New upper bound for the neutrino magnetic moment from its Dirac/Majorana nature and Borexino data

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Massive neutrinos can have helicity $s_\parallel \neq -1$. This fact can be used to distinguish Dirac from Majorana neutrinos in neutrino-electron scattering. Since neutrino helicity changes when it interacts with a magnetic field, the left-handed neutrinos born inside the sun are expected to evolve leaving the sun with a different helicity. Using a model for the magnetic field of the Sun, it is shown that the number of $^7$Be solar neutrino events detected by the Borexino Collaboration can be used to set a new upper bound for the neutrino magnetic moment of $\mu_\nu < 1.4 \times 10^{-13}\mu_B$.

INTRODUCTION

A fundamental challenge in the particle physics community is to determine the Majorana or Dirac nature of the neutrino. In order to assess this question, experimentalist are exploring different reactions where the Majorana nature may manifest (for a recent review see e.g. [1]). Well known facts concerning this problem are:

1. a Majorana particle is identical to its antiparticle leading to reactions where the lepton number is not conserved. The prototypical example of those processes is the neutrinoless double beta decay [2, 3] and,

2. massive neutrinos can have helicity $s_\parallel \neq -1$ and there are helicity-driven effects yielding a sizable difference in the scattering cross sections for Majorana and Dirac neutrinos off electrons [4, 5, 6].

Although these facts are well known, most of the experimental efforts are concentrated in the search of the neutrinoless double beta decay. Multiple experiments were constructed for this purpose like the Heidelberg-Moscow experiment [7], IGEX [10], EXO [11] or Kamland-ZEN [12] among others that are currently running like CUORE [13].

The purpose of this note is to further elaborate on the second possibility. Previous work on this topic have concentrated in a fully conversion of left handed Majorana neutrino into right handed Majorana anti-neutrino [14, 15]. The non observation of electron anti-neutrinos in solar detectors have set strong limits on the neutrino magnetic moment [17]. Here, we will show that it is not necessary to have a full neutrino-antineutrino conversion to have a positive signal of this effect, but only a change in the vector polarization will lead to measurable differences, obtaining a new upper bound for the neutrino magnetic moment from Borexino data and a model for the magnetic profile of the Sun.

THE $\nu$-E SCATTERING CROSS SECTION INCLUDING NEUTRINO POLARIZATION

Possible differences of the $\nu$-e scattering cross section for Dirac or Majorana neutrinos have been previously considered concluding that such differences are proportional to the neutrino masses [2, 3]. Given the smallness of the neutrino masses, in practice, no measurable difference in the Majorana or Dirac $\nu$-e scattering cross section seems to be possible. Nevertheless, according to [1, 3], when the neutrino polarization is taken into account, a clear difference between Majorana and Dirac neutrinos in neutrino-electron scattering appears. If the incident neutrino polarization vector is defined in the neutrino rest frame as $s_\nu = (0, s_\perp, 0, s_\parallel)$, we can calculate the differential cross sections for each case, Dirac and Majorana, in term of the helicity $s_\parallel$.

In [3, 8] the cross section was computed in the center of mass frame. Here we present the same expression but in the laboratory frame, which is more suitable for the purposes of this paper. The differential cross sections for this process are given by

\[
\frac{d^2\sigma^D}{dE dT} = \frac{d^2\sigma^D}{dE dT} (s_\parallel = -1) + (s_\parallel + 1) \frac{m_\nu G_F^2}{4\pi P^3} \left\{ -E_\nu \times \left[ (g_A + g_V) P^2 + (g_A - g_V) (E_\nu - T)^2 + (g_A^2 - g_V^2) m_\nu T \right] + m_\nu^2 \left[ (g_A - g_V)^2 (E_\nu - T) \left( 1 + \frac{T}{m_\nu} \right) - (g_A^2 - g_V^2) T \right] \right\}, \tag{1}
\]

for the Dirac case, while if the neutrino is a Majorana particle the cross section is:

\[
\frac{d^2\sigma^M}{dE dT} = \frac{d^2\sigma^M}{dE dT} (s_\parallel = -1) + (s_\parallel + 1) \frac{m_\nu G_F^2}{\pi P^3} E_\nu T g_A g_V (T - 2E_\nu) \left( 1 + \frac{m_\nu^2}{E_\nu m_\nu} \right), \tag{2}
\]

In the last equations, $P = \lvert \vec{P}_\nu \rvert$ is the momentum of the incident neutrino whereas $T$ represent the electron recoil energy. From Eqs. (1) or (2), with $m_\nu = 0$ and
s_|| = -1, the usual differential cross section for \( \nu e \) scattering is recovered. Presently, cosmological data sets a limit on the sum of the neutrino masses \( \sum m_\nu < 0.183 \) eV \[23\]. Furthermore, terrestrial experiments designed to measure the effect of neutrino masses on the tritium \( \beta \)-decay spectrum near its endpoint have set an upper bound for the electron neutrino mass of \( m_\nu < 2.3 \) eV/c\(^2\) at 95% C.L. \[24, 25\]. Thus, neutrino masses are really small, and the only variable left to produce a difference between a Dirac neutrino and a Majorana neutrino is \( s_|| \).

