival probability for the electron neutrino: $P_{\nu_e \to \nu_e}(t)$. In particular, for Be-neutrinos with energy $E = 0.862$ MeV it equals to

$$P(t) = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 a}{4E} (1 + e \cos \frac{2\pi t}{T}) \right) \quad (2)$$

where $a = 1.496 \cdot 10^{13}$ cm is the semi-major axis, $e = 0.01675$ is the eccentricity of the Earth's orbit, and $T = 1$ yr is the orbital period.

As seen in Fig.8, the case of the HEE VO (solid curve) is dramatically different from the just-so VO case: there are two maxima and minima during one year and the survival probability oscillates between $1 - \sin^2 2\theta \approx 0.14$ and 1. The explanation is obvious: the HEE VO solution has a large Δm^2, which results in a phase $\Delta m^2 a/(4E) \approx 93$, large enough to produce two full harmonics during one year, when the phase changes by about 3% due to the factor $(1 + e\cos 2\pi t/T)$.

The HEE VO solution predicts (see Fig.8) that *Be* electron neutrinos should arrive almost unsuppressed during about four months a year!

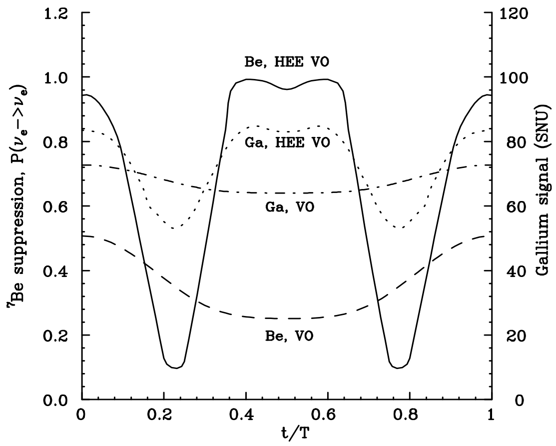

Fig. 8. *Anomalous seasonal variations of the beryllium neutrino flux and gallium signal for the VO and HEE VO* [56] *solutions. The survival probability $P_{\nu_e \to \nu_e}$ for Be neutrinos is given for the HEE VO (solid curve) and for just-so VO (dashed curve) as function of time (T is an orbital period). The dotted (dash-dotted) curve shows the time variation of gallium signal in SNU for the HEE VO* [56] *and for just-so VO* [22] *solutions.*

According to the SSM, beryllium neutrinos contribute 34.4 SNU out of the total gallium signal of 129 SNU. Therefore, the strong ^{7}Be neutrino oscillation predicted by the HEE VO solution also implies an appreciable variation of total gallium signal. In Fig.9 the dotted curve shows this variation for the HEE VO solution, which can be compared with the weaker variation in the just-so VO solution (dashed-dotted curve).

In Fig.9 the predictions of the HEE VO solution for seasonal time variations are compared with observations of GALLEX, SAGE, Homestake and Superkamiokande. While the agreement of each of the observational data with the HEE VO solution might appear accidental and not statistically significant, the combined agreement between this model and experiment looks like indication in favour of the HEE VO solution.

