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SNO results and neutrino magnetic moment solution to the solar neutrino problem

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Abstract. We have analysed the solar neutrino data obtained from chlorine, gallium and Super-Kamiokande (SK) experiments (1258 days) and also the new results that came from Sudbury Neutrino Observatory (SNO) charge current (CC) and elastic scattering (ES) experiments considering that the solar neutrino deficit is due to the interaction of neutrino transition magnetic moment with the solar magnetic field. We have also analysed the moments of the spectrum of scattered electrons at SK. Another new feature in the analysis is that for the global analysis, we have replaced the spectrum by its centroid.

Keywords. Neutrino oscillation; solar magnetic field.

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1. Introduction

In past few years there have been a lot of activities in the area of neutrino physics. The chlorine [1] and gallium experiments (with GNO) [2] already reported a solar neutrino deficit from the predicted value. Recently, Super-Kamiokande (SK) experiments [3] have published the data for their 1258 days of observation and more recently Sudbury Neutrino Observatory has made available their first solar neutrino rates data [4] using charge current (CC) and elastic scattering interactions (ES) of the solar neutrinos with the detector fluid D_2O. All the above experiments have seen a deficit of total neutrino flux from that predicted by standard solar model (SSM) [5]. The favourite solution of this solar neutrino problem is that the electron neutrino ν_e produced in the core of the sun oscillates to another flavour before being detected at the earth-bound detectors and hence we see a depletion of solar neutrino flux at the detectors. The oscillation of neutrinos can occur if neutrinos are massive and the mass eigenstates are not their flavour eigenstates. This neutrino flavour conversion may also be induced by the passage of neutrinos through matter when they interact with the matter constituents. The elastic forward scattering of the neutrinos give rise to mean potentials V_a for neutrinos which are proportional to the number density of the scatterers. This V_a plays a crucial role in affecting neutrino oscillation and this matter induced oscillation is known as MSW effect [6]. In this work we have considered an alternate possibility of solar neutrino oscillation and that is of spin flip flavour conversion.

If a neutrino has a non-vanishing magnetic moment, it experiences a rotation of its spin in the presence of a magnetic field which has a component perpendicular to the direction of motion to the neutrino. But if the neutrino is a Dirac particle, this change of helicity makes the neutrino a right handed one and thus it will be a sterile neutrino. For the Majorana neutrinos however they can not have diagonal magnetic moment due to CPT invariance but the Majorana neutrinos can have transition magnetic moments such as $\mu(\nu_{e,L} \to \nu_{\mu,R}) = \mu(\nu_e \to \bar{\nu_\mu})$. As a result they experience simultaneous rotation of their spin and flavour in external magnetic fields.

The presence of magnetic fields in the convective zone of the sun is now well-known [7]. This field can induce a spin flavour precision of the neutrinos produced in the sun. This can transform a $\nu_{eL} \to \nu_{\mu L}$ (if the neutrinos are Majorana types) if $\mu_\nu \sim 10^{-10} - 10^{-11}\mu_{\mathrm{B}}$ where μ_{B} is Bohr magneton and the transverse component of the solar magnetic field $B_{\mathrm{max}} \geq$ few $\times 10$ kilo Gauss (kG). The exact nature of the magnetic field profile in the sun is not known precisely but various estimates of field profiles and their absolute magnitudes B_{max} are given in the literature [7–9]. The solar neutrino deficit with this spin flavour transition is discussed and analysed by Akhmedov and co-workers [10,11] and also in a recent work, Rashba *et al* [12] analysed the solar neutrino data with a realistic magnetic field profile for the sun. The parameters to be determined by these analyses are the mass squared difference Δm^2 of two flavour changing neutrinos and the absolute magnitude B_{max} of the transverse magnetic field of the sun. Hence from these kind of analyses one can also obtain an idea of the absolute value of the solar magnetic field. In this work too we have adopted the magnetic field profile given as a solid curve in figure 2 in Rashba *et al* [12]. As SNO has made available the CC and electron scattering results [4] and Super-Kamiokande has published their 1258 day solar neutrino observational results [3] it is important to make the analysis with these results in the light of spin flavour precision solution of the solar neutrino problem. With this in mind, we have made a detailed analysis of the total rates which include the SNO CC and electron scattering rates, the 1258 day SK rate and the 1258 day SK scattered electron spectrum along with chlorine and gallium experimental results, considering spin flavour transition solution of the solar neutrino problem. Two new kinds of analyses are performed in this work. Firstly the moments of the scattered electron spectrum for daytime observations and the same for nighttime observations for 1258 day SK experiments were analysed. Secondly, for global analysis of rate and spectrum the scattered electron spectrum (day-night) was replaced by two centroids corresponding to day spectrum and night spectrum respectively.

