Neutrino Magnetic Moment Solution for the Solar Neutrino Problem and the SNO Experiment

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The motivations for the magnetic moment solution to the solar neutrino problem are briefly reviewed and the expected values for a number of observables to be measured by the SNO experiment are calculated assuming three different solar magnetic field profiles. The observables examined are the charged current event rate, the ratio of the neutral current to the charged current event rates and the charged current electron spectrum as well as their first and second moments. The dependence of results on the *hep* neutrino flux is also analysed and a comparison is made with the corresponding oscillation results.

The solar neutrino deficit may be explained on the assumption that neutrinos have a large magnetic moment $\mu_\nu = O(10^{-12})\mu_B$ which upon interaction with a magnetic field in the sun not exceeding $3 \times 10^5 G$ may cause a flip in their helicity. For Dirac and Majorana neutrinos we have respectively

$$\nu_{e_L} \to \nu_{e_R} \tag{1}$$

$$\nu_{e_L} \to \bar{\nu}_{\mu(\tau)_R}. \tag{2}$$

In the first case they become sterile for weak interactions while in the second they remain active for neutral currents, undergoing a simultaneous flip in chirality and flavour [1]. This conversion process can be resonantly enhanced in matter [2], which results in an energy dependent neutrino deficit. Those neutrinos whose resonances are located in regions where the magnetic field is the largest will undergo maximum suppression. Resonance location is determined by the neutrino energy, so that the smaller the energy, the higher the resonance density. In this way the resonance spin flavour precession of solar neutrinos in the matter and magnetic field of the sun (RSFP) implies an energy dependent neutrino deficit and possibly a most valuable information on the profile of the inner magnetic field of the sun.

RSFP has been overlooked by the physics comunity as a solution to the solar neutrino problem. The main reasons for this fact may be that it requires a large neutrino magnetic moment, several orders of magnitude above the electroweak standard model prediction [3] and that no anticorrelation with the 11 year solar cycle seems to be observed in the data. This was the idea that a maximum of sunspot activity would be correlated with a minimum of the observed neutrino flux. However such would only be the case if resonances were located in the sunspot range (the outer convective zone). Instead they could be located anywhere inside the sun, the depth of sunspots is unknown and the field intensity is too small in sunspots to allow for a significant conversion.

All oscillation scenarios including the two most favoured ones (LMA, LOW) [4] along with RSFP [5] indicate a sudden drop in the survival probability from the low energy (pp) to the intermediate energy neutrino sector (^{7}Be, CNO, pep) and a subsequent moderate rise as the energy increases further (^{8}B). RSFP offers a unique explanation for this probability shape, relating it to a sharp rise of the transverse magnetic field inten-

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sity somewhere in the solar interior, followed by a progressive, moderate decrease. Such a sharp rise is known to occur along the tachoclyne, the region extending from the upper radiation zone to the lower convective zone where the gradient of the angular velocity of solar matter is different from zero [6], [7]. Two recent investigations [8], [5] of a large number of field profiles have shown that the rate fits that can be obtained are excellent and far better than those for oscillations [9], $\chi^2_{rates}(RSFP) << \chi^2_{rates}(oscillations)$. In the present discussion the following three profiles will be considered

$$B = 0, \qquad x < x_R \tag{3}$$

$$B = B_0 \frac{x - x_R}{x_C - x_R}, \quad x_R \leq x \leq x_C \tag{4}$$

$$B = B_0 \left[1 - \frac{x - x_C}{1 - x_c}\right], \quad x_C < x \leq 1 \tag{5}$$

with $x_R = 0.65$, $x_C = 0.80$,

$$B = 0, \qquad x < x_R \tag{6}$$

$$B = \frac{B_0}{cosh30(x - x_R)}, \quad x \geq x_R \tag{7}$$

with $x_R = 0.71$, and

$$B = 2.16 \times 10^3, \qquad x \leq 0.7105 \tag{8}$$

$$B = B_1 \left[1 - \left(\frac{x - 0.75}{0.04}\right)^2\right], 0.7105 < x < 0.7483 \tag{9}$$

$$B = \frac{B_0}{cosh30(x - 0.7483)}, \quad 0.7483 \leq x \leq 1 \tag{10}$$

with $B_0 = 0.998 B_1$ in the last two equations. The rate best fits were obtained respectively at $\Delta m^2_{21} = 1.2 \times 10^{-8} eV^2$ and $B_0 = 1.23 \times 10^5 G$, $\Delta m^2_{21} = 2.1 \times 10^{-8} eV^2$ and $B_0 = 1.45 \times 10^5 G$ and $\Delta m^2_{21} = 1.6 \times 10^{-8} eV^2$ and $B_0 = 9.6 \times 10^4 G$.

The following five SNO observables were investigated[10]

(a) the charged current (CC) electron spectrum

$$S_i = \frac{\int_{T_i}^{T_{i+1}} dT \frac{dR_{CC}}{dT}}{\int_{T_i}^{T_{i+1}} dT \frac{dR^{st}_{CC}}{dT}} \tag{11}$$

Table I: Double ratio $\bar{r}_{NC} = r_{NC}/r_{CC}$. The values of the electron threshold energy for the CC reaction and of the *hep* neutrino flux scaling factor f_{hep} are indicated in the parentheses in the first line. The errors correspond to 90% CL.

