SPECTROSCOPY OF SOLAR NEUTRINOS: PRESENT STATUS AND FUTURE PROSPECTIVES

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The status of the current solar neutrino measurements is reviewed and its implications are discussed. All experiments observe a depletion of the solar neutrino flux in comparison with theoretical predictions. Solar model explanations appear unlikely to reconcile the discrepancy. There are strong indications for a particle physics solution. The next generation of solar neutrino experiments have the potential to clarify the Solar Neutrino Problem unambiguously.

1 Introduction

The unrevealed intrinsic properties of the neutrino particle are considered as one of the most intriguing questions in fundamental physics. Recent results of the four solar neutrino experiments [1,2,3,4] imply such non-standard properties. In particular, non-zero neutrino rest mass and flavour mixing is evoked in order to reconcile solar neutrino observations with theoretical predictions. A discovery of non-zero neutrino rest masses would imply new physics beyond the Standard Model of Electroweak Interaction. In addition to the impact on fundamental physics, this would have major impact on the fields of astrophysics and cosmology.

The depletion of the solar neutrino flux is redundantly established experimentally, and is e.g. referred to as the Solar Neutrino Problem. A 'proof' however, that it is related to neutrino masses could not be shown yet. This is due to the fact that up to now source properties can not be clearly separated from particle properties. Both, however are of great interest: with neutrinos as a probe, the primary fusion processes in the sun can be investigated and hence stellar evolution models tested. On the other hand, the sun serves as a neutrino source in order to probe neutrino properties. Additional handles are provided in order to disentangle the Solar Neutrino Problem: helioseismology data are being utilized successfully with the purpose to test solar models [5]. Moreover, solar model independent methods have been developed in order to investigate solar neutrino properties and they will be exploited in the next generation of experiments.

The particular interest in solar neutrinos for the study of elementary particle physics is related to the unique experimental conditions, i.e. the long base line (1.5 10^8 km) in combination with the enormous source strength

($\sim 10^{10}$ cm^{-2}s^{-1} flux on earth) and the low neutrino energies (MeV).

1.1 Massive Neutrinos

At present there exists no firm experimental evidence for non-zero neutrino rest masses. Kinematical measurements provide upper mass limits and the current ('96) experimental constraints [6] are summarized in Table 1. From LEP data it is known [7] that there exist only three light neutrinos with masses below about 45 GeV. If neutrinos are massive the constraints indicate that their masses are orders of magnitude smaller than the masses of their corresponding charged leptons.

Table 1: Experimental constraints on neutrino masses from kinematical measurements

Limit	Decay
$m_{\bar{\nu}\,e} < 4.5$ eV	^{3}H β-decay
$m_{\nu\,\mu} < 160$ keV	$\pi^+ \to \mu^+ \nu_\mu$
$m_{\nu\,\tau} < 23$ MeV	$\tau^- \to 3\pi^- 2\pi^+ \nu_\tau$

Within the Standard Model of Electroweak Interaction, the neutrino particle is massless and the concept of flavour-mixing, as it is observed in the quark sector (CKM mixing), is not provided. The vanishing neutrino mass term is a consequence of the non-observance of Lepton number violation and of the left-handedness of the neutrino particle. The first prevents a Majorana and the latter a Dirac mass term to occur. In theories beyond the Standard Model, as for example in most Grand Unified Theories (GUTS), a right handed neutrino state is demanded and Lepton number is e.g. not conserved [8]. Non-zero neutrino masses would consequently be natural in such theories. The observed smallness of neutrino masses could then be related to the large value of the unification mass M_{GUT} through a scheme named see-saw mechanism [9,10]. In such a scenario, light neutrinos with masses $\sim m_u^2/M, m_c^2/M, m_t^2/M$ are predicted, where m corresponds to the u, c, t-quark masses and M to the unification mass M_{GUT} which is expected to be many orders of magnitudes larger then typical fermion mass.