In our analysis we have considered Majorana neutrinos and a two flavour scenario for simplicity. We did not consider the mass mixing of the neutrinos i.e. in our formulation the mass eigenstates are flavour eigenstates as was done in previous works [12]. A more detailed analysis considering the mass mixing and MSW effect is in progress.

The paper is organized as follows: In §2 we have discussed the formalism of spin flavour oscillation induced by solar magnetic field. In §3 we describe the χ^2 analysis of total rates, SK 1258 day data for scattered electron spectrum and the combined rate and spectrum analysis. Section 4 deals with the moment analysis and the analysis of total rates and two centroids for daytime spectrum and nighttime spectrum respectively. Finally in §5 we conclude with some remarks and future outlook.

2. Formalism

In the case of Majorana neutrinos with transition moment μ, the equation of motion for a ν_e going to ν_μ can be written as

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \bar{\nu_\mu}\end{pmatrix} = \frac{1}{2E}\begin{pmatrix} m_e^2 & 2E\mu B\\ 2E\mu B & m_\mu^2\end{pmatrix}\begin{pmatrix}\nu_e\\ \bar{\nu_\mu}\end{pmatrix}, \tag{1}$$

where m_e and m_μ are the mass eigenstates of ν_e and $\bar{\nu_\mu}$. Here we have not considered the usual mass flavour mixing for simplicity and therefore for this case the mass eigenstates are the flavour eigenstates. Diagonalization of the effective Hamiltonian in (1) gives the effective neutrino eigenstates in a magnetic field B:

$$\begin{aligned}\nu_{\mathrm{MA}} &= \nu_e\cos\theta + \bar{\nu_\mu}\sin\theta,\\ \nu_{\mathrm{MB}} &= -\nu_e\sin\theta + \bar{\nu_\mu}\cos\theta,\end{aligned} \tag{2}$$

where the mixing angle θ is given by

$$\tan 2\theta = \frac{2(2E\mu B)}{\Delta m^2} \tag{3}$$

and hence

$$\sin^2 2\theta = \frac{(4E\mu B)^2}{(\Delta m^2)^2 + (4E\mu B)^2}. \tag{4}$$

Now the probability that a ν_e with transition magnetic moment μ will oscillate to $\bar{\nu_\mu}$ in the presence of a magnetic field B is given by

$$P_{\nu_e\to\bar{\nu_\mu}} = \sin^2 2\theta\sin^2\left(\frac{\pi L}{\lambda_{\mathrm{B}}}\right), \tag{5}$$

where L is the distance traversed by the neutrinos from the sun before being detected by an earth-bound detector and λ_{B} is the oscillation length given by

$$\lambda_{\mathrm{B}} = \frac{2\pi}{E_{\mathrm{MA}} - E_{\mathrm{MB}}} = \frac{2\pi}{\sqrt{\left(\frac{\Delta m^2}{2E}\right)^2 + 4\mu^2 B^2}}. \tag{6}$$

In the above equation $E_{\mathrm{MA}} - E_{\mathrm{MB}}$ is obtained by diagonalizing the matrix in eq. (1).

In the present calculation the transition magnetic moment μ is expressed in Bohr magneton μ_{B}, the solar magnetic field in kilo Gauss (kG), Δm^2 in eV^2 and E in MeV. The term $\pi L/\lambda_{\mathrm{B}}$ in the probability equation with these units reduces to

$$\frac{\pi L}{\lambda_{\mathrm{B}}} = \frac{5(\pi L)(\sqrt{(\Delta m^2\ )^2 + 16(5.788\mu)^2 B^2 E^2})}{4\pi E} \tag{7}$$

and

$$\sin^2 2\theta = \frac{(4E(5.788\mu)B)^2}{(\Delta m^2\ )^2 + (4E(5.788\mu)B)^2}. \tag{8}$$

Table 1. Solar neutrino experiments and the ratio of experimental results (flux) to BP2000 SSM predictions.