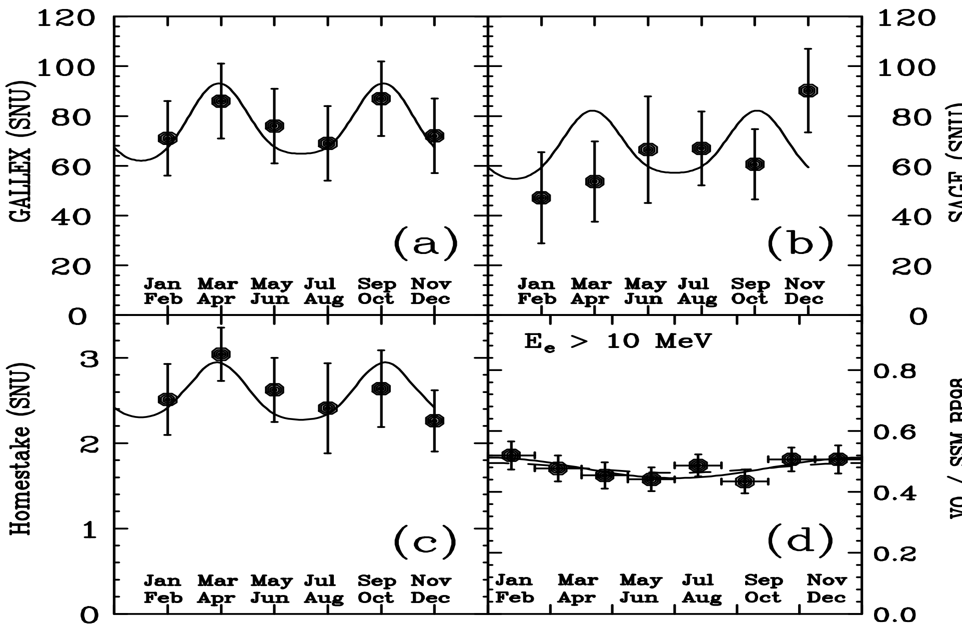

Fig. 9. *Seasonal variations predicted by the HEE VO solution in comparison with the GALLEX data* [2] *(a), with the SAGE preliminary data* [3] *(b), with the Homestake data* [4] *(c) and with the Superkamikande data for electrons with energy $E_e > 10$ MeV (d). The fits are characterized by $\chi^2/d.o.f.$ equals to 0.87/4 for the GALLEX data, 8.9/5 for the SAGE, 3.1/5 for Homestake and 2.7/7 for Superkamikande.*

A status of VO solutions was analyzed in ref.[57] using global χ^2 analysis of the following set of data: global rate of the chlorine experiment (1 data point), global rates of two gallium experiments (2 data points), Superkamiokande energy spectrum (18 data points) and the seasonal variation data from Superkamiokande (8 data points). The best fit solutions corresponds to the HEE VO, discussed above: $\Delta m^2 = 4.2 \cdot 10^{-10}\ eV^2$, $\sin^2 2\theta = 0.93$, with $\chi^2/d.o.f. = 36.7/26$. The authors conclude, that this model "gives a consistent explanation of all solar neutrino data". I think however that formally correct analysis [57] needs another conclusion, similar to that of [56]. The chlorine global rate enters in the analysis as one degree of freedom out of 26. Even very large deviation of a model prediction from the Homestake rate, e.g. $(5-6)\sigma$, will not affect strongly the value of $\chi^2/d.o.f.$, but the model can be excluded on this basis. The good $\chi^2/d.o.f.$ is a necessary condition, but not a sufficient one. The 3.4σ excess in prediction of the HEE VO solution over the measured chlorine rate is some problem for this solution.

The anomalous seasonal variation of ν_{Be}- flux is a cruicial prediction of the HEE VO solution. It can be reliably tested by BOREXINO and LENS.

6.3. RSFP solution

As has been recently demonstrated [41], the RSFP solution can successfully explain the rates (see also [58,59] for early calculations) and high-energy excess in the Superkamiokande spectrum.

This solution has more free parameters, than other solutions, to fit the data. For the Majorana neutrino they are: Δm^2, transition magnetic moment μ_ν, scale of toroidal magnetic field in the convective zone, B, and radial profile for magnetic field, $B(r)$, in the wide range of distances. The mixing angle is an arbitrary parameter in the RSFP solution which determines the magnetic moment, but it must be small enough, $sin 2\theta < 0.25$ [37]. The Majorana neutrino can have only transition magnetic moment μ_ν. The scale needed for the RSFP solution with $B \sim 20 - 100\ kG$ is $\mu_\nu \sim 10^{-11}\mu_B$. This scale is (marginally) consistent with astrophysical bounds. The strong bound on μ_ν obtained from SN 1987A observations is not applicable to the transition moment of Majorana neutrinos. The theoretical models for Majorana neutrinos with small m_ν and large $\mu_\nu \sim 10^{-11}\mu_B$ can be constructed (*e.g. see* [60].)

The scale of magnetic field needed for RSFP solution, $B \sim 20 - 100\ kG$, is a natural one for the bottom of convective zone.

