Neutrino Magnetic Moment Upper Bound From Solar Neutrino Observations

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Abstract

Using the data from SuperKamiokande, Kamiokande and Homestake solar neutrino experiments we derive an upper bound on the magnetic moment of the neutrino and find $\mu_{\nu_e} \leq (2.2 - 2.3) \times 10^{-10} \mu_B$, within four 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. In our work we consider an energy dependent suppression of solar neutrinos. We also point out that the limit may be further reduced if the detector threshold energy in $\nu_{e,x}e^-$ scattering with solar neutrinos 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 \[4\] and Gallex \[5\] experiments, observing different parts of the neutrino spectrum, started operation. Besides these experiments, several theoretical solar models \[6\] - \[13\] 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 \[14\], 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 \[15\] - \[19\]. 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 \[20\], vacuum \[21\], the magnetic moment \[22\], \[23\] or a ”hybrid scenario” \[24\].

In this paper we aim at establishing a new upper bound on the electron neutrino magnetic moment. Our work starts from the analysis of the weak and electromagnetic cross section for neutrino electron scattering in the Kamiokande detector and uses the most recent data from the Homestake (Chlorine), Kamiokande and SuperKamiokande experiments. The first of these experiments is looking at a purely weak charged current process, namely

$$\nu_e + ^{37} Cl \rightarrow ^{37} Ar + e^-$$  \hspace{1cm} (1)

whereas the second is based on elastic scattering,

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$  \hspace{1cm} (2)

with $x = \mu, \tau$ and where possible electromagnetic properties of the neutrino may play a significant role. These are parametrized in terms of the electromagnetic form factors which at $q^2 \approx 0$ ammount 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 aimed at deriving bounds on the neutrino magnetic moment $\mu_\nu$ using neutrino electron scattering cross sections with electromagnetic interactions exist already in the litterature \[25\], \[26\]. They did not however include the possibility of origins for 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 \[15\] - \[19\], \[27\]. Several authors \[24\] have on the other hand performed investigations using the combined resonant spin-flip precession mechanism and oscillations which are based on specific assumptions on the magnitude and/or solar magnetic field profile and obtain iso-SNU and survival probability plots for the solar neutrino fluxes. The scope of our analysis is however quite different, since it takes into account the neutrino-electron scattering (weak and electromagnetic) in the Kamiokande detector and the actual
mechanism suppressing solar electron neutrinos ($\nu_{e_L}$) is totally irrelevant here. Further, we use the assumption of an energy dependent neutrino deficit as indicated by the combined experimental data. Our results are derived for four different theoretical solar models [6, 7, 8, 9]. They show a smooth dependence on $P_H$, the survival probability of the intermediate energy neutrinos, a parameter which to a very good accuracy (better than $2\sigma$) can be assumed zero [17, 18]. For all models we obtain an upper bound in the range $(2.2 - 2.3) \times 10^{-10} \mu_B$ for the electron neutrino magnetic moment, an improvement with respect to the most stringent laboratory bound existing to date, $\mu_{\nu_e} \leq 10.8 \times 10^{-10} \mu_B$ (90% CL), from the LAMPF group [28]. More stringent bounds exist, however, for the electron anti-neutrino magnetic moment at the same order of magnitude of the numbers obtained here: $\mu_{\bar{\nu}_e} \leq 1.8 \times 10^{-10} \mu_B$ [29]. Astrophysical and cosmological bounds are on the other hand even more restrictive. They come from supernova analysis [30] ($\mu_\nu \leq 10^{-13} \mu_B$), energy loss in Helium stars [31] ($\mu_\nu \leq 8 \times 10^{-12} \mu_B$), cooling of red giants by plasmon decay into neutrino pairs [32] ($\mu_\nu \leq 3 \times 10^{-12} \mu_B$) and nuclear synthesis in the big bang [33] ($\mu_\nu \leq 1.5 \times 10^{-11} \mu_B$). All these bounds cannot be taken as literally as the laboratory ones and especially the supernova one [30] is considered by some to be avoidable. Morgan’s bound [33] can be violated by one transition magnetic moment.

We restrict ourselves to the case of Dirac neutrinos. For Majorana neutrinos the analysis would be different because an active $\bar{\nu}_e R$ could also be present and be detected through the process $\bar{\nu}_e R + p \rightarrow n + e^+$ for which there exists however the firm upper bound from the LSD experiment $\Phi_{\bar{\nu}_e}/\Phi_{\nu_e} \leq 1.7\%$ [34]. Furthermore the states $\bar{\nu}_\mu,\tau R$ would now be active under weak interactions.