Experiment	Observed/BP2000
Chlorine	0.335 ± 0.029
Gallium	0.584 ± 0.039
SK	0.459 ± 0.015
SNO (CC)	0.347 ± 0.027
SNO(ES)	0.473 ± 0.074

3. Solar neutrino results and spin flavour oscillation

Total rates

The ratio of the experimental rate at various solar neutrino experiments including the latest results from SNO and the BP2000 solar model predictions [6] are given in table 1.

For this analysis the χ^2 is defined as

$$\chi^2 = \sum_{i,j=1,5} (F_i^{\rm th} - F_i^{\rm exp})(\sigma_{ij}^{-2})(F_j^{\rm th} - F_j^{\rm exp}). \tag{9}$$

Here $F_i^\zeta = T_i^\zeta / T_i^{\rm BP2000}$, where ζ is 'th' or 'exp' for theoretical predictions or experimental results respectively and T_i is the total rate for the ith experiment. The error matrix σ_{ij} contains the experimental errors, the theoretical errors and their correlations. The theoretical errors have contributions arising out of detector cross-section as well as from astrophysics. The off-diagonal elements in the error matrix come from the astrophysical sources.

In the presence of neutrino conversions, the detection rate on the earth for the radiochemical chlorine and gallium experiments is predicted to be

$$T_i^{\rm th} = \sum_\alpha \int_{E_{\rm th}} X_\alpha \phi_\alpha(E_\nu) \sigma_i(E_\nu) \langle P_{ee}(E_\nu) \rangle_\alpha {\rm d}E_\nu, \tag{10}$$

where $\sigma_i(E_\nu)$ is neutrino capture cross-section for the ith detector [13] and $E_{\rm th}$ is the neutrino threshold energy for detection. $\phi_\alpha(E_\nu)$ stands for the neutrino spectrum for the αth source [13] and X_α is an overall normalization factor for this spectrum such that $X_\alpha = 1$ corresponds to the SSM. For the present calculations however we have parametrized only for ^{8}B neutrino flux. The sum is over all the individual neutrino sources. $\langle P_{ee}(E_\nu) \rangle_\alpha$ is the neutrino survival probability for the αth source averaged over the distribution of neutrino production regions in the sun,

$$\langle P_{ee}(E_\nu) \rangle_\alpha = \int {\rm d}r \, P_{ee}(E_\nu, r) \Phi_\alpha(r). \tag{11}$$

$\Phi_\alpha(r)$ is a normalized function which gives the probability of the αth reaction occurring at a distance r from the centre of the sun and $P_{ee}(E_\nu, r)$ is obtained by averaging the survival probability over a year taking the eccenticrity of the earth's orbit into account, i.e.,

$$P_{ee}(E_\nu, r) = \frac{1}{T} \int_0^T {\rm d}t \left[1 - \sin^2 2\theta \sin^2 \left\{ \frac{\pi R(t)}{\lambda} \left(1 - \frac{r}{R(t)} \right) \right\} \right], \tag{12}$$

where $R(t)$ is the Sun-Earth distance given by

$$R(t) = R_0 \left[1 - \varepsilon \cos\left(2\pi \frac{t}{T}\right)\right]. \tag{13}$$

Here, $R_0 = 1.49 \times 10^{11}$ m is the mean Sun-Earth distance and $\varepsilon = 0.0167$ is the ellipticity of earth's orbit. t is the time of the year at which the solar neutrino flux is measured and T is 1 year.

The theoretical prediction according to the BP2000 standard solar model, T_i^{BP2000}, is obtained by setting the survival probability as 1 in the above.

