ENERGY DEPENDENCE OF SOLAR NEUTRINO SUPPRESSION AND BOUNDS ON THE NEUTRINO MAGNETIC MOMENT

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An analysis of neutrino electron scattering as applied to the SuperKamiokande solar neutrino experiment with the data from the Homestake experiment leads to an upper bound on the neutrino magnetic moment in the range $\mu_{\nu_e} \leq (2.9 - 3.7) \times 10^{-10} \mu_B$. This range is determined by the spread in the flux predictions from six different standard solar models. We assume equal magnetic moments for all neutrino flavours. This limit is obtained when neutrinos do not undergo any “disappearance” mechanism other than the magnetic moment conversion due to the solar magnetic field and for a total or nearly total suppression of the intermediate energy neutrinos. We also point out that the limit may be further reduced if the threshold energy of the SuperKamiokande detector is decreased.

1. Introduction

The solar neutrino problem, which first appeared as a deficit of the solar neutrino flux in the Homestake experiment [1] relative to the solar model prediction [2], has remained with us since its first acknowledgement in the late 1960’s. In more recent years the Kamiokande [3], SAGE [4], Gallex [5] and SuperKamiokande [6] experiments, observing different parts of the neutrino spectrum, started operation. Besides these experiments, several theoretical solar models [7] - [12] have been developed and our understanding of the situation has changed. It now appears that the solar neutrino problem is not merely a deficit of the measured flux in the Kamiokande or the Homestake experiment. If it were so, it could be substantially reduced and even absorbed within the theoretical uncertainties in the $^8B$ neutrino flux [13], the only component observed in Kamiokande and the main one in Homestake. More important, it is the problem of the disappearance of the intermediate energy neutrinos [14] - [18]. This is practically independent of any solar model considerations and relies essentially on a detailed analysis of the experimental data on the basis of the pp cycle dominance. There are therefore increasingly stronger indications that the solution to the solar neutrino problem must rely on non-standard neutrino properties, either neutrino oscillations in matter [19], vacuum [20], the magnetic moment [21, 22] or a hybrid scenario [23].

We will present here a new upper bound on the electron neutrino magnetic moment. Our work starts with an analysis on the dependence of the neutrino survival probability on its energy and uses the most recent data from the Homestake (Chlorine) and

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SuperKamiokande experiments. The first of these is looking at a purely weak charged current process, namely
\[ \nu_e + ^{37}Cl \rightarrow ^{37}Ar + e^- \] (1)
whereas the second is based on elastic scattering,
\[ \nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^- \] (2)
with \( x = \mu, \tau \) and where possible electromagnetic properties of the neutrino may play a significant role. These are parametrised in terms of the electromagnetic form factors which at \( q^2 \approx 0 \) amount to the magnetic moment and charge radius. We allow for the solar neutrino deficit to be jointly explained in terms of these electromagnetic effects and any other sources like, for instance, oscillations. The upper bound on the magnetic moment is of course obtained when these other sources are absent. Previous analyses of solar neutrino data aimed at deriving bounds on the neutrino magnetic moment \( \mu_\nu \) using neutrino electron scattering cross sections with electromagnetic interactions exist already in the literature [24, 25]. They did not however include the possibility of origins of the solar neutrino deficit other than the magnetic moment transition, resulting therefore in upper and lower bounds for \( \mu_\nu \). Furthermore they assumed an energy independent neutrino deficit, which now appears not to be the case [14] - [18], [26].

Our results are derived for six different theoretical solar models [7] - [12]. They show a smooth dependence on \( P_I \), the survival probability of the intermediate energy neutrinos, a parameter which to a very good accuracy (better than 2\( \sigma \)) can be assumed zero [16, 17]. For all models we obtain an upper bound in the range \((2.9 - 3.7) \times 10^{-10} \mu_B\), an improvement with respect to the most stringent laboratory bound existing to date, \( \mu_{\nu_e} \leq 6.1 \times 10^{-10} \mu_B \) (90\% CL), from the LAMPF group [27]. More stringent bounds exist, however, for the electron anti-neutrino magnetic moment at the same order of magnitude of the numbers obtained here: \( \mu_{\bar{\nu}_e} \leq 1.8 \times 10^{-10} \mu_B \) [28].

We restrict ourselves to the case of Dirac neutrinos. For Majorana neutrinos the analysis would be different because an active \( \bar{\nu}_e^M \) could also be present and be detected through the process \( \bar{\nu}_e^M + p \rightarrow n + e^+ \) for which there exists however the firm upper bound from the Kamiokande II experiment \( \Phi(\bar{\nu}_e^M) \leq (0.05 - 0.07) \Phi_{\nu_e}(^8B) \) [29]. Furthermore the states \( \bar{\nu}_{\mu,\tau}^M \) would now be active under weak interactions.