The plan of the paper is as follows: in section 2 we describe the method used for deriving the upper bound on $\mu_{\nu_e}$ starting from the cross sections for $\nu_{e,x} e$ scattering. We discuss its dependence on $P_H$, the survival probability for high energy ($^8B$) neutrinos which is related to $P_I$, and on $\alpha$ which parametrizes the disappearence due to flavour oscillations in each of the available solar models. In this way the present paper also differs from our previous work [26], where only essentially one model was available and neutrino suppression was considered energy independent, affecting equally the $^8B$ and the intermediate energy ($^7Be, CNO$) neutrinos which is presently known as not being the case. Moreover in [26] no matter oscillation effect was considered. It is remarkable that, although the $^8B$ flux prediction differs by sizeable amounts for different models with a relative spread of 43% (see table I), the prediction for the upper bound on $\mu_\nu$ using the recent SuperKamiokande data ranges over a 5% spread only (see fig. 3). Finally in section 3 we draw our main conclusions and comment on possible future directions.

2. 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:

$$S_{\text{exp}} = \sum_i \int dE_\nu_i \int \frac{d^2\sigma}{dT dE_\nu_i} f(E_\nu_i) dT$$

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

$$S_K = \int dE_\nu \int f(E_\nu) \left( X_W \frac{d^2 \sigma_W}{dT dE_\nu} + \frac{d^2 \sigma_{+EM}}{dT dE_\nu} + \frac{d^2 \sigma_{-EM}}{dT dE_\nu} + X_{int} \frac{d^2 \sigma_{int}}{dT dE_\nu} \right) dT \tag{4}$$

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 [35]. Denoting by $f_\nu$ the neutrino magnetic moment in Bohr magnetons $\mu_B$ we have

$$\frac{d^2 \sigma_W}{dT dE_\nu} = \frac{G_F^2 m_e}{2\pi} \left( (g_\nu + g_A)^2 + (g_\nu - g_A)^2(1 - \frac{T}{E_\nu})^2 - (g_\nu^2 - g_A^2) \frac{m_e T}{E_\nu^2} \right) \tag{5}$$

$$\frac{d^2 \sigma_{+EM}}{dT dE_\nu} = <r^2> \frac{\pi \alpha^2}{9} m_e \left( 1 + \frac{T}{E_\nu} ight)$$

$$\frac{d^2 \sigma_{-EM}}{dT dE_\nu} = f_\nu^2 \frac{\pi \alpha^2}{m_e} \left( \frac{1}{1 - \frac{T}{E_\nu}} \right) \tag{7}$$

$$\frac{d^2 \sigma_{int}}{dT dE_\nu} = -<r^2> \frac{\sqrt{2}}{3} \alpha G_F m_e \left( g_\nu \frac{m_e T}{E_\nu^2} - (g_\nu + g_A) - (g_\nu - g_A)(1 - \frac{T}{E_\nu})^2 \right) \tag{8}$$

There are upper and lower experimental bounds for the mean square radius of the neutrino [28] (90% CL):

$$-7.06 \times 10^{-11} < < r^2 > < 1.26 \times 10^{-10} \text{MeV}^{-2} \tag{9}$$

We will restrict ourselves to positive values. In equations (5)-(8) we have

$$g_\nu = -\frac{1}{2} + 2 \sin^2 \theta_W , \quad g_A = -\frac{1}{2} \tag{10}$$

for $\nu = \nu_\mu, \nu_\tau$,

$$g_\nu = \frac{1}{2} + 2 \sin^2 \theta_W , \quad g_A = \frac{1}{2} \tag{11}$$

for $\nu = \nu_e$ and we use $\sin^2 \theta_W = 0.23$.

From the inequality [20]

$$E_\nu \geq \frac{T + \sqrt{T^2 + 2m_e T}}{2} \tag{12}$$

and the maximum $^8\text{B}$ neutrino energy [2]

$$E_{\nu_M} = 15\text{MeV}, \tag{13}$$

one can derive the lower and upper integration limits in eq.(4). These are

$$E_{\nu_m} = \frac{T_m + \sqrt{T_m^2 + 2m_e T_m}}{2} , \quad E_{\nu_M} = 15\text{MeV} \tag{14}$$
\[ T_m = E_{e\text{th}} - m_e \quad , \quad T_M = \frac{2E_{\nu M}^2}{2E_{\nu M}^2 + m_e} \]  

(15)

where \( E_{e\text{th}} \) is the electron threshold energy in the Kamiokande detector.