1.2 Neutrino Oscillations

For massive neutrinos it is e.g. expected that mixing occurs. This means that the flavour eigenstates can be expressed as a linear combination of the physical mass eigenstates. For simplicity, the mixing between two states is

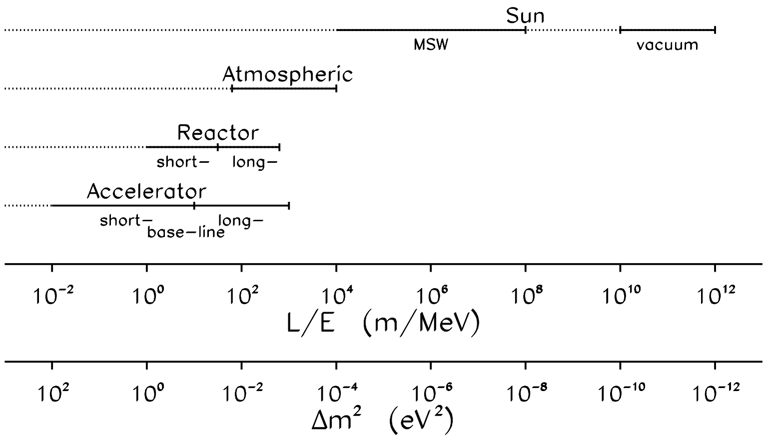

Figure 1: Range of sensitivity for different types of neutrino experiments depending on the mass difference Δm^2 and on the ratio between source-detector distance (L) and neutrino energy (E). In the case of the dotted lines, the oscillations are averaged or coherence is lost. In both cases the suppression corresponds to $P(\nu_{initial}) = 1 - 1/2 \sin^2 2\Theta$.

considered. The mixing matrix U which links the mass eigenstates with the flavour eigenstates can then be written as

$$U = \begin{pmatrix} \cos\Theta & \sin\Theta \\ -\sin\Theta & \cos\Theta \end{pmatrix}. \tag{1}$$

Neutrino oscillations, neutrino decay and shape distortions in weak decays would be inevitable consequences of neutrino mixing.

Very small neutrino masses are unlikely to be measured directly. Mass differences seem easier accessible experimentally. In order to explore small mass differences $\Delta m^2 = |m_1^2 - m_2^2|$, the search for neutrino oscillations is the most sensitive technique and it has been pursued comprehensively for a large range of Δm^2. Wave packets which are related to the different mass eigenstates, propagate with their genuine group velocities. Hence, the interference pattern between these wave packets change with time and the probability $P(\nu_\beta, t)$ to find a neutrino in a particular flavour eigenstate ν_β is given by [11]

$$P(\nu_\beta, t) = \frac{1}{2}\sin^2 2\Theta[1 - \cos(\frac{\Delta m^2}{2E_\nu}t)], \tag{2}$$

with neutrino energy E_ν and time t. The The mixing angle Θ determines the oscillation amplitude whilst the quantity $\Delta m^2/E_\nu$ is responsible for the oscillation frequency. In practical units the oscillation length Λ can be written as $\Lambda = 2.5 E_\nu/\Delta m^2$, where E_ν, Δm^2 and Λ are expressed in MeV, eV^2 and m respectively.

Oscillations can be amplified resonantly when neutrinos are propagating through matter. This effect has been proposed by Wolfenstein, Smirnow and Mikheyev (MSW-effect) [12,13,14]. The elastic forward scattering off electrons introduces a different refraction for ν_e and $\nu_{\mu,\tau}$ which causes an effective neutrino mass and mixing angle in matter. For a distinct combination of the parameters $E_\nu, \Delta m^2, \Theta$ and electron density N_e one obtains maximal mixing. For solar neutrinos, a wide range of neutrino parameters ($\Delta m^2 \sim 10^{-4} - 10^{-8}$ eV^2, $\sin^2 2\Theta \geq 10^{-4}$) can lead to a resonant flavour conversion. Further resonant processes for neutrino conversion in matter and magnetic fields have been proposed and the reader is referred to reference [15].

The particular combination of E_ν and the distance L between source and detector defines the sensitivity for Δm^2. Figure 1 depicts the ratio L/E_ν together with Δm^2 and illustrates the sensitivity of accelerator, reactor, atmospheric and solar neutrino experiments. Owing to the low energies of solar neutrinos (~MeV) and the large distance L, solar neutrino experiments are currently the only possibility to search for very small Δm^2.