In order to illustrate the differences between Dirac and Majorana cross sections driven by \( s_|| \) we calculate the cross section for specific polarization

\[
\sigma^{M,D}(s_\parallel) \equiv \int_{T_{\max}}^{T_{\min}} dT \int_0^\infty dE_\nu \lambda(E_\nu) \frac{d^2\sigma^{M,D}}{dE_\nu dT}(E_\nu, T, s_\parallel),
\]

where \( \lambda(E_\nu) \) is the neutrino spectrum which depends of the neutrino source under consideration. For definitiveness, we will use the \(^7\)Be line of the solar neutrino spectrum. In this case, the spectrum will be a Dirac delta centred in \( E_\nu = 0.862 \) MeV. For the recoil energy \( T \), we will assume a detector with the characteristics of Borexino, i.e., we consider \( T \in [250, 750] \) KeV.

To exhibit the size of the helicity-driven effects, in Fig. 1 we plot the integrated cross sections for Dirac and Majorana neutrinos taking \( m_\nu = 1 \) eV in the numeric calculations. We can see three important features in this figure:

1. A left handed Dirac neutrino has the same cross section as a left handed Majorana neutrino.
2. A right handed Majorana neutrino has the same cross section as a left handed Dirac antineutrino, and,
3. A right handed Dirac neutrino has zero cross section, i.e. it is an sterile neutrino.

Besides these three limits, there are differences in the Majorana and Dirac cross section for \(-1 < s_\parallel < 1\). A way to quantify this difference is through the function

\[
D(s_\parallel) = \frac{|\sigma^{M}(s_\parallel) - \sigma^{D}(s_\parallel)|}{\sigma^{D}(s_\parallel)},
\]

which depends only on the helicity \( s_\parallel \). We remark that neutrino-mass-driven effects cancel in the difference and this function reflects more properly the helicity-driven effects. The function \( D(s_\parallel) \) with \( \sigma^{M,D} \) integrated assuming \( \lambda(E_\nu) = \delta(E_\nu - 0.862\text{MeV}) \) and \( T \in [0.250, 0.750] \) MeV is shown in Fig. 2.

The analysis of Borexino Collaboration assumes \( s_\parallel = -1 \) in whose case Dirac and Majorana cross sections coincide. However, if we consider the change in the neutrino helicity induced by the magnetic field in the Sun, there is a difference in \( d\sigma/dT \) (spectrum of the electron recoil energy) and in the total cross section. Since the number of events is computed through the cross section, i.e. \( N \sim n_t \phi \int dE_\nu dT P(E_\nu) \lambda(E_\nu) \frac{d^2\sigma}{dE_\nu dT} \), the \(^7\)Be line of the solar neutrino spectrum offers a unique way of testing neutrino-electron cross section. Indeed, in this case, the spectrum fixes \( E_\nu = 0.862 \) MeV and thus Eq. 4 coincide with the normalized uncertainty in the number of events. In this concern, the uncertainty in the data of Borexino number of events translates into an uncertainty in the Dirac-Majorana difference \( D(s_\parallel) \), putting an upper bound on this quantity.

From the number of neutrino events \( N = 49 \pm 1.5_{\text{stat}}^{+1.5}_{\text{syst}} \text{counts/day/100 ton} \) reported by Borexino \[19, 20\] we obtain that the Dirac-Majorana difference should be less than 4.4%. Solving for \( D(s_\parallel) < 0.044 \) (see Fig. 2) we obtain the constraint \( s_\parallel < -0.68 \) for the helicity of the neutrinos caught in Borexino detectors.

Now, the possible change in the neutrino helicity in the sun is due to the interaction of the neutrino magnetic moment with the magnetic field in the Sun. The question is.
if the Sun can produce sizable changes in the helicity of neutrinos to yield a measurable effect in terrestrial detectors. After a characterization of the magnetic field in the Sun and a study of its effect on the neutrino helicity, we will come back to this important question and show that a new upper bound on the neutrino magnetic moment is obtained.