For the water Čerenkov detector Super-Kamiokande, in the case of oscillation to ν_μ the scattering of electrons by ν_μ also has to be taken into account. With this, the prediction at SK is

$$T^{\mathrm{th}}_{\mathrm{K,SK}} = \sum_\alpha \int_{E_{\mathrm{A_{th}}}} \mathrm{d}E_{\mathrm{A}} \int_{E_{\mathrm{T_{min}}}}^{E_{\mathrm{T_{max}}}} \mathrm{d}E_{\mathrm{T}}\, \rho(E_{\mathrm{A}}, E_{\mathrm{T}}) \int_{E_{\nu_{\mathrm{min}}}}^{E_{\nu_{\mathrm{max}}}} \mathrm{d}E_\nu\, X_\alpha\, \phi_\alpha(E_\nu)$$
$$\left[\langle P_{ee}(E_\nu)\rangle_\alpha \frac{\mathrm{d}\sigma_{\nu_e}}{\mathrm{d}E_{\mathrm{T}}} + \langle P_{e\mu}(E_\nu)\rangle_\alpha \frac{\mathrm{d}\sigma_{\nu_\mu}}{\mathrm{d}E_{\mathrm{T}}}\right]. \tag{14}$$

E_{T} and E_{A} denote the true and apparent electron energies respectively. $E_{\mathrm{T_{min}}}$ and $E_{\mathrm{T_{max}}}$ are determined by kinematics. $\rho(E_{\mathrm{A}}, E_{\mathrm{T}})$ is the energy resolution function for which we use the expression given in [14]. $E_{\mathrm{A_{th}}}$, the threshold value for apparent electron energy E_{A} is taken to be 5 MeV for SK. The differential cross-section for the production of an electron with true relativistic energy E_{T}, $\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{T}}}$, is obtained from the standard electroweak theory.

At SNO the neutrinos are detected by three processes, namely, (a) charge current (CC) break-up of the deuteron, (b) electron scattering by the neutrino and (c) neutral current (NC) break-up of the deuteron

$$\nu_e + d \to p + p + e^- \qquad (\text{CC reaction}), \tag{15}$$
$$\nu + e^- \to \nu + e^- \qquad (\text{scattering}), \tag{16}$$
$$\nu + d \to \nu + p + n \qquad (\text{NC reaction}). \tag{17}$$

For the scattering (16) and NC (17) reactions, ν stands for any active neutrino. For the CC reaction and for scattering, the electrons are detected by the emitted Čerenkov radiation and hence their detection is similar to SK. For NC reaction, on the other hand, only calorimetric measurement is possible. At present, data is made available for the total rates for the first two processes and below we discuss only these.

For the scattered electrons, the formalism for theoretical prediction would be similar to that for SK (see eq. (14)) except for the fact that here in SNO, the detector fluid is 1 K ton of D_2O instead of 32 K ton of water in SK.

The charge current scattering cross-section σ_{CC} at SNO is taken from Bahcall home page [13]. For the CC interactions, the theoretical predictions for electron energy spectrum is given by

$$T^{\mathrm{th}}_{\mathrm{SNO}} = \sum_\alpha \int_{E_{\mathrm{A_{th}}}} \mathrm{d}E_{\mathrm{A}} \int_{E_{\mathrm{T_{min}}}}^{E_{\mathrm{T_{max}}}} \mathrm{d}E_{\mathrm{T}}\, \rho(E_{\mathrm{A}}, E_{\mathrm{T}}) \int_{E_{\nu_{\mathrm{min}}}}^{E_{\nu_{\mathrm{max}}}} \mathrm{d}E_\nu\, X_\alpha\, \phi_\alpha(E_\nu)$$
$$\langle P_{ee}(E_\nu)\rangle_\alpha \;\; \sigma_{\mathrm{CC}}(E_\nu). \tag{18}$$

The resolution function $\rho(E_{\mathrm{A}}, E_{\mathrm{T}})$ for SNO is as given in [4]. We have set $E_{\mathrm{A_{th}}}$ to 6.75 MeV for SNO as given in [4].