1.3 Sun as Neutrino Source

The energy in the interior of the sun is released in fusion reactions of type $2e^- + 4p \rightarrow ^4He + 2\nu_e + 26.7$ MeV. According to Standard Solar Models [16,17] the pp-cycle is dominating and there are three different possibilities for terminating the above reaction. This is illustrated in the in Figure 2 together with the expected neutrino spectrum.

2 Experimental Results of Solar Neutrino Experiments: The Solar Neutrino Problem

At present there are four operating solar neutrino experiments which all measure a lower solar neutrino flux than predicted by Standard Solar Models. The discrepancy between theoretical predictions and experimental observations ranges from about 30% to 60% and this is in general referred to as the Solar Neutrino Problem.

In the radio-chemical experiments HOMESTAKE [1], GALLEX [3] and SAGE [4] electron neutrinos are detected via inverse beta decay of ^{37}Cl and ^{71}Ga. Due

Figure 2: The hydrogen burning nuclear fusion (pp-cycle) with its different terminations and the corresponding solar neutrino spectrum (solid line) is illustrated. The units are $cm^{-2}s^{-1}MeV^{-1}$ for the continuous spectra and $cm^{-2}s^{-1}$ for the line spectra.

to the low energy threshold of the detection reaction of 233 keV in the gallium experiments GALLEX and SAGE (cf. Table 2), they are sensitive to the complete neutrino spectrum inclusive the primary pp-neutrinos. The HOMESTAKE experiment can detect neutrinos with energies above 814 keV and hence is sensitive to both ^{7}Be and ^{8}B neutrinos. In the water-cerenkov detector KAMIOKANDE [2], neutrinos were measured via neutrino-electron scattering above a detection threshold of 7.5 MeV. Consequently, the experiment is sensitive to the high energetic ^{8}B neutrinos only.

In Table 2 the experimental results and the predictions derived from Standard Solar Models (SSM) are listed. The recent calibration experiments of the Gallium experiments with an artificial ^{51}Cr neutrino source have not shown any significant deviations from the expected signal and hence have increased the confidence in the results of the solar neutrino measurements.

3 Implications of the Experimental Results

The impact of the Solar Neutrino Puzzle has evolved over the last decade. It initially arose from the discrepancy between the theoretical prediction and the experimental result of the HOMESTAKE experiment. Only about one third of the expected flux is observed. As the dominating contribution of the expected rate is related to the high energetic ^{8}B neutrino branch, a subdominant termination of the pp-cycle (cf. Figure 2), many theoretical efforts have been undertaken in order to reduce the predicted rate of this particular termination.

The result of the KAMIOKANDE experiment provided a direct measurement of the ^{8}B flux which amounts to about one half of the expected flux. As the suppression rate in the HOMESTAKE experiment is larger than in the

Table 2: Experimental results and theoretical predictions of solar neutrino experiments. The interaction rate in radio chemical experiments HOMESTAKE, GALLEX and SAGE is given in units of (a) SNU ($= 1\nu$ capture / 10^{36} target atoms and second). For the neutrino electron scattering experiment KAMIOKANDE, the ^{8}B flux (Φ_B) is given in units of $10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (b).

Experiment	Threshold [MeV]	Data units cf. above	SSM Prediction [16]
HOMESTAKE [1] :			
$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$	0.814	$2.56 \pm 0.22\ ^a$	$9.3 \pm 1.3\ ^a$
KAMIOKANDE [2] :			
$\nu + e^- \rightarrow \nu' + e'^-$	7.5	$\Phi_B = 2.8 \pm 0.4\ ^b$	$\Phi_B = 5.7 \pm 0.8\ ^b$
GALLEX [3] :			
$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$	0.233	$77 \pm 10\ ^a$	$132 \pm 7\ ^a$
SAGE [4] :			
$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$	0.233	$69 \pm 12\ ^a$	$132 \pm 7\ ^a$

