Remaining inconsistencies with solar neutrinos: can spin flavour precession provide a clue?

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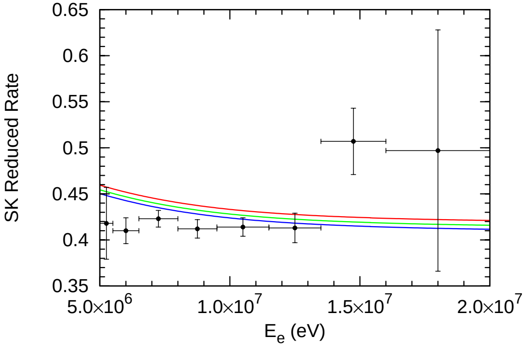
Introduction

Intriguing questions remain open in this area:
(conventional LMA solution does not explain them)

- Why the SuperKamiokande energy spectrum appears to be flat?



- Does the active solar neutrino flux vary in time or is it constant?
- Why is the Cl rate more than 2σ above the observed one?

The Model

The model we developed is inspired in the originally proposed (1987) RSFP of $\odot$ ν's. As a reminder in RSFP neutrinos are endowed with a magnetic moment μ_ν. At times of large solar activity:

$$\textit{Strong } B_\odot \rightarrow \textit{large } \mu_\nu B_\odot \rightarrow \textit{large conversion}$$

and no conversion otherwise.

THE HAMILTONIAN

We consider three active neutrinos and a light sterile one ν_S.
Flavour and mass basis are related by

$$\begin{pmatrix} \nu_S \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & \\ & U^{PMNS}(3\text{x}3) \end{pmatrix} \begin{pmatrix} \nu_0 \\ \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = U \begin{pmatrix} \nu_0 \\ \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The Model

The idea is to have, besides the LMA resonance, an RSFP one connecting the actives to the sterile so that an extra order of magnitude mass square difference is necessary. We take it as Δm^2_{01}. (Other mass square differences are therefore $\Delta m^2_{02} \simeq \Delta m^2_{21}$, and $\Delta m^2_{03} \simeq \Delta m^2_{31}$).

Free propagating part (mass basis)

$$(H_0)_M = \begin{pmatrix} E_0 & & & \\ & E_1 & & \\ & & E_2 & \\ & & & E_3 \end{pmatrix}$$

Matter (interaction) part in the mass basis

$$H_M = U^\dagger \begin{pmatrix} 0 & \mu_{es}B & \mu_{\mu s}B & \mu_{\tau s}B \\ \mu_{es}B & V_c + V_n & 0 & 0 \\ \mu_{\mu s}B & 0 & V_n & 0 \\ \mu_{\tau s}B & 0 & 0 & V_n \end{pmatrix} U$$

The Model

Full Hamiltonian

$$H_M = \begin{pmatrix} \frac{\Delta m^2_{01}}{2E} & \tilde{\mu}_1 B & \tilde{\mu}_2 B & \tilde{\mu}_3 B \\ \tilde{\mu}_1 B & V_n + V_c u^2_{e_1} & V_c u_{e_1} u_{e_2} & V_c u_{e_1} u_{e_3} \\ \tilde{\mu}_2 B & V_c u_{e_1} u_{e_2} & \frac{\Delta m^2_{21}}{2E} + V_n + V_c u^2_{e_2} & V_c u_{e_2} u_{e_3} \\ \tilde{\mu}_3 B & V_c u_{e_1} u_{e_3} & V_c u_{e_2} u_{e_3} & \frac{\Delta m^2_{31}}{2E} + V_n + V_c u^2_{e_3} \end{pmatrix}$$

- $\tilde{\mu}_{1,2,3}$ - transition magnetic moments between mass eigenstates 0 and 1, 2, 3
- u_{e_i}- first row entries of the (3×3) U^{PMNS} matrix.

The Model

The two resonances

- LMA one between two oscillating active neutrinos is determined by $sin\theta_\odot = 0.559$. Its location near the solar core is fixed by $\Delta m^2_\odot = 7.67 \times 10^{-5} eV^2$.
  It is strongly adiabatic, so the Landau Zener approximation $P_{LZ} = exp\left(-\frac{\pi}{2}\gamma_c\right)$ works well here.
- RSFP one is determined by the transition moment between one of the active flavours and the sterile one (no vacuum mixing). Its location closer to the solar surface is fixed by $\Delta m^2_{01} < \Delta m^2_\odot$.
  May/may not be adiabatic because μB may/may not be large enough for adiabaticity to prevail.

Hence the LZ approximation may not be reliable and we resort to the numerical integration of the Hamiltonian equation.