In the calculation, the absolute value of the transverse component of the solar magnetic field $B_{\max}$ is varied alongwith Δm^2 and X_α and χ^2 is found out using eqs (9)–(18) and table 1. The neutrino transition magnetic moment is taken as $10^{-11}\mu_{\mathrm{B}}$ for the present calculation. The magnetic field profile of the sun is taken from [12] as mentioned earlier. The results corresponding to minimum χ^2 are shown in the following:

$$\begin{aligned}
B_{\max} &= 68 \text{ kG},\\
\Delta m^2 &= 8.8\times 10^{-12} \text{ eV}^2,\\
X_\alpha &= 0.89,\\
\chi^2_{\min} &= 5.91,\\
\text{d.o.f.} &= 2.
\end{aligned}$$

From the above results it is seen that the fit values for $B_{\max}$ is around 68 kG. Although the value of $B_{\max}$ is not known exactly, a safe estimation is $B_{\max} \geq 50$ kG for spin flavour oscillation to occur [10]. Although the predictions from earlier fits [10] gave varied best fit values for $B_{\max}$, the recent fit by Rashba *et al* [12] gave a fit of 77 or 80 kG for $B_{\max}$. The value of $B_{\max}$ obtained in [10] is $\sim 10^2$ kG but they have used a different field profile. In figure 1 we show the allowed zones with 90% confidence limit in the $B_{\max}$ and Δm^2 plane.

SK day-night spectrum from 1258 day observation

The Super-Kamiokande collaboration has recently published their 1258 day solar neutrino spectrum with respect to the scattered electron energy. They have given both spectrum

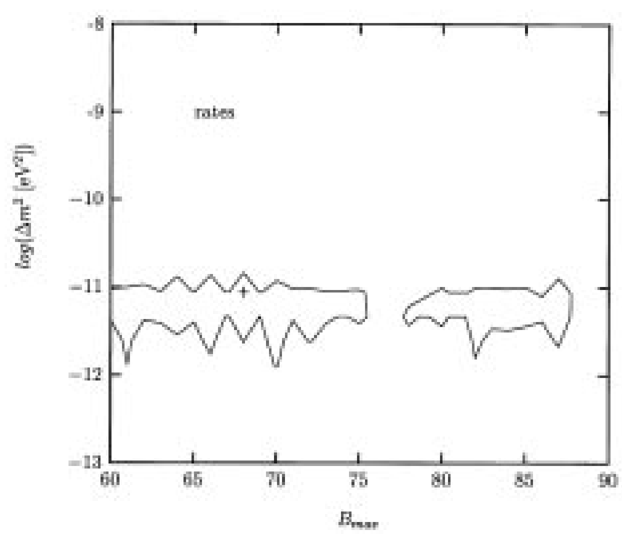

Figure 1. Allowed regions with 90% c.l. for total rates of solar neutrinos in $\Delta m^2 - B_{\max}$ plane. The best fit point is shown with a + sign.

from daytime measurements and nighttime measurements. The spectrum is essentially a flat one. The results for each daytime and nighttime measurements have been presented in the form of the number of events in the 18 electron recoil energy bins of width 0.5 MeV in the range 5.0 MeV to 14 MeV and a 19th bin which covers the events in the range 14 to 20 MeV [3,15]. Therefore in total we have 38 data points for the spectrum in the energy range 5 MeV to 20 MeV out of which 19 points are for daytime measurements and the rest 19 points are for nighttime measurements in the same range for recoil electron energies.

In this section we analyse the spectrum in the light of flavour changing spin magnetic moment discussed in §1. The χ^2 is defined as

$$\chi^2 = \sum_{i,j=1,18} \left(R_i^{\rm th} - R_i^{\rm exp}\right) (\sigma_{ij}^{-2})_{\rm sp} \left(R_j^{\rm th} - R_j^{\rm exp}\right), \tag{19}$$