It should be noted at this stage that the integrated cross section in (4) 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 \( ^8B \) flux produced in the core of the Sun has a survival probability \( P_H \) of reaching the Kamiokande 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 \( \nu_\mu \) (or \( \nu_\tau \)) with a probability \( \alpha \), thus interacting via the weak neutral and electromagnetic currents only. Alternatively it will have flipped to \( \nu_eR \) (or \( \nu_\mu,\tau R \)) 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 Kamiokande \( \sigma_K^W \) may therefore be decomposed as follows

\[
\sigma_K^W = P_H \sigma_{\nu e} + \alpha(1 - P_H)\sigma_{\nu \mu,\tau}
\]

\[
\simeq \sigma_{\nu e}(0.15\alpha + P_H(1 - 0.15\alpha))
\]

(16)

where \( \sigma_{\nu \mu,\tau} \) denotes the weak neutral cross section and \( \sigma_{\nu e} \) denotes the total \( \nu_e \) cross section which includes the neutral and charged current contributions. In eq. (16) we have used the well known fact that

\[
\sigma_{\nu_e} \simeq 6.7\sigma_{\nu \mu,\tau}.
\]

(17)

This yields the parameter \( X_W \) in equation (4):

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

(18)

In order to determine \( X_{int} \), we decompose the interference cross section [eq.(8)] into its \( \nu_e \) and \( \nu_{\mu,\tau} \) parts, recalling as above that \( \nu_e \) has partly survived with probability \( P_H \) and partly oscillated to \( \nu_\mu \) with probability \( \alpha(1 - P_H) \):

\[
\sigma_{int}^K = P_H \sigma_{\nu e,\text{int}} + \alpha(1 - P_H)\sigma_{\nu_{\mu,\tau},\text{int}}
\]

\[
\simeq \sigma_{\nu e,\text{int}}(P_H - 0.37\alpha(1 - P_H)).
\]

(19)

In the last step we used (8), (10), (11) to obtain

\[
\frac{\sigma_{\nu_{\mu,\tau},\text{int}}}{\sigma_{\nu e,\text{int}}} \simeq -0.37
\]

(20)

for the integrated cross sections, which yields

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

(21)

If neutrinos are standard, they do not oscillate nor have any electromagnetic properties and only the \( \sigma_W \) term survives in equation (4). This corresponds to \( X_W = 1 \) (\( \alpha = 0, P_H = 1 \)). In such a case the prediction of eq. (4) for the Kamiokande event rate is wrong by

\[ 1 \] Since we are interested in the upper bound for the magnetic moment which is obtained as will be seen for vanishing charge radius, we assume \( <r^2>_{\nu_e} = <r^2>_{\nu_{\mu,\tau}} \) and \( \mu_{\nu_e} = \mu_{\nu_{\mu,\tau}} \).
a solar model dependent factor $R_K$ which is the ratio between the data and the model prediction:

$$S_K = R_K \int dE_\nu \int f(E_\nu) \frac{d^2 \sigma_W}{dT dE_\nu} dT.$$  \hfill (22)

The basic point of the paper is to equate the right hand sides of (4) and (22). We note that in doing so we are not merely attempting to explain the neutrino deficit in Kamiokande which is model dependent. Even if $R_K = 1$ (no neutrino deficit appears in Kamiokande) there may still be electromagnetic properties related to the main problem of the disappearance of the intermediate energy neutrinos.