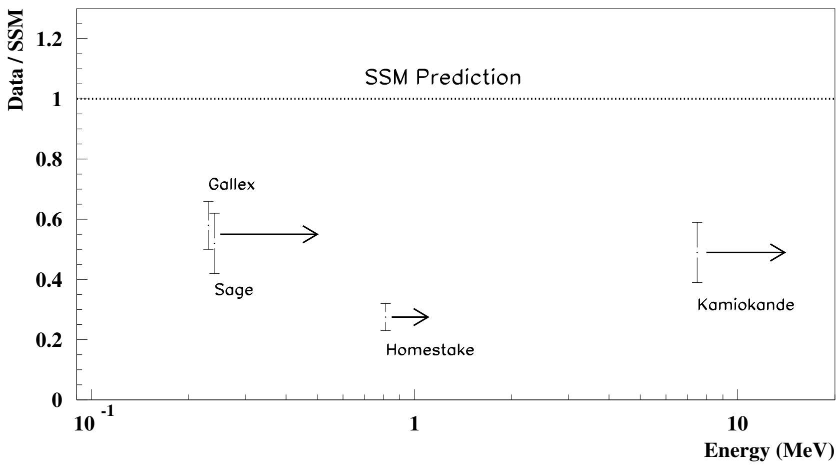

Figure 3: The ratios between experimental observations of the four solar neutrino experiments and Standard Solar Model predictions are illustrated. The ratios are depicted at the particular detection thresholds.

KAMIOKANDE experiment, and as the first is sensitive to both ^{7}Be and ^{8}B while the second can detect ^{8}B only, one can conclude that the ^{7}Be neutrino line at 862 keV is substantially suppressed. This has been confirmed by the recent results obtained by the gallium experiments. By taking the luminosity of the sun and the ^{8}B neutrino flux as measured by the Kamiokande experiment, it was concluded [18] that the ^{7}Be neutrino flux is lower than 20% (90% CL) of its predicted SSM value.

3.1 Astrophysical Solution

Variations of SSM and non-Standard Solar Models were proposed in order to obtain a reduced ^{8}B neutrino flux [19,20] to be consistent with observations. However, astrophysical models can not explain a strong depletion of the ^{7}Be flux and at the same time keeping the ^{8}B flux at a 50 % suppression level. This can be inferred from a simple argument: In the pp-cycle ^{7}Be is created prior to ^{8}B (cf. Figure 2). A competing channel to the termination of the cycle via ^{8}B production ($^7\mathrm{Be} + \mathrm{p} \rightarrow {}^8\mathrm{B} + \gamma$) is to terminate via electron capture in ^{7}Be ($^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu$) which is the dominant process. In the latter process monoenergetic ^{7}Be neutrinos are emitted. No mechanism to date has been proposed which will sustain the ^{8}B creation process and at the same time suppress the concurring ^{7}Be electron capture process. This is a necessary precondition *assuming standard neutrino properties*, to accomodate the experimental observations.

3.2 Particle Physics Solution

Scenarios which adopt *non-standard neutrino properties* can provide a substantial flux suppression. The magnitude and the energy dependence of this suppression factor, depends strongly on the particle physics assumption. The MSW solution predicts a substantial suppression at intermediate energies, i.e. in the range of the ^{7}Be, pep and the lower part of the ^{8}B spectrum. In Figure 5 the suppression factors are depicted for $\Delta m^2 \sim 10^{-6}$ eV^2 and for a variety of values of $\sin^2\Theta$. The best fit to the combined data is shown in the left plot of Figure 6. If vacuum oscillations are the explanation for the solar neutrino deficit, the parameter combinations for $\Delta m^2 - \sin^2 2\Theta$ are constraint to the area depicted in the right plot of Figure 6. Owing to the eccentricity of the earth's orbit, vacuum oscillations would result in a seasonal varying flux of the mono-energetic ^{7}Be neutrinos.

Figure 4: The ^{8}B and ^{7}Be flux, normalized to SSM predictions, allowed by the combined experimental data are compared with a selection of different solar models.

Table 3: Future neutrino experiments. (cc) and (nc) are related to charged current and neutral current interaction respectively.