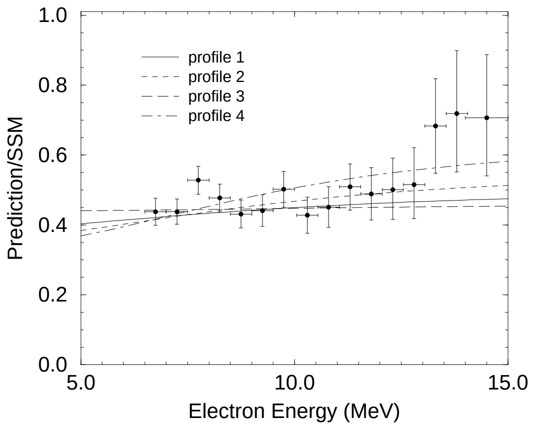

Fig. 10. *RSFP spectra for recoil electrons for four different magnetic radial profiles, compared with 504d Superkamiokande data.*

In Fig.10 the calculated recoil-electron spectra (for four magnetic radial profiles from [41]) are compared with the 504d Superkamiokande data. The agreement is reasonably good, though from deflections of the individual points one can guess that χ^2 is not very small. In Fig.11 the regions explaining the rates in four solar-neutrino experiments are shown in parameter space Δm^2 and the mean magnetic field $\bar{B}$ for two magnetic radial profiles [41]. One can see there the allowed range of parameters.

One of the signatures of the RSFP solution, the time-variation of the neutrino signal, is probably testable now. There are two widely discussed effects: 11 year periodicity (see Section 4) and (June+December)/(March+Sept) ratio of fluxes.

There are some indications to 11yr periodicity in the Homestake signal, especially when correlations with various solar phenomena (sun spot number, green coronal line, surface magnetic field *etc*) are included. My personal opinion is that correlation is allowed as an argument, if the the time variability of the signal is established. Such a lesson was taught us by a bitter experience with Cyg X-3, when correlation with X-ray variability was used as a proof of high-energy gamma-ray signal. Meanwhile, the Homestake signal is perfectly compatible [61] with constant flux ($\chi^2/d.o.f. = 0.6$). The data of all other detectors are also consistent with time-independent flux.

The suppression of neutrino flux in the RSFP model disappears when magnetic field vanishes. It happens in two cases: when polarity of magnetic field in the Sun changes and when neutrino flux arrives, propagating in the plane of solar equator (June 5 and December 5). Both effects are strongest for Be-neutrinos, which have strongest suppression in magnetic field (see Fig.3). The GALLEX data do not show

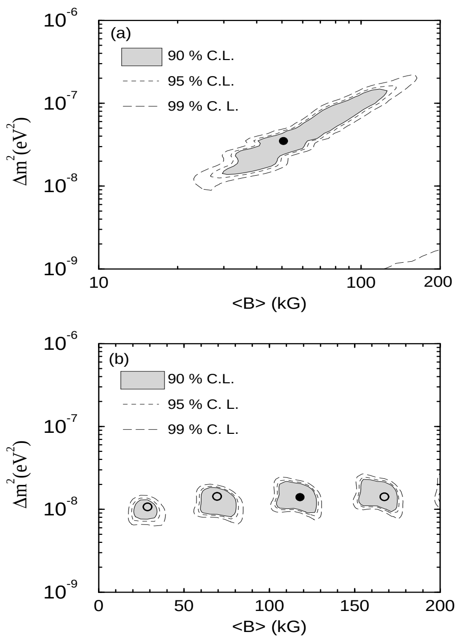

Fig. 11. *RSFP regions allowed by rates for two magnetic field radial profiles* [41].

an excess of the rate in June and December or the deficit in March and September. Using three month intervals centered at June 5 and December 5 ("high" rates) and at March 5 and September 5 ("low" rates) the GALLEX collaboration has obtained as a mean rate 78.5 ± 12 SNU for 20 "high" runs and 90 ± 12 SNU for 19 "low" runs, *i.e.* within limited statistics the wrong-sign effect (T.Kirsten, private communication).

In Fig. 9d one can see a similar wrong-sign effect in Superkamiokande data. On the other hand there are no accurate model calculations of this effect in the RSFP models, to compare with the data above.