Field Profiles and Rates

We consider two plausible field profiles

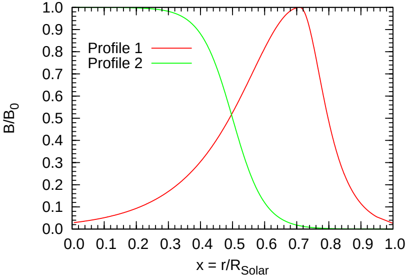
Profile 1

$$B_1 = \frac{B_0}{\cosh[6(x - 0.71)]} \quad 0 < x < 0.71$$

$$B_1 = \frac{B_0}{\cosh[15(x - 0.71)]} \quad 0.71 < x < 1$$

Profile 2

$$B_2 = \frac{B_0}{1 + \exp[10(2x - 1)]} \quad 0 < x < 1$$



Field Profiles and Rates

We use the experimental data on all rates (Cl, Ga, SK rate and spectrum, SNO rates and spectrum, Borexino) to assess the quality of the fits using the following standard χ^2 definition

$$\chi^2 = \sum_{j_1,j_2} (R^{th}_{j_1} - R_{j_1}{}^{\exp}) \left[\sigma^2(tot)\right]^{-1}_{j_1 j_2} (R^{th}_{j_2} - R_{j_2}{}^{\exp})$$

$\Delta m^2_{\odot},\ \Delta m^2_{atm},\ \theta_{\odot},\ \theta_{atm}$ fixed to their experimental values. B_0 (field at the peak) and Δm^2_{01} kept free.

Hence 84 (exp.) - 2 (par.) = 82 dof.

Field Profiles and Rates

Profile 1 (peaks at the bottom of the conv. zone)

$B_0(kG)$	$\sin\theta_{13}$	Ga	Cl	SK	$\mathrm{SNO_{NC}}$	$\mathrm{SNO_{CC}}$	$\mathrm{SNO_{ES}}$	χ^2_{rates}	$\chi^2_{SK\,sp}$	χ^2_{SNO}	χ^2_{gl}
0	0	67.2	2.99	2.51	5.62	1.90	2.49	0.07	42.7	57.2	99.9
	0.1	66.0	2.94	2.49	5.62	1.87	2.46	0.30	42.1	55.2	97.6
	0.13	65.0	2.90	2.46	5.62	1.84	2.44	0.62	41.7	53.7	96.0
140	0	66.4	2.82	2.32	5.37	1.76	2.31	0.20	37.6	46.0	83.8
	0.1	65.3	2.77	2.29	5.37	1.73	2.28	0.53	37.9	44.9	83.3
	0.13	64.3	2.72	2.27	5.37	1.70	2.25	0.95	38.4	44.1	83.4

Note: a clear preference is seen for the case with a sizable field (B.f. B_0=140 kG, $\Delta m^2_{01} = 1.25 \times 10^{-7} eV^2$).

Field Profiles and Rates

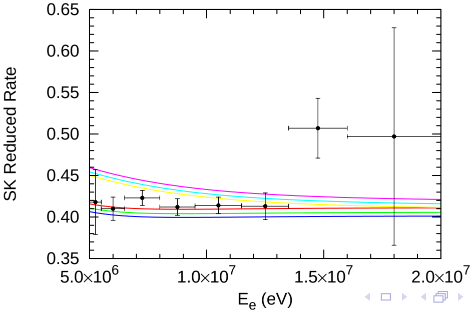
$B_0 = 140kG$ corresponds to an average magnetic activity over solar cycles corresponding to all data.

(Recall $B_0 \leq O(300kG)$ at the solar activity's maximum).

Neutrino magnetic moment

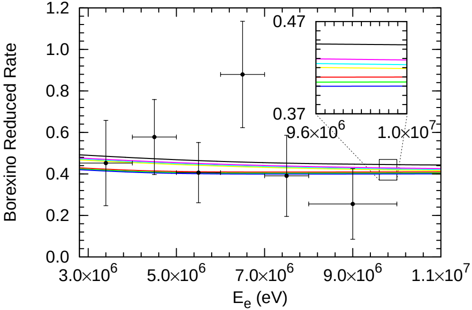
$$\mu_{(\mu,\tau)s} = 1.4 \times 10^{-12}\mu_B, \quad \mu_{es} \leq \mu_{(\mu,\tau)s} \text{ (incl. } \mu_{es} = 0)$$

SK spectrum → preference for $B_\odot$ is clear



Field Profiles and Rates

Borexino spectrum



All error bars are much larger here. Hence the conclusion is not clear.

Quantitavely (with 4 dof=6 exp - 2 par)

- for $B_0 = 0 \rightarrow \chi^2 \simeq 4.5$
- for $B_0 = 140kG \rightarrow \chi^2 \simeq 5$

Field Profiles and Rates

$B_0(kG)$	$sin\theta_{13}$	χ^2	$\Delta\chi^2$
0	0	4.55	0
0	0.1	4.55	0
0	0.13	4.56	0
140	0	4.93	2.4
140	0.1	4.98	2.5
140	0.13	5.03	2.6

The preference for $B_0 = 0$ is only marginal. If Borexino were able to reduce their errors to 1/3, a vanishing field would clearly be favoured.