Experiment	Threshold [MeV]	Interaction	SSM Rate events/day
S-KAMIOKANDE:			
$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$	5.	(cc+nc)	30
SNO:			
$\nu_e + d \rightarrow p + p + e^-$	5.	(cc)	20
$\nu_x + d \rightarrow p + n + \nu_x$	2.225	(nc)	7
$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$	5.	(cc+nc)	2.7
BOREXINO:			
$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$	0.250	(cc+nc)	50
^{127}I :			
$\nu_e + ^{127}\mathrm{I} \rightarrow e^- + ^{127}\mathrm{Xe}$	0.789	(cc)	

Figure 5: The energy dependent suppression factor for the MSW effect is depicted for a value of $\Delta m^2 = 10^{-6}$ eV^2 and different values of $\sin^2 \Theta$ from reference [22]

4 New Experiments

A new round of solar neutrino experiments has started. Since april '96 the SUPER-KAMIOKANDE water cherenkov experiment [24] is acquiring data and in 1997 the SNO experiment [25] will commence operation. Both experiments are sensitive to the ^{8}B neutrino branch above about 5 MeV. New information on the ^{7}Be flux will be provided in the near future by the BOREXINO [27] experiment at the Gran Sasso Laboratories. Neutrinos will be measured via neutrino electron scattering in a liquid scintillator target above a threshold of 250 keV. A radio-chemical ^{127}I experiment [26] is currently being installed at the Homestake mine. Similar to the ^{37}Cl experiment, however with a lower threshold and higher interaction rate, it will be sensitive to ^{7}Be and ^{8}B neutrinos. However, there are uncertainties in the expected neutrino detection rate due to unknown cross sections to excited states in ^{127}Xe. A further interesting experiment under discussion is the real time detection of ^{7}Be neutrinos via the inverse beta decay of ^{115}In. This measurement would be complementary to the BOREXINO experiment as it is sensitive to electron neutrinos only.

Figure 6: The plots show the best fits to reconcile the solar neutrino data with SSM predictions within the MSW (left) and within the vacuum oscillation (right) scenarios [23]

There are further interesting projects and the reader is referred to reference [28]. In Table 3 the main characteristics of the above mentioned experiments are listed.

The new generation of experiments have the potential to clarify independent of astrophysical assumptions the Solar Neutrino Problem. In particular, the following measurement will provide essential information:

- The spectral shape of the ^{8}B neutrinos will be determined by the Super-Kamiokande and SNO experiments. A deviation from the expected spectrum would provide evidence for neutrino oscillations.

- In the SNO experiment, the ratio of the electron neutrino flux to the flux of all neutrino types will be determined above an energy threshold of about 5 MeV. From this measurement one can conclude whether solar electron neutrinos have converted into other flavors.

- The ^{7}Be neutrino flux will be ascertained by the Borexino experiment via neutrino electron scattering in a liquid scintillator target. Both charged current and neutral current interaction contribute to the detection rate. The ratio between electron neutrinos and neutrinos other flavors at this energy can be inferred from the combined results of the Borexino and ^{115}In, or ^{127}I together with the ^{8}B flux measurements.

- The increased statistical accuracy of the future experiments will allow a comprehensive study of time dependent effects. Vacuum oscillations would for example become evident as seasonal variations of the mono-energetic ^{7}Be neutrinos and hence would be a clear signal in the BOREXINO detector. A variation between the day and night detection rate would indicate a matter induced conversion within the earth. Long term variations, correlated with the solar cycle would imply possible magnetic moment effects.

5 Conclusion

The forthcoming experiments together with the statistically improving results of the Gallium experiments will provide comprehensive spectroscopic information on the complete solar neutrino flux. Moreover, the flux of electron neutrinos and of neutrinos of other flavors will be separately determinable for both the ^{8}B and ^{7}Be neutrino branches. This will allow to clarify independent of solar model assumptions, whether the Solar Neutrino Problem is caused by non-zero neutrino masses.

In the case that the MSW effect turns out to be the solution of the solar neutrino deficit with a mass difference $\Delta m^2 \sim 10^{-6}$ eV^2 between the electron and the muon neutrino, and assuming the see-saw mechanism, one expects a tau neutrino mass in the range of 10 eV, i.e. the range of interest to hot or mixed dark matter models.

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