7. Future Experiments

SNO, e.g. [62], is 1 kt heavy water detector, which will start to operate this year. In contrast to Superkamiokande, electron neutrinos will be directly seen here in the CC current reaction $\nu_e + D \to p + p + e^-$. Thanks to the large cross-section, event rate is close to that of Superkamiokande. Neutrino energy is given by electron energy and mass difference of D and H. The SNO data can be helpful in detection of Hep neutrinos above the end of B-neutrino spectrum. The NC reactions $\nu_x + D \to \nu_x + p + n$, seen by presence of neutrons result in anomalous NC/CC ratio in case of oscillation of ν_e to active neutrino component. This is a signature of neutrino oscillation. SNO is more sensitive than Superkamiokande to the day/night effect, which is a "smoking gun" of MSW effect. This is because ν_e neutrinos are directly measured in CC reaction. Detection of day/night effect in Superkamiokande, SNO and probably ICARUS is the last hope for this effect, because all other planned now detectors are not sensitive to it.

ICARUS [63] is a liquid argon detector. Detection of solar neutrinos is based on CC-reaction $\nu_e +^{40}Ar \to^{40}K + e^-$ and νe scattering. With excellent energy resolution (about 5%) and low threshold of electron detection (about 5 MeV), ICARUS has great potential for super-precise measurement of electron spectrum and flux of Hep neutrinos. The first stage of ICARUS is 600t module, which is under construction in Gran Sasso Laboratory.

KamLand [50] is 1kt liquid scintillator detector for $\bar{\nu}_e$ neutrinos, based on the Reines reaction $\bar{\nu}_e+p \to e^+ +n$. Registration of neutrons by $n+p \to D+\gamma$ inrease a realibility of neutrino detection. Solar $\bar{\nu}_e$ can be detected, though without clear signature of solar origin (*e.g.* no directionality).

Detection of $\bar{\nu}_e$ neutrinos with $E_\nu \sim 3\ MeV$ from a nuclear reactor at distance $L \sim 100\ km$ can test the oscillations with $\Delta m^2 \sim E_\nu/L \sim 3 \cdot 10^{-6}\ eV^2$, *i.e.* close to that of LMA MSW solution. More accurate calculations show that considerable part of LMA MSW solution can be tested using a nearby (160 km) nuclear reactor, due to disappearance effect.

HELLAZ [64] is a low temperature and high pressure hellium detector, registering neutrinos in νe scattering. The recoil electron energy and scattering angle are measured with high precision and thus the energy of neutrino is known with comparable accuracy. This detector is designed for pp neutrinos, but probably Be neutrinos can be registered too.

BOREXINO at Gran Sasso is 300t liquid scintillator detector for registering Be-neutrinos due to νe scattering. It measures CC+NC signal from ν_e neutrinos together with NC signal from ν_μ and ν_τ, in case of ν_e oscillation to active neutrino components. This is a real-time experiment. The threshold for neutrino detection is 450 keV. BOREXINO will start to operate in beginning of the next millennium.

LENS is a new proposal to the Gran Sasso Laboratory based on the recent idea put forward by R.S.Raghavan [66]. This is a low energy real-time detector for measuring the fluxes of pp and Be ν_e neutrinos. Three nuclei, ^{176}Yb, ^{160}Gd and ^{82}Se, are proposed as possible targets with following CC-reactions for neutrino detection: $\nu_e + ^{176}Yb \to ^{176}Lu^* + e^-$ with threshold neutrino energy 244 keV, $\nu_e + ^{160}Gd \to ^{160}Tb^* + e^-$ with a threshold 301 keV, and $\nu_e + ^{82}Se \to ^{82}Br^* + e^-$ with threshold 173 keV. LENS is proposed as sectioned liquid-scintillator detector loaded ($\sim$ 5%) with one kind of target nuclei above. The signal in each cell is given by prompt electron and delayed photon or conversion electron from an excited nuclei. This strongly reduces the background. The rate expected for SSM is about 100/yr for Be-neutrinos and 10t target. For pp-neutrinos the rate is about 50% higher. The discussed mass of the target is 20 - 30 t.