$R_i^{\xi} = S_i^{\xi}/S_i^{\rm BP2000}$ with ξ being 'th' or 'exp' as before and S_i stands for the number of events in the ith energy bin. The theoretical prediction is given by eq. (14) but the integration over the apparent (i.e., measured) energy will now be over each bin. The error matrix σ_{ij} used by us is [16]

$$(\sigma_{ij}^2)_{\rm sp} = \delta_{ij}(\sigma_{i,{\rm stat}}^2 + \sigma_{i,{\rm uncorr}}^2) + \sigma_{i,{\rm exp}}\sigma_{j,{\rm exp}} + \sigma_{i,{\rm cal}}\sigma_{j,{\rm cal}}, \tag{20}$$

where we have included the statistical error, the uncorrelated systematic errors and the energy-bin-correlated experimental errors [3] as well as those from the calculation of the shape of the expected spectrum [17]. The results are presented below:

$$\begin{aligned} B_{\rm max} &= 66 \text{ kG}, \\ \Delta m^2 &= 4.64 \times 10^{-10} \text{ eV}^2, \\ X_\alpha &= 0.49, \\ \chi^2_{\rm min} &= 30.68, \\ \text{d.o.f.} &= 35. \end{aligned}$$

Although the best fit values are different from the rate analysis, we have checked that the best fit points for rates are within the allowed region of the parameter space for the spectrum analysis. If we use $\Delta m^2 = 8.8 \times 10^{-12}$ eV^2 and $B_{\rm max} = 68$ kG and $X_\alpha = 0.89$ − the best fit values from total rates analysis − for the spectrum case, we get $\chi^2 = 32.05$.

Global analysis of rates and SK spectrum

In this section we discuss the global analysis of rates (chlorine, gallium, SK and SNO (CC and ES)) and SK spectrum.

Here the χ^2 is defined as

$$\chi^2 = \chi^2_{\rm rate} + \chi^2_{\rm spectrum}. \tag{21}$$

The definitions of both $\chi^2_{\rm rate}$ and $\chi^2_{\rm spectrum}$ are given in the previous two sections. We obtain the best fit values as

$$\begin{aligned} B_{\max} &= 68\ \text{kG}, \\ \Delta m^2 &= 8.8 \times 10^{-12}\ \text{eV}^2, \\ X_\alpha &= 0.85, \\ \chi^2_{\min} &= 38.15, \\ \text{d.o.f.} &= 40. \end{aligned}$$

The best fit values are same for those of rates. The allowed region with 90% c.l. for this analysis is almost identical to that of the rate analysis.

4. Analysis of spectral moments

Although the spectral shape of ^{8}B solar neutrino flux is known from electroweak theory, the uncertainty remains in absolute normalization of the flux. Therefore for interpretation of solar neutrino experimental results it is of interest to look for variables which is independent of this absolute normalization. One such variable is the moments of the spectrum. The moment of nth order is defined as

$$\mathscr{M}_n = \frac{\sum_i N(E_i) E_i^n}{\sum_i N(E_i)}, \tag{22}$$

where E_i is the mean energy of the ith bin and $N(E_i)$ is the number of events in that bin. In practice, for comparison with the data it is convenient to standardize these moments with respect to the SSM predictions and thus the expression for the moment used for the analysis is

$$M_n = \frac{\sum_i \left[\frac{N(E_i)}{\{N(E_i)\}_{\text{SSM}}}\right] E_i^n}{\sum_i \left[\frac{N(E_i)}{\{N(E_i)\}_{\text{SSM}}}\right]}. \tag{23}$$

$N(E_i)$ is obtained either from the experimental spectrum or from the theoretical calculations as the case may be.

For the analysis of these moments, M_n's are calculated first with experimentally obtained values of N_i. For 1258 day SK data, we have 19 values of $N(E_i)$ for 19 energy bins for daytime spectrum and 19 values of $N(E_i)$ for 19 energy bins for nighttime spectrum. The moments are calculated up to the sixth order for each of the daytime and nighttime spectrum. We have analysed these spectral moments separately for three cases corresponding to orders of the moments 6, 5 and 4. For analysis of moments up to order 6, we have therefore 12 moments obtained from experimental data (6 moments from daytime spectrum and 6 from nighttime spectrum), for analysis of moments of order 5, we have 10 moments to analyse (5 from daytime spectrum and 5 from nighttime spectrum) and for order 4 we have 8 moments to analyse.

The calculated moments, from day-night data for 1258 day observation on the electron energy spectrum presented by Super-Kamiokande, are presented in table 2. Using those

Table 2. Moments of the observed electron spectrum and their calculated errors obtained from SK (1258 days) day-night data.