Equating (4) and (22) and taking $R_K$ 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 $P_I$ as will be seen. We obtain

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

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

where

$$\sigma_W = \int dE_\nu \int f(E_\nu) \frac{d^2 \sigma_W}{dT dE_\nu} dT$$  \hfill (24)

$$<r^2>^2 B_{+EM} = \int dE_\nu \int f(E_\nu) \frac{d^2 \sigma_{+EM}}{dT dE_\nu} dT$$  \hfill (25)

$$f_\nu^2 B_{-EM} = \int dE_\nu \int f(E_\nu) \frac{d^2 \sigma_{-EM}}{dT dE_\nu} dT$$  \hfill (26)

$$<r^2> A_{int} = \int dE_\nu \int f(E_\nu) \frac{d^2 \sigma_{int}}{dT dE_\nu} dT.$$  \hfill (27)

For a given $R_K$, maximizing the magnetic moment for fixed $P_H$ ammounts to minimizing $\alpha$ and $<r^2> (\alpha = 0, <r^2> = 0)$. This is to be expected since it corresponds to the absence of oscillations and vanishing mean square radius, so the neutrino deficit would only rely on the magnetic moment. Furthermore, it is seen that $f_\nu$ also decreases with increasing $P_H$. A relation between $P_H$ and $P_I$ can be obtained from the Chlorine data and the solar model predictions. It involves in each model the ratio between the measured Chlorine event rate and its prediction, $R_{Cl}$, and the quantities $R_{Cl}^{8B}, R_{Cl}^{CNO}$ denoting the fractions of $^8B$ and intermediate energy neutrinos ($^7Be, CNO$) (see table I). These quantities are evaluated by dividing the model predicted rate for the corresponding neutrino component by the total predicted rate in the model. We have

$$R_{Cl} = R_{Cl}^{8B} P_I + R_{Cl}^{CNO} P_H.$$  \hfill (28)

In fig.2 we show $P_H$ as a function of $P_I$ in the four models considered $[6, 7, 8, 9]$.

Recent numerical analyses $[17, 18]$ provide us valuable information on the degree of suppression of the neutrino fluxes. It is found that the survival probability of intermediate neutrinos (in the sense that their flux should be positive, $\phi_{Be,CNO} > 0$) is in the range $2\% - 4\%$. The authors of $[17, 18]$ base their analyses on the central values of the $^8B$ flux quoted by Kamiokande ($\phi_B = (2.95 \pm 0.32 \pm 0.36) \times 10^6 cm^{-2} s^{-1}$ $[17]$ and $\phi_B = (2.73 \pm$
0.17 ± 0.34) × 10^6 cm^-2 s^-1 [18]), while the recent values quoted by SuperKamiokande are manifestly lower. They obtained the fits

ref.17) \[ \phi_{\text{Be}+\text{CNO}} = (-2.5 \pm 1.1) \times 10^9 cm^{-2} s^{-1} \] (29)
ref.18) \[ \phi_{\text{Be}+\text{CNO}} \leq 0.7 \times 10^9 cm^{-2} s^{-1} \] (3σ) (30)

which, compared with the theoretical predictions for eight solar models [6] - [18] (see table II), gives

\[ P_I(3\sigma, \text{all eight models}) \leq 0.18. \] (31)

A straightforward argument which is practically independent of any solar model assumptions shows that by decreasing \( \phi_B (= \phi_B^{Kam}) \), the flux of the intermediate energy neutrinos is further decreased. In fact, using the equations [18]

\[ S_{Ga} = \sum_i \sigma_{Ga,i} \phi_i \quad (i = pp, pep, ^7\text{Be}, \text{CNO}, ^8\text{B}) \] (32)
\[ S_{Cl} = \sum_j \sigma_{Cl,j} \phi_j \quad (j = ^7\text{Be}, \text{CNO}, ^8\text{B}) \] (33)

together with the luminosity constraint [1, 18] \( L_\odot = 1.367 \times 10^{-1} W cm^{-2} \)

\[ L_\odot = \sum_k \left( \frac{Q}{2} - <E_\nu>_k \right) \phi_k \] (k = pp, pep, ^7Be, CNO, ^8B) (34)

with \( Q = 26.73 MeV \) (total energy released in each neutrino pair production) and taking \( \phi_{\text{pp}} = 0.0021 \phi_{pp} \), one gets upon elimination of \( \phi_{pp} \):

\[ \phi_{\text{Be}} = 10.4 \phi_B - 28.8 \] , \[ \phi_{\text{CNO}} = -8.46 \phi_B + 22.2 \] . (35) (36)