**THE CHANGE OF NEUTRINO HELICITY INSIDE THE SUN**

Neutrinos are born in the Sun as left handed-particles. Indeed, for instance, in the decay of a pseudo-scalar meson $P^+ \to \ell^+ + \nu$, the neutrino helicity $s_||$, can be computed as $s_|| = (E - W)|\vec{k}|/(WE - |\vec{k}|^2)$ with $W$ and $E$ the energies of the charged lepton $\ell$ and the neutrino respectively [20]. Due to the smallness of the neutrino mass, effectively the initial vector polarization can be written as $s_\nu = (0, s_\perp = 0, 0, s_|| = -1)$ and as we have shown before, Dirac or Majorana $\nu - e$ cross section for small neutrino masses and left handed Dirac or Majorana neutrinos are identical. Nevertheless, neutrinos may have a magnetic moment if they are massive. The standard model value of the magnetic moment of a Dirac neutrino was computed in [27] and it is given by

$$\mu_\nu \sim 3.2 \times 10^{-19} \mu_B \left( \frac{m_\nu}{eV} \right),$$

where $\mu_B$ is the Bohr magneton and $m_\nu$ is the neutrino mass. Any particle that has a magnetic moment can change its longitudinal part of the polarization vector. In the case of the neutrino, in presence of an external magnetic field, the helicity may change according to the equation [28]:

$$\frac{ds_||}{dr} = -2\mu_\nu B_\perp s_||,$$

where $B_\perp$ is the perpendicular component of the external magnetic field with respect to the propagation of the neutrino. The Majorana magnetic moment of the neutrino is introduced via the effective electromagnetic Hamiltonian $H_{em}^M = -\frac{i}{2}\bar{\nu}_L \gamma^1 C \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + h.c.$ [28]. Here $\lambda = \mu - id$ is an antisymmetric arbitrary complex matrix. On the other hand, the corresponding Dirac electromagnetic effective Hamiltonian $H_{em}^D = \frac{i}{2}\bar{\nu}_L \lambda_1 \gamma^0 \nu_L F^{\alpha\beta} + h.c.$ and in this case, $\lambda = \mu - id$ is an arbitrary complex hermitian matrix [30]. Experiments are sensitive only to some process-dependent effective neutrino magnetic moment $\mu_\nu$, given by a superposition of the matrix elements of $\lambda$ (see for instance [31]). It is this effective moment the one that will affect the neutrino helicity $s_||$ according to Eq. (6). Experimental limits on this effective magnetic neutrino moment have been obtained for different sources and are shown in Table I.

The other relevant ingredient to describe the change of $s_||$ is the external magnetic field $B_\perp$. Here, we follow the magnetic profile proposed in [18] obtained through fully self-consistent and analytical solutions of the magnetohydrodynamic equations inside the Sun. The magnetic field inside the Sun can be compute as a family of those solutions given by:

$$B_{z'}^e(r, \theta) = 2\hat{B}^k \cos \theta \left[ 1 - \frac{3}{r^2 z_k \sin z_k} \left( \frac{\sin(zkr)}{zkr} - \cos(zkr) \right) \right],$$

$$B_{\theta'}^e(r, \theta) = -\hat{B}^k \sin \theta \times \left[ 2 + \frac{3}{r^2 z_k \sin z_k} \left( \frac{\sin(zkr)(1 - (zkr)^2)}{zkr} - \cos(zkr) \right) \right],$$

$$B_{\phi'}^e(r, \theta) = \hat{B}^k z_k \sin \theta \left[ r - \frac{3}{r^2 z_k \sin z_k} \left( \frac{\sin(zkr)}{zkr} - \cos(zkr) \right) \right],$$

where $z_k$ denotes the roots of the spherical Bessel function, $\theta$ is the polar angle and the distance $r$ has been normalized to the solar radius $R_\odot$. The coefficient $\hat{B}^k(B_{core})$ is given by

$$\hat{B}^k = \frac{B_{core}}{2(1 - z_k/\sin z_k)}.$$

There is an upper limit on the magnitude of the Solar magnetic moment in the core. It should be smaller than