Spectrum	Order of moment	Value of moment	Calculated error in moment
Day	1	9.953	0.398
	2	108.288	7.003
	3	1271.564	147.249
	4	15911.832	3137.823
	5	209914.812	65120.356
	6	2894518.250	1314343.000
Night	1	10.039	0.401
	2	110.523	7.932
	3	1317.407	177.167
	4	16779.106	3859.845
	5	225696.281	80803.227
	6	3175339.500	1637233.000

Table 3. The number of moments, the best fit values and χ^2 from analysis of moments of day-night electron spectrum from SK data (1258 days).

Order of moments (day)	Order of moments (night)	B_{max} (in kG)	Δm^2 (in eV^2)	χ^2	d.o.f
6	6	66.06	2.7×10^{-9}	0.71	12–2=10
5	5	66.06	2.7×10^{-9}	0.67	10–2=8
4	4	66.06	2.7×10^{-9}	0.61	8–2=6

variables a χ^2 fitting is performed to obtain the best fit values for B_{max} and Δm^2. The results for different fits with different number of moments are tabulated in table 3.

From the results of table 3 it is found that fitting the first four moments results in the same best fit values for B_{max} and Δm^2 as those obtained fitting the first five or six moments.

From table 3 we also see that the best fit value for B_{max} is the same as that obtained from day-night spectrum fit. Although the Δm^2 is one order of magnitude less than that obtained from the fit of the spectral data, this is within the allowed region (with 90% c.l.) for spectral data analysis. The very low value of χ^2 also does not necessarily indicate a very good fit but is a reflection of very high values of calculated errors for the moments.

Analysis of rates and spectral centroids

In order to explore different analyses with the existing data other than the conventional ones, we replace SK electron spectrum by its centroid, in the global analysis of rate and spectrum. The centroid is the first order moment of the spectrum. This enables us, on the one hand, to perform the analysis without worrying about the uncertainties in the absolute normalization for ^{8}B neutrino flux and on the other hand, the 38 data points for SK day-night electron spectrum is replaced by just two centroids, one due to day spectrum and the other due to night spectrum given in the 19 energy bins.

We perform a global analysis of rates for five different experiments tabulated in table 1 and the centroids for day spectrum and night spectrum (M_1 for day and night spectrum are given in table 2) of SK 1258 day electron spectrum data. The χ^2 is defined as $\chi^2 = \chi^2_{\rm rate} + \chi^2_{\rm centroid}$. The results are furnished below:

$$\begin{aligned} B_{\max} &= 67.99\ \text{kG}, \\ \Delta m^2 &= 8.73 \times 10^{-12}\ \text{eV}^2, \\ \chi^2_{\min} &= 6.26, \\ \text{d.o.f.} &= (5+2) - 2 = 5. \end{aligned}$$

From the above results we see that the best fit values for parameters $B_{\max}$ and Δm^2 agree with the results for global fit of rates and spectrum.

5. Discussions and conclusion

We have analysed here the latest solar neutrino data that include the SNO data and SK day-night data for 1258 days of observation in the light of spin flavour conversion of electron neutrinos during its passage through the sun's magnetic field. We have obtained good fits for global rate analysis and global rate and SK spectrum analysis. The best fit values gave the maximum magnitude $B_{\max}$ of transverse solar magnetic field and Δm^2 , the mass squared difference of two types of neutrinos.

We have explored different kinds of analyses other than those commonly used. In order to avoid the uncertainties in the absolute normalization of ^{8}B solar neutrino flux we have considered the moments of the electron spectrum in our analysis. Also, for the global fit for rate and spectrum, the day-night spectrum is replaced by their respective centroids. The best fit values for $B_{\max}$ and Δm^2 for the latter analysis is the same as those for global analysis of rate and spectrum. Similar analyses including the matter effects is in progress and will be reported in the near future.

In this work we have considered the transition magnetic moment of the neutrino to be $10^{-11}\mu_{\rm B}$. Although this value is larger than that predicted by the standard model, it is within the range of direct laboratory measurements. In a recent work by Joshipura *et al* [18] it is also shown using SNO and SK results that $\mu_e < 10^{-10}\mu_{\rm B}$.

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