Field Profiles and Rates

Profile 2 (peak at $\odot$ center,
strong decrease along (0.3-0.7)R_S)

Conclusions drawn for profile 1 remain the same here except for the difference in the best fit

	Profile 2	Profile 1
Δm^2_{01}	$2.7 \times 10^{-6} eV^2$	$1.25 \times 10^{-7} eV^2$
B_0	$0.75 MG$	$140 kG$

Discussion

non-Borexino data

A clear preference for a sizable magnetic field is apparent. In fact:

- SuperKamiokande spectrum becomes flat.
- Rate prediction for the Cl experiment strongly improves (2σ discrepancy $\rightarrow$ prediction within 1σ).
- As for the Ga rate, vanishing and sizable fields are equivalent, as both classes of predictions lie within 1σ of the central value.
- No conclusion can be drawn as for the magnitude of $sin\theta_{13}$.

Discussion

Borexino data

- It is unclear whether Borexino can favour either a negligible or a sizable solar magnetic field owing to the size of the experimental errors.
- An improved significance could be obtained if Borexino were able to substantially reduce their errors. Then it could clearly favour either a vanishing or a large field.
- As for the non-Borexino data, no conclusion is obtained regarding the magnitude of $sin\theta_{13}$.

Discussion

Time dependence?

Examine the period in which the data were taken.

- SuperKamiokande spectrum refers to the period from May 31, 1996 to July 15, 2001 during which the average sunspot number was 65.
- The Borexino ^8B spectrum refers to the period from July 15, 2007 to June 21, 2008 when the average sunspot number was 4.
- In most of the former period the solar magnetic activity increased and reached an 11-year peak in the Summer of 2000, whereas in the latter the activity was continuously at its minimum.
- Therefore in the light of this model, one expects the Borexino spectrum for ^8B to coincide with the LMA prediction and the SuperKamiokande one to reflect a moderately active sun.

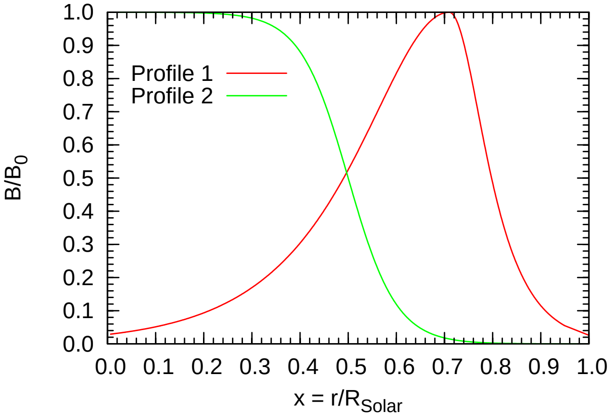
Discussion

Time dependence (continued)

- If and when Borexino are able to reduce their errors to 1/3 (2/3 reduction), solar activity will probably have increased. Then our model predicts a substantial and visible reduction in the event rate.
- We may therefore conclude that it is of prime importance that Borexino will continue monitoring both the low energy and the ^8B flux during the present increasing solar activity period.

Discussion

Distinguishing between profiles 1,2 - is it possible?



Discussion

For profile 1 (b.f. $\Delta m^2_{01} = 1.25 \times 10^{-7} eV^2$) and Borexino phase 1 all observed $\nu's$ ($E < 1.7 MeV$) have their resonances at $x < 0.5$. In this range

- Field is weak, matter density is large $\rightarrow$ modulation too small ($\simeq 1\%$) to ever be seen

For profile 2 (b.f. $\Delta m^2_{01} = 2.7 \times 10^{-6} eV^2$) and Borexino phase 1 all $\nu's$ have their resonances at $x < 0.23$ where field is close to maximal ($O(1MG)$). Here

- Strong, varying field $\rightarrow$ modulation ($\simeq 9\%$) may be seen by Borexino in the future.

Summary and conclusions

- ^{8}B flux (seen by SK and Borexino) can detect modulation for both classes of profiles, so it cannot tell profile 1 from 2
- Low energy fluxes ($CNO, pp, ^{7}Be, ...$) can detect modulation for profile 2 (concentrated in the $\odot$ core and radiation zone) but not for profile 1 (concentrated at the bottom of the convection zone)

If all fluxes (^{8}B and LE) see modulation → evidence for profile 2
If only ^{8}B flux sees modulation → evidence for profile 1

Varying field	^{8}B flux	Others
Profile 1 (CZ)	Yes	No
Profile 2 (WS)	Yes	Yes

- Hence we believe it extremely important to keep Borexino taking data for all neutrino fluxes during at least the first half of the present solar cycle expected to peak in 2011 or 2012 and present their data in time bins.