The combination of the BOREXINO and LENS data will provide us with the following physical information. (i) With *pp*- and *Be*- neutrino fluxes measured separately, the whole neutrino spectroscopy of the Sun will be completed. The suppression of neutrino fluxes at different energies will be explicitly known. (ii) With *Be* ν_e-neutrino flux known from LENS, BOREXINO will give a signal from ν_μ and ν_τ, in case of ν_e oscillation to active neutrinos. Thus, the combination of both experiments have a status of *appearance oscillation experiment.* In case of ν_e oscillation to sterile neutrino, BOREXINO should not show the signal in excess of that predicted by LENS. (iii) Just-so VO and HEE VO solutions predict strong seasonal variation of *Be* neutrino flux. The BOREXINO/LENS observations will confirm or reject these models. EIS VO model predicts absence of anomalous seasonal variation accompanied by suppression (by factor $\sim$ 2) of both *pp* and *Be* ν_e neutrinos. This is also can be tested by the combined BOREXINO and LENS data. (iv) Both detectors can observe 11yr periodicity in *Be*-neutrino flux and measure (June+Dec)/(March+Sept) ratio, which are signatures of the RSFP solution.

8. Conclusions

Solar Neutrino Problem (SNP) is deficit of neutrino fluxes as compared to the SSM predictions detected in all solar-neutrino experiments. The astrophysical (including nuclear physics) solution to SNP is excluded or strongly disfavoured. SNP has a status of disappearance oscillation experiment. No direct signature of oscillations has been found yet.

Currently there are six oscillation solutions to SNP: SMA MSW, LMA MSW, LOW MSW, Just-so VO, EIS VO, and RSFP. Two of them are disfavoured: EIS VO (vacuum oscillations with energy-independent suppression) is excluded by observed rates at 99.8% CL and can survive if the Homestake result is excluded from analysis; LOW MSW is seen only at $\geq 99\%$ CL.

Distortion of B-neutrino spectrum (as compared with the SSM specrum) is a common signature of oscillation solutions (which is absent only in EIS VO and weak in the LMA MSW).The ratio of the observed electron spectrum (708d of Superkamiokande data) to that of predicted by the SSM model is flat at $5.5\ MeV \leq E_e \leq 13\ MeV$ and has an excess at $E_e \geq 13\ MeV$. This excess cannot be explained by the MSW solutions and by those just-so VO solutions, which explain the rates. It is not excluded that this excess is due to Hep neutrinos or small systematic experimental error.

Day/Night effect and zenith-angle dependence of neutrino flux is a signature of MSW solutions. After 708d of Superkamiokande observations this effect (in percent) is $2.9 \pm 1.7 \pm 0.30$, i.e. consistent with zero at 1.7σ. Statistics, if increased by factor 5, might make this effect statistically significant. SNO, in the operation soon, is more sensitive than Superkamiokande to day/night effect (due to CC events). There are still chances that day/night effect will be discovered in this round of observations. If not, the future detectors planned at present (BOREXINO, LENS and HELLAZ), will not also be able to see it.

The HEE VO solution with $\Delta m^2 = 4.2 \cdot 10^{-10}\ eV^2$ and $\sin^2 2\theta = 0.93$ explains the spectrum with high energy excess and the rates, if B-neutrino flux is assumed to be $15 - 20\%$ smaller than in SSM and if the chlorine signal is about 30% larger than in the Homestake observations. This solution predicts high amplitude semi-annual time variation of Be-neutrino flux, that can be reliably observed by BOREXINO.

Another oscillation solution which explains all rates and Superkamiokande spectrum (including high energy excess) is the RSFP model. An open problem for this model is prediction of 11yr (or 22yr) variations and (June+Dec)/(March+Sept) excess, that are not observed.

Future low-energy neutrino detectors, BOREXINO and LENS, are very sensitive to VO solutions and they will either confirm or reject them.

With future experiments, SNO, BOREXINO and LENS, the full-scale task of solar-neutrino spectroscopy will be accomplished: SNO and Superkamiokande will provide fluxes of ν_e and ν_μ/ν_τ of ^8B origin, BOREXINO and LENS - ν_e and ν_μ/ν_τ from ^7Be, LENS - ν_e -from pp-reaction, while GALLEX (SAGE) and Homestake will give in redundancy the fluxes of ν_e in combination from all sources of solar neutrinos.

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