The plan of the present work is to first derive in section 2 the possible constraints of the survival probabilities of the intermediate and high energy solar neutrinos which follow from the experimental data. In section 3 the expression for the event rate in the SuperKamiokande experiment is written in terms of these survival probabilities, the magnetic moment \( \mu_\nu \) and the mean square radius \( < r^2 > \). From the lower laboratory bound on \( < r^2 > \) [27] and the probability constraints, the upper bound on \( \mu_\nu \) will follow. Finally in section 4 we derive our main conclusions and comment on possible future directions.

2. Energy Dependent Solar Neutrino Suppression

All six solar models ([7] - [12]) whose relevant predictions are given in table I include heavy element diffusion except for TCL [8] and TCCCD [9]. It is now generally acknowledged that a 'standard' solar model (SSM) should include diffusion, owing to the fact that such models give a remarkably good agreement with data from helioseismology [30].
The absence of the intermediate energy neutrinos, consisting principally of the $^7\text{Be}$ line at $E = 0.86\text{MeV}$ and the CNO continuum, has been realised several years ago [14] from the comparison of the Homestake and Kamiokande data. It is considered by some as the ‘true’ solar neutrino problem in the sense that it is independent from normalisation to any solar model, either standard or non-standard [31]. It appears as a natural consequence of the luminosity constraint [7], [17] ($L_\odot = 1.367 \times 10^{-1} W\text{cm}^{-2}$)

$$L_\odot = \sum_k \left( \frac{Q}{2} - <E_\nu>_k \right) \phi_k \quad (k = pp, pep, ^7\text{Be}, CNO, ^8\text{B})$$

with $Q = 26.73\text{MeV}$ (total energy released in each neutrino pair production) and the equations [17]

$$S_\text{Ga} = \sum_i \sigma_{\text{Ga},i} \phi_i \quad (i = pp, pep, ^7\text{Be}, CNO, ^8\text{B})$$

$$S_\text{Cl} = \sum_j \sigma_{\text{Cl},j} \phi_j \quad (i = ^7\text{Be}, CNO, ^8\text{B})$$

$$\phi_{\text{pep}} = 0.021 \phi_{pp}$$

where we used the weighted average from SAGE [4] and Gallex [5] $S_{\text{Ga}} = 73.8 \pm 7.7\text{SNU}$ and the Chlorine data, $2.54 \pm 0.14 \pm 0.14\text{SNU}$ [32].

One has in fact from this system of four equations, upon elimination of the $pp$ flux $\phi_{pp}$ and using the nuclear cross sections [17] $\sigma_{\text{Ga},i}, \sigma_{\text{Cl},j}$ the following intermediate energy neutrino flux (in units $\text{cm}^{-2}\text{s}^{-1}$)

$$\phi_{^7\text{Be}} = 1.04 \times 10^4 \phi_B - 2.88 \times 10^{10}$$

$$\phi_{\text{CNO}} = -8.46 \times 10^3 \phi_B + 2.22 \times 10^{10}.$$

Inserting $\phi_B$ from SuperKamiokande, [6] the total flux from these neutrinos is negative:

$$\phi_{^7\text{Be}} = -3.42 \times 10^{10} \text{cm}^{-2}\text{s}^{-1}$$

$$\phi_{\text{CNO}} = 1.56 \times 10^{10} \text{cm}^{-2}\text{s}^{-1}.$$ 

Better fits were done by the authors of [16], [17] who obtained

$$\phi_{^7\text{Be}+\text{CNO}} \leq 0.7 \times 10^9 \text{cm}^{-2}\text{s}^{-1} \quad (3\sigma)$$

$$\phi_{^7\text{Be}+\text{CNO}} = (-2.5 \pm 1.1) \times 10^9 \text{cm}^{-2}\text{s}^{-1}$$

which, compared with the theoretical predictions for six solar models [7] - [12] (see table I), gives