In these equations \( \phi_B \) is given in units of \( 10^6 cm^{-2} s^{-1} \) while \( \phi_{\text{Be}}, \phi_{\text{CNO}} \) are given in units of \( 10^9 cm^{-2} s^{-1} \) and we used \( S_{Cl} = 2.55 \pm 0.25 SNU \) [17] and the weighted average of SAGE [1] and Gallex [5] data, \( S_{Ga} = 73.8 \pm 7.7 SNU \). Since \( \phi_{\text{Be}} \) is of the order of 5 times \( \phi_{\text{CNO}} \) or larger, it is obvious from (35), (36) that a decrease in \( \phi_B^{Kam} \) leads to a decrease in the total flux \( \phi_{\text{Be}+\text{CNO}} \). We therefore conclude that SuperKamiokande data strengthen the general belief that the intermediate energy neutrinos (mainly \( ^7\text{Be} \)) are strongly suppressed. Thus it appears from eqs. (29), (30) to within 97% CL at least, one can take a vanishing \( P_I \).

Clearly if the neutrino is endowed with electromagnetic properties, it may in principle have a magnetic moment \( \mu_\nu \) and a mean square radius \( <r^2> \). The upper bound on the magnetic moment is obtained from eq. (23) in the limiting situation of vanishing \( <r^2> \) and \( \alpha \) (absence of flavour oscillations). We are bound to restrict ourselves to solar models [1, 2, 3, 4, 5] for which the ratios \( R_i^c \) and \( R_i^g \) are available and with comparatively small error bars. Using eqs. (23) and (28) we display the neutrino magnetic moment in Bohr magnetons \( f_\nu \) against \( P_I \), the survival probability for intermediate energy neutrinos, up to \( P_I = 0.18 \) (see eq. (31)) and with \( <r^2> = 0, \alpha = 0 \). We consider two situations: in fig. 3 we use the preliminary results [39] from SuperKamiokande, \( \phi_B^{SK} = (2.51 \pm 0.14 \pm 0.18) \times 10^9 cm^{-2} s^{-1} \) with a threshold \( E_{\nu_{th}} = 7.0 MeV \) and in fig. 4 we use the Kamiokande results [39], \( \phi_B^{Kam} = (2.80 \pm 0.19 \pm 0.33) \times 10^6 cm^{-2} s^{-1} \) and threshold \( E_{\nu_{th}} = 7.0 MeV \). We also
show in figs. 5, 6 the behaviour of $\mu_{\nu_e}$ as a function of $< r^2 >$ in the limit $\alpha = 0$ and as a function of $\alpha$ in the limit $< r^2 > = 0$ respectively.

It is clear that the results for the upper bounds on $\mu_{\nu_e}$ obtained using SuperKamiokande are not only stricter than the ones using Kamiokande, but their spread for the different models is also much smaller. As shown above, up to more than $2\sigma$ one can take $P_I = 0$, so it is appropriate to consider the left ends of these curves as the actual upper limits on $\mu_{\nu_e}$ from experiment and theoretical models. We have in these conditions

$$
\mu_{\nu_e} \leq (2.18 - 2.29) \times 10^{-10} \mu_B \quad \text{SuperKamiokande} \quad (37)
$$

$$
\mu_{\nu_e} \leq (3.46 - 4.13) \times 10^{-10} \mu_B \quad \text{Kamiokande.} \quad (38)
$$

These may increase by approximately 50% if one relaxes the constraint of a vanishing $P_I$ and let it approach its $3\sigma$ upper limit of 0.18 (see figs. 3, 4). We also note that the disparities on the predictions for the $^8B$ flux among solar models (table I), related to uncertainties in the astrophysical factor $S_{17}$, are hardly reflected on the upper bound on $\mu_{\nu}$ for all neutrino types.

An essential development which may further improve the bound (37) is the decrease in $E_{\text{eth}}$, the recoil electron threshold energy in $\nu_{e,e^{-}}e$ scattering. This decrease implies a decrease in the ratio of integrals $\sigma_W/B_{-EM}$ appearing in equation (23). This is related to the fact that for decreasing energy and a sizeable neutrino magnetic moment, the electromagnetic contribution to the scattering increases faster than the weak one. The above referred ratio of integrals leads through (23) for constant values of $R_K$ and $P_H$ to a decrease in the upper bound for $f_{\nu}$. Both the Kamiokande and the SuperKamiokande detector so far operate with a threshold of 7.0 MeV. The SuperKamiokande collaboration plans to improve their threshold down to 5.0 MeV in the near future. The forthcoming SNO experiment [41] also aims to operate near this threshold. For $E_{\text{eth}} = 5.0$ MeV and the same ratio of data/model prediction for the $^8B$ neutrino flux ($R_K$), the bound (37) would be decreased to $(1.6 - 1.7) \times 10^{-10} \mu_B$. Hence a further decrease in the electron threshold energy will be a welcome improvement.