| Experiment | Limit | Ref. |
|------------|-------|------|
| GEMMA$_{\text{Reactor}}\nu_e - e^-$ | $\mu_\nu < 2.9 \times 10^{-11} \mu_B$ | [32] |
| LSND$_{\text{Accelerator}}\nu_\mu, \bar{\nu}_\mu - \mu^-$ | $\mu_\nu < 6.8 \times 10^{-10} \mu_B$ | [33] |
| Borexino$_{\text{Solar}}\bar{\nu}_e - e^-$ | $\mu_\nu < 5.4 \times 10^{-11} \mu_B$ | [19] |
Finally, the perpendicular component \( \vec{B} \) of the magnetic field is computed as
\[
\vec{B} = \sum_{K} c_K \vec{B}_K.
\]
More details in the method for computing \( c_K \) can be found in [18]. Finally, the perpendicular component \( B_\perp \), which is relevant to the neutrino evolution of \( s_\parallel \) can be computed as
\[
B_\perp = \sqrt{B_\parallel^2 + B_\perp^2}.
\]
In Fig. 3 we show the so obtained magnetic field profile for \( B_\perp(r) \).

Once we have set the magnetic profile of the Sun, we can solve Eq. (5) to find \( s_\parallel(r) \) for different values of \( \mu_\nu \). As an example, in the bottom panel of Fig. 3 we show \( s_\parallel \) as a function of the radial coordinate \( r \) for the upper bound of the neutrino magnetic moment \( \mu_\nu = 10^{-11} \mu_B \). From this plot, it is clear that the magnetic field in the Sun may produce a considerable change in the neutrino helicity and it is worthy to study the effects of this change in observables for terrestrial detectors.

**UPPER BOUND FOR THE NEUTRINO MAGNETIC MOMENT**

In order to assess possible effects of the helicity change of solar neutrinos in terrestrial detectors, we need the value of the neutrino helicity when it leaves the Sun, \( s_\parallel(r = R_\odot) \). This quantity depends on the neutrino magnetic moment. Assuming that a left handed neutrino was born in the center of the Sun and using the previously described magnetic profile in the Sun, we calculate \( s_\parallel(r = R_\odot) \) as a function of the neutrino magnetic moment. Our results are shown in Fig. 4. Since most of the magnetic fields between the Earth and the Sun are negligible, neutrinos detected in terrestrial experiments will have an upper bound the polarization given by \( s_\parallel(r = R_\odot) \). The actual polarization can be lower depending on the site in the Sun where the neutrino is produced, but it is expected that most of them be produced in the core of the Sun. If the terrestrial detector uses as detection channel the \( \nu - e \) elastic scattering, for a neutrino helicity differing from \( s_\parallel = -1 \) there will be a difference of neutrino counts due to the different cross sections in Eqs. (12).

As mentioned before, the number of Borexino neutrino counts requires \( s_\parallel < -0.68 \). The neutrino helicity does not change when traveling from the Sun to the Earth hence \( s_\parallel(r = R_\odot, \mu_\nu) < -0.68 \). Solving for the neutrino magnetic moment (see Fig. 4), finally we obtain a new upper bound, \( \mu_\nu < 1.4 \times 10^{-13} \mu_B \), for the neutrino magnetic moment.

**CONCLUSIONS**

The discovery of solar neutrino oscillations was possible, in part, due to the precise determination of the solar neutrino fluxes obtained through accurate solar models. Neutrino oscillations imply new properties of the neutrino that were not considered before in the standard model of particle physics. In particular, a massive neutrino can change its helicity in the presence of a magnetic field due to the interaction of the magnetic moment with the field. On the other hand, it has been shown that there are helicity-driven effects in neutrino-electron scattering producing a sizable difference in the corresponding cross sections for Dirac and Majorana neutrinos. These effects could be important in the interpretation of data in experiments using neutrino-electron detectors with solar neutrinos, since the left-handed neutrinos born in the Sun can change its helicity due to the interaction of the neutrino magnetic moment with the magnetic field in the Sun.

In this letter we calculate the difference in the neutrino-electron cross section for Dirac and Majorana neutrinos as a function of the neutrino helicity, using the parameters of the Borexino Collaboration setup. This difference between Majorana and Dirac cross sections cannot be larger than the corresponding one extracted from the uncertainty in the number of events reported by the Borexino Collaboration.

Using a model for the magnetic profile of the Sun, we calculate the helicity change of solar neutrinos induced by the interaction of the magnetic moment with the Sun magnetic field and estimate the maximum helicity change for neutrinos leaving the Sun, as a function of their magnetic moment. From the upper limit for the difference between Dirac and Majorana cross sections extracted from Borexino uncertainty in the number of events, we establish a new upper bound for the neutrino magnetic mo-

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**FIG. 4.** The value of \( s_\parallel \) evaluated at \( r = R_\odot \), i.e. the final value of the neutrino helicity as the neutrino leaves the Sun, for different values of the neutrino magnetic moment \( \mu_\nu \). Borexino Sensitivity.
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