$$P_I(3\sigma, \text{all six models}) \leq 0.16.$$ 

These authors used the former Kamiokande flux data which were higher than SuperKamiokande. From equations (7) and (8) it is seen that the total flux $\phi_{^7\text{Be}+\text{CNO}}$ decreases with decreasing $\phi_B$, so that the results (11), (12) should be further aggravated in the non-physical direction. Hence the probability that neutrinos are standard is no greater than 1%, while, if the luminosity constraint is dropped, it may increase to 4% [16]. So intermediate energy neutrinos appear in practice to be completely suppressed.
| Model         | $R^I_{Cl}$ | $R^H_{Cl}$ | $R_{Cl}$ | $\phi_B$ | $R_{SK}$ | $\phi_{Be+CNO}$ |
|---------------|-----------|-----------|---------|---------|---------|-----------------|
| BP95         | 0.209     | 0.791     | 0.274   | 6.62    | 0.379   | 6.31            |
| TCL          | 0.248     | 0.752     | 0.401   | 4.43    | 0.567   | 5.37            |
| TCCCD        | 0.292     | 0.706     | 0.443   | 3.8     | 0.661   | 4.94            |
| P94          | 0.214     | 0.790     | 0.280   | 6.48    | 0.387   | 6.38            |
| RVCD96       | 0.204     | 0.799     | 0.397   | 5.84    |         |                 |
| FRANEC96     | 0.230     | 0.774     | 0.345   | 5.47    |         |                 |

Table I - The columns $R^I_{Cl}, R^H_{Cl}, R_{Cl}, \phi_B, R_{SK}, \phi_{Be+CNO}$ denote respectively the fractions of intermediate and high energy neutrinos in the Chlorine experiment, the ratio of the total measured signal and the model prediction, the $^8B$ flux prediction, the ratio data/model prediction for the SuperKamiokande data and the intermediate neutrino flux in each of the six models [7] - [12]. Units of $\phi_B$ are in $10^6 \text{cm}^{-2}\text{s}^{-1}$ and units of $\phi_{Be+CNO}$ are in $10^9 \text{cm}^{-2}\text{s}^{-1}$.

As far as high energy ($^8B$) neutrinos are concerned and denoting by $R_{Cl}$ the ratio data/SSM prediction one may write

$$R_{Cl} = R^I_{Cl}P_I + R^H_{Cl}P_H.$$  \hspace{1cm} (14)

Here $R^{I(H)}_{Cl}$ is the fraction of intermediate (high) energy neutrinos in the Chlorine experiment as theoretically predicted and $P^{I(H)}$ is the fraction of intermediate (high) energy $\nu_e$ produced in the Sun that are detected on Earth. Using $P_I = 0$ (99%CL) and the models listed in table I one gets for $P_H$ the range

$$0.35 < P_H < 0.63$$  \hspace{1cm} (15)

with the smaller value corresponding to BP95 [7] and the larger to TCCCD [9]. This will be the range of values used for $P_H$ in the following section.

3. Event Rates and Cross Sections

The event rate in a solar neutrino experiment in which recoil electrons are produced is given by the corresponding cross section per unit neutrino energy $E_{\nu}$ per unit kinetic energy $T$ of the recoil electron times the neutrino flux and summed over all possible neutrino fluxes:

$$S_{exp} = \sum_i \int dE_{\nu_i} \int \frac{d^2\sigma}{dT dE_{\nu_i}} \phi(E_{\nu_i})dT$$  \hspace{1cm} (16)

The quantity $\phi(E_{\nu_i})$ represents the i-th normalised neutrino flux. For SuperKamiokande, which is based on neutrino electron scattering, and where only the $^8B$ neutrino flux is seen, we have

$$S_{SK} = \int dE_{\nu} \int \phi(E_{\nu}) \left( X_W \frac{d^2\sigma_W}{dT dE_{\nu}} + \frac{d^2\sigma_{+EM}}{dT dE_{\nu}} + \frac{d^2\sigma_{-EM}}{dT dE_{\nu}} + X_{int} \frac{d^2\sigma_{int}}{dT dE_{\nu}} \right) dT$$  \hspace{1cm} (17)