3. Conclusions

We have investigated the existence of an upper bound on the electric 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 ($\mu_{\bar{\nu}_e} < 1.8 \times 10^{-10} \mu_B$ [27]) and a new experiment [10] aimed at providing new constraints is expected to start operation soon. Regarding laboratory bounds on $\mu_{\nu_e}$, the limit is higher: $\mu_{\nu_e} < 10.8 \times 10^{-10} \mu_B$ [28]. We believe the present work, where we used SuperKamiokande data, provides a new bound on $\mu_{\nu_e}$ of the order of the one available on $\mu_{\bar{\nu}_e}$. We find $\mu_{\nu_e} < (2.2 - 2.3) \times 10^{-10} \mu_B$. This was derived on the assumption of equal neutrino magnetic moments for different flavours and a total suppression of intermediate energy neutrinos: $P_I = 0$.

From the theoretical 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 [41] examining this process with a 5 MeV threshold or possibly lower will be essential for the purpose.

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Table I - The columns $R_{Cl}^I$, $R_{Cl}^\mu$, $R_{Cl}$, $\phi_B$, $R_{SK}$, $R_K$ 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 and the ratio data/model prediction for the SuperKamiokande and Kamiokande data in each of the four models [6] - [9]. Units of $\phi_B$ are in $10^6 cm^{-2} s^{-1}$.

| Model   | $R_{Cl}^I$ | $R_{Cl}^\mu$ | $R_{Cl}$ | $\phi_B$ | $R_{SK}$ | $R_K$ |
|---------|-----------|--------------|----------|---------|---------|-------|
| BP95    | 0.209     | 0.791        | 0.274    | 6.62    | 0.379   | 0.423 |
| BP92    | 0.221     | 0.777        | 0.319    | 5.69    | 0.441   | 0.492 |
| TCL     | 0.248     | 0.752        | 0.401    | 4.43    | 0.567   | 0.632 |
| TCCCD   | 0.292     | 0.706        | 0.443    | 3.8     | 0.661   | 0.737 |

Table II - The flux of $^7Be$ and CNO neutrinos in each of the eight models considered in eq. (31).

| Model     | $\phi_{Be+CNO}$ ($\times 10^6 cm^{-2} s^{-1}$) |
|-----------|-----------------------------------------------|
| BP95      | 6.31                                          |
| BP 92     | 5.81                                          |
| TCL       | 5.37                                          |
| TCCCD     | 4.94                                          |
| P94       | 6.38                                          |
| DS96      | 4.47                                          |
| RVCD96    | 5.84                                          |
| FRANEC96  | 5.47                                          |
Figure 1: A fraction $P_H$ of the initial $\nu_{eL}$ flux remains unaltered and interacts with $e^-$ in Kamiokande. Its cross section contains a weak contribution (charged (CC) and neutral current (NC)), an electromagnetic one and the interference between them. Of the remaining $(1 - P_H)$, a fraction $\alpha$ is converted to $\nu_{\mu,\tau L}$ and interacts without the weak charged current while the remaining $(1 - \alpha)(1 - P_H)$ interacts only electromagnetically.
Figure 2: $P_H$ as a function of $P_I$ up to $P_I = 0.18$ for each of the four models [6]-[9].
Figure 3: The neutrino magnetic moment as a function of $P_I$ for $\alpha = 0$, $< r^2 >= 0$ in each of the four models [6]-[9]. Within 97% CL at least, one can take $P_I = 0$, so the corresponding upper bound on $\mu_{\nu e}$ is in each model the value at the left end of the curve. The experimental data used are from SuperKamiokande.
Figure 4: Same as fig. 3 with Kamiokande data.
Figure 5: Neutrino magnetic moment as a function of the mean square radius $< r^2 > = 0$ ion the limit $\alpha = 0$ and in each of the four models [6]-[9]. The upper bound on $\mu_{\nu_e}$ is in each model the left end of the curve.
Figure 6: Same as fig. 5 as a function of $\alpha$ in the limit $< r^2 > = 0$. 

\[ \mu(0, 0) \]