Profile	$\bar{r}_{NC}$ (5 MeV; 1)	$\bar{r}_{NC}$ (5 MeV; 20)
1	$2.375\pm^{0.204}_{0.576}$	$2.315\pm^{0.184}_{0.533}$
2	$2.463\pm^{0.198}_{0.331}$	$2.387\pm^{0.174}_{0.303}$
3	$2.410\pm^{0.199}_{0.320}$	$2.336\pm^{0.180}_{0.296}$

with the differential event rate given by

$$\frac{dR_{CC}}{dT} = \int_Q^\infty dE f(E) P(E) \int_0^{E-Q} dT' \frac{d\sigma_{CC}}{dT'}(T') R(T,T') \tag{12}$$

and with $\frac{dR^{st}_{CC}}{dT}$ denoting the same quantity in the denominator except for the replacement $P(E) \rightarrow 1$.

(b) the ratio of CC event rate to the standard CC event rate

$$r_{CC} = \frac{\int_{T_m}^\infty dT \frac{dR_{CC}}{dT}}{\int_{T_m}^\infty dT \frac{dR^{st}_{CC}}{dT}} = \frac{R_{CC}}{R^{st}_{CC}} \tag{13}$$

(c), (d) the first and second moments of the recoil electron kinetic energy distribution

$$< T > = \frac{1}{R_{CC}} \int_{T_m}^\infty T \frac{dR_{CC}}{dT} dT \tag{14}$$

$$\sigma = \sqrt{< T^2 > - < T >^2} \tag{15}$$

(e) the double ratio of the non-standard to standard neutral current to charged current event rates

$$\bar{r}_{NC} = \frac{r_{NC}}{r_{CC}} = \frac{R_{NC}/R^{st}_{NC}}{R_{CC}/R^{st}_{CC}}. \tag{16}$$

In order to correctly incorporate the energy resolution function $R(T,T')$, the differential event rate per unit recoil electron energy must in fact be considered in eqs. (11), (12) [5]. On the other hand for the neutral current event rate, one has in (16)

$$R_{NC} = \int_{E_B}^\infty f(E) [P(E) \sigma^{\nu d}_{NC}(E) + (1 - P(E)) \sigma^{\bar{\nu} d}_{NC}(E)] \epsilon(E) dE. \tag{17}$$

Table II: Double ratio $\bar{r}_{NC} = r_{NC}/r_{CC}$ extracted from ref. [4] at 90% CL (left column) and its possible overlap with RSFP predictions given in Table I.

Osc. scenario	$r_{\bar{N}C}(5\ MeV)$	overlap with RSFP (90%CL+90%CL)
LMA	$3.37\pm^{0.89}_{0.55}$	no
SMA	$2.53\pm^{0.79}_{0.65}$	yes
LOW	$2.71\pm^{0.34}_{0.21}$	yes
VAC_S	$2.67\pm^{0.98}_{0.65}$	yes
VAC_L	$1.90\pm^{0.13}_{0.19}$	yes (pr. 1)
Sterile	$0.96\pm^{0.02}_{0.02}$	no

Here the value $\epsilon(E) = 0.5$ was used for the detector efficiency. The observable $\bar{r}_{NC}$ is the best indicator for non-standard neutrino properties, as the uncertainties inherent to fluxes and cross sections mostly cancel out [10]. Its predictions for a 5 MeV threshold of the recoil electron kinetic energy T_m are given in Table I. In the left column the *hep* neutrino flux considered is its BP'98 [11] prediction ($f_{hep} = 1$) and in the right column $f_{hep} = 20$. A comparison between the corresponding oscillation predictions and RSFP ones can be seen from Tables I and II. It is seen that on the basis of the SNO experiment alone it will be hard to distinguish RSFP from other oscillation scenarios. Assuming a peak magnetic field of the order of $3 \times 10^5 G$ [6], [7], it is found that the neutrino magnetic moment should lie in the interval $\mu_\nu = (2-4) \times 10^{-12} \mu_B$, consistent with most astrophysical bounds [12].

REFERENCES

1. J. Schechter and J. W. F. Valle, Phys. Rev. **D24**(1981) 1883, Erratum-*ibid.* **D25** (1982) 283.
2. C. S. Lim and W. J. Marciano, Phys. Rev. **D37**, 1368 (1988); E. Kh. Akhmedov, Sov. J. Nucl. Phys. **48**, 382 (1988); E. Kh. Akhmedov, Phys. Lett. **B 213**, 64 (1988).
3. K. Fujikawa and R. E. Schrock, Phys. Rev. Lett. **45** 963 (1980).
4. J. N. Bahcall, P. I. Krastev and A. Yu. Smirnov, Phys. Rev. **62**, 093004 (2000).
5. J. Pulido and E. Kh. Akhmedov, Astrop. Phys. **13**, 227 (2000).
6. E. N. Parker in "The Structure of the Sun", Proc. of the VI Canary Islands School, Ed. Roca Cortes and F. Sanchez, Cambridge University Press 1996, p. 299.
7. H. M. Antia, S. M. Chitre, M. J. Thompson, astro-ph/0005587, to appear in Astron. and Astrophys..
8. M. Guzzo and H. Nunokawa, Astrop. Phys. **12** 87 (1999).
9. M. C. Gonzalez-Garcia, P. C. de Holanda, C. Pena-Garay. J. W. F. Valle, Nucl. Phys. **B573** 3 (2000).
10. E. Kh. Akhmedov and J. Pulido, Phys. Lett. **B485** 178 (2000).
11. J. N. Bahcall, S. Basu and M. H. Pinsonneault, Phys. Lett. **B433** 1 (1998).
12. S. I. Blinnikov, Institute for Theoretical and Experimental Physics Report No. ITEP-88-19 (1988), unpublished; S. I. Blinnikov, V.S. Imshennik, D.K. Nadyozhin, Sov. Sci. Rev. **E** Astrophys. Space Sci. **6**, 185 (1987); G.G. Raffelt, Phys. Rev. Lett. **64** (1990) 2856; Astrophys. J. **365** (1990) 559; V. Castellani and S. Degl'Innocenti, Astrophys. J. **402**, 574 (1993).