The quantities $X_W, X_{int}$ will be derived below. The weak ($d^2\sigma_W/dT dE_{\nu}$), electromagnetic spin non-flip ($d^2\sigma_{+EM}/dT dE_{\nu}$), electromagnetic spin flip ($d^2\sigma_{-EM}/dT dE_{\nu}$) and interference ($d^2\sigma_{int}/dT dE_{\nu}$) parts of the differential cross section were taken from [83]. Denoting
by \( \phi \), the neutrino magnetic moment in Bohr magnetons \( \mu_B \) we have
\[
\frac{d^2 \sigma_W}{dTdE_\nu} = \frac{G_F^2 m_e}{2\pi} \left( (g_\nu + g_A)^2 + (g_\nu - g_A)^2 (1 - \frac{T}{E_\nu})^2 - (g_\nu^2 - g_A^2) \frac{m_e T}{E_\nu^2} \right)
\] (18)
\[
\frac{d^2 \sigma_{+EM}}{dTdE_\nu} = < r^2 >^2 \frac{\pi \alpha^2}{9} m_e \left( 1 + (1 - \frac{T}{E_\nu})^2 - \frac{m_e T}{E_\nu^2} \right)
\] (19)
\[
\frac{d^2 \sigma_{-EM}}{dTdE_\nu} = f_\nu \frac{\pi \alpha^2}{m_e^2} \left( \frac{1}{T} - \frac{1}{E_\nu} \right)
\] (20)
\[
\frac{d^2 \sigma_{\text{int}}}{dTdE_\nu} = - < r^2 > - \frac{\sqrt{2}}{3} \alpha G_F m_e \left( g_\nu \frac{m_e T}{E_\nu^2} - (g_\nu + g_A) - (g_\nu - g_A) (1 - \frac{T}{E_\nu})^2 \right)
\] (21)

where \( g_\nu = -1/2 + 2 \sin^2 \theta_W \), \( g_A = -1/2 \) for \( \nu = \nu_\mu, \nu_\tau \) and \( g_\nu = 1/2 + 2 \sin^2 \theta_W \), \( g_A = 1/2 \) for \( \nu = \nu_e \). We use \( \sin^2 \theta_W = 0.23 \). There are upper and lower experimental bounds for the mean square radius of the neutrino [27] (90% CL):
\[
-7.06 \times 10^{-11} < < r^2 > < 1.26 \times 10^{-10} \text{MeV}^2.
\] (22)

From the inequality [25]
\[
E_\nu \geq T + \sqrt{T^2 + 2m_e T}
\] ,
(23)
the maximum \(^8\text{B} \) neutrino energy \( E_{\nu_M} = 15 \text{MeV} \) and the electron threshold energy in the SuperKamiokande detector \( E_{e_{th}} = 7 \text{MeV} \), one can derive the lower and upper integration limits in eq. (17).

It should be noted at this stage that the integrated cross section in (17) refers to a neutrino flux which is assumed to have been modified either due to the magnetic moment spin flip inside the Sun or through flavour oscillations in the Sun or on its way to the detector. So an electron neutrino from the \(^8\text{B} \) flux produced in the core of the Sun has a survival probability \( P_H \) of reaching the SuperKamiokande detector, thus interacting weakly with the electron via the neutral or the charged current. The remaining \( (1 - P_H) \) fraction of the flux will have oscillated to \( \nu_{\mu L} \) (or \( \nu_{\tau L} \)) with a probability \( \alpha \), thus interacting via the weak neutral and electromagnetic currents only. Alternatively it will have flipped to \( \nu_{eR} \) (or \( \nu_{\muR} \) or \( \nu_{\tauR} \)) with a probability \( (1 - \alpha) \) via the magnetic moment, thus interacting only through the electromagnetic current (see fig.1).

The weak part of the total cross section in SuperKamiokande \( \sigma_w^K \) may therefore be decomposed as follows
\[
\sigma_w^K = P_H \sigma_w + \alpha (1-P_H) \sigma_{NC}
\]
\[
\simeq \sigma_w (0.15 \alpha + P_H (1 - 0.15 \alpha))
\] (24)

where \( \sigma_{NC} \) denotes the weak neutral cross section and \( \sigma_w \) denotes the total \( \nu_e e \) cross section which includes the neutral and charged current contributions. In eq. (24) we have used the well known fact that [34]
\[
\sigma_w \simeq 6.7 \sigma_{NC}.
\] (25)
This yields the parameter $X_W$ in equation (17):

$$X_W = 0.15\alpha + P_H (1 - 0.15\alpha).$$

In order to determine $X_{int}$, we decompose the interference cross section [eq.(21)] into its $\nu_e$ and $\nu_{\mu,\tau}$ parts, recalling as above that $\nu_{e,L}$ has partly survived with probability $P_H$ and partly oscillated to $\nu_{\mu,\tau,L}$ with probability $\alpha(1 - P_H)$:

$$\sigma_{int}^K = P_H \sigma_{\nu_e,int} + \alpha(1 - P_H)\sigma_{\nu_{\mu,\tau},int} \approx \sigma_{\nu_e,int}(P_H - 0.37 \alpha (1 - P_H)).$$

In the last step we used (21) and the definitions above for $g_A, g_V$ to obtain

$$\frac{\sigma_{\nu_{\mu,\tau},int}}{\sigma_{\nu_e,int}} \approx -0.37$$

for the integrated cross sections, which yields

$$X_{int} = (P_H - 0.37 \alpha (1 - P_H)).$$

If neutrinos are standard, they do not oscillate nor have any electromagnetic properties and only the $\sigma_W$ term survives in equation (17). This corresponds to $X_W = 1$ ($\alpha = 0, P_H = 1$). In such a case the prediction of eq. (17) for the SuperKamiokande event rate is wrong by a solar model dependent factor $R_{SK}$ which is the ratio between the data and the model prediction:

$$S_{SK} = R_{SK} \int dE_\nu \int dE_{\nu} \int dT \int dE_{\nu} \frac{d^2\sigma_W}{dTdTdE_\nu}.$$
The basic point of the paper is to equate the right hand sides of (17) and (30). We note that in doing so we are not merely attempting to explain the neutrino deficit in SuperKamiokande which is model dependent. Even if $R_{SK} = 1$ (no neutrino deficit appears in SuperKamiokande) there may still be electromagnetic properties related to the main problem of the disappearance of the intermediate energy neutrinos.

Equating (17) and (30) and taking $R_{SK}$ as an input, leaves us four parameters ($\alpha, P_H$ and the electromagnetic ones – $f_\nu, < r^2 >$) of which $P_H$ is directly related to $P_I$ (see eq.(14)). We obtain

$$f_\nu^2 = (R_{SK} - 0.15 \alpha - P_H (1 - 0.15 \alpha )) \frac{\sigma_W}{B_{-EM}}$$

$$- < r^2 > (P_H - (1 - P_H) 0.37 \alpha ) \frac{A_{int}}{B_{-EM}} - < r^2 >^2 \frac{B_{+EM}}{B_{-EM}}$$

where

$$\sigma_W = \int dE_\nu \int \phi(E_\nu) \frac{d^2\sigma_W}{dTdE_\nu} dT$$

$$< r^2 > B_{+EM} = \int dE_\nu \int \phi(E_\nu) \frac{d^2\sigma_{+EM}}{dTdE_\nu} dT$$

$$f_\nu^2 B_{-EM} = \int dE_\nu \int \phi(E_\nu) \frac{d^2\sigma_{-EM}}{dTdE_\nu} dT$$

$$< r^2 > A_{int} = \int dE_\nu \int \phi(E_\nu) \frac{d^2\sigma_{int}}{dTdE_\nu} dT.$$
operated with a threshold of 7.0 MeV and plans to improve it down to 5.0 MeV in the near future. The forthcoming SNO experiment also aims to operate near this threshold. For $E_{\text{th}} = 5.0$ MeV and the same ratio of data/model prediction for the $^8B$ neutrino flux ($R_{SK}$), the bound (36) would be decreased by approximately 50%. Hence a further decrease in the electron threshold energy will be a welcome improvement.

4. Conclusions

We have investigated the existence of an upper bound on the electron neutrino magnetic moment $\mu_{\nu_e}$ from solar neutrino experiments. Besides laboratory bounds, this looks a promising source for constraining all neutrino magnetic moments and thus establishing upper limits on these quantities. The strictest laboratory bounds existent up to date refer to electron anti-neutrinos ($\mu_{\bar{\nu}_e} < 1.8 \times 10^{-10} \mu_B$ \cite{28}) and a new experiment aimed at providing new constraints is expected to start operation soon. Regarding laboratory
bounds on $\mu_{\nu_e}$, the limit is higher: $\mu_{\nu_e} < 6.1 \times 10^{-10} \mu_B$ \cite{27}. We believe the present work, where we used SuperKamiokande data, improves this bound by a factor of approximately 2. We find $\mu_{\nu_e} < (2.9 - 3.7) \times 10^{-10} \mu_B$. Both were obtained on the assumption of equal neutrino magnetic moments for different flavours. Furthermore we assumed a total suppression of intermediate energy neutrinos: $P_I = 0$.

From the solar models standpoint, the uncertainties in $S_{17}$, the parameter describing the $^8B$ flux prediction, although not irrelevant, do not play a crucial role. In fact, the upper bound on $\mu_{\nu_e}$ is only very moderately sensitive to them.

On the other hand, the decrease in the recoil electron threshold energy in the solar neutrino electron scattering may further constrain this bound. Thus not only the expected improvement in SuperKamiokande, but also the SNO experiment \cite{36} examining this process with a 5 MeV threshold or possibly lower will be essential for the purpose.

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