

# NEW TESTS FOR NEUTRINOS IN LOW-ENERGY SOLAR EXPERIMENTS

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## ABSTRACT

We show how future solar neutrino experiments in the low energy region can be used to test novel neutrino properties. Information on the Majorana nature or neutrino magnetic moments can be extracted from the observation of electron anti-neutrinos from the Sun and the measurement of an azimuthal asymmetry in the total number of events, respectively.

### 1. Low-energy electron Anti-neutrinos from the Sun

Finding a signature for the Majorana nature of neutrinos or, equivalently, for the violation of lepton number in Nature is a fundamental challenge in particle physics<sup>1</sup>. All attempts for distinguishing Dirac from Majorana neutrinos *directly* in laboratory experiments have proven to be a hopeless task, due to the V-A character of the weak interaction, which implies that all such effects vanish as the neutrino mass goes to zero. We suggest an alternative way in which one might probe for the possibility of  $L$ -violation which is not *directly* induced by the presence of a Majorana mass. Although, Majorana masses will be required at some level, but the quantity which is directly involved is the transition amplitude for  $\nu_e \rightarrow \bar{\nu}_e$  conversions in the Sun.

Here we propose to probe for the possible existence of  $L$ -violating processes in the solar interior that can produce an  $\bar{\nu}_e$  component in the neutrino flux. The idea is that, even though the nuclear reactions that occur in a normal star like our Sun do not produce directly right-handed active neutrinos ( $\bar{\nu}_a$ ) these may be produced by combining the chirality-flipping transition  $\nu_{eL} \rightarrow \bar{\nu}_{aR}$  with the standard chirality-preserving MSW conversions  $\nu_{eL} \rightarrow \nu_{\mu L}$  through cascade conversions like  $\nu_{eL} \rightarrow \bar{\nu}_{\mu R} \rightarrow \bar{\nu}_{eR}$  or  $\nu_{eL} \rightarrow \nu_{\mu L} \rightarrow \bar{\nu}_{eR}$ . These conversions arise as a result of the interplay of two types of mixing<sup>2</sup>: one of them, matter-induced flavour mixing, leads to MSW resonant conversions which preserve the lepton number  $L$ , whereas the other is generated by the resonant interaction of a Majorana neutrino transition magnetic moment with the solar magnetic field<sup>3</sup>. This violates the  $L$  symmetry by two units ( $\Delta L = \pm 2$ ) and is an explicit signature of the Majorana nature of the neutrino<sup>4</sup>.

We consider neutrino-electron scattering in future underground solar neutrino experiments in the low-energy region, below the threshold for  $\bar{\nu}_e + p \rightarrow n + e^+$ , such as HELLAZ<sup>5</sup> or BOREXINO<sup>6</sup>. They will have low energy thresholds (100 keV and 250 keV, respectively). BOREXINO is designed to take advantage of the

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characteristic shape of the electron recoil energy spectrum from the  ${}^7\text{Be}$  neutrino line, while the HELLAZ experiment is intended to measure the fundamental  $pp$  neutrinos.

The complete expression for the differential cross section of the weak process  $\nu e \rightarrow \nu e$ , as a function of the electron recoil energy  $T$ , in the massless neutrino limit, can be written as (see for instance ref. <sup>7</sup>)

$$\frac{d\sigma}{dT}(\omega, T) = \frac{2G_F^2 m_e}{\pi} \left[ P_e h(g_{eL}, g_R) + P_{\bar{e}} h(g_R, g_{eL}) + P_a h(g_{aL}, g_R) + P_{\bar{a}} h(g_R, g_{aL}) \right] \quad (1)$$

where  $h(a, b) \equiv a^2 + b^2(1 - T/\omega)^2 - abm_e T/\omega^2$  and  $g_{eL} = \sin^2 \theta_W + 0.5$ ,  $g_{aL} = \sin^2 \theta_W - 0.5$  ( $a = \mu, \tau$ ) and  $g_R = \sin^2 \theta_W$  are the weak couplings of the Standard Model, and  $\omega$  is the energy of the incoming neutrino. The parameter  $P_e$  in the equation above is the survival probability of the initial left-handed electron neutrinos, while  $P_{\bar{e}}$ ,  $P_a$  and  $P_{\bar{a}}$  are the appearance probabilities of the other species, that may arise in the Sun as a result of the processes  $\nu_{eL} \rightarrow \bar{\nu}_{eR}$ ,  $\nu_{eL} \rightarrow \nu_{aL}$  or  $\nu_{eL} \rightarrow \bar{\nu}_{aR}$ , respectively. These parameters obey the unitarity condition  $P_e(\omega) + P_{\bar{e}}(\omega) + P_a(\omega) + P_{\bar{a}}(\omega) = 1$ . In general they are obtained from the complete  $4 \times 4$  Hamiltonian describing the evolution of the neutrino system <sup>4</sup>. They depend on the neutrino energy  $\omega$ , on the solar magnetic field through  $\mu_\nu B_\perp$  and on the neutrino mixing parameters  $\Delta m^2$ ,  $\sin^2 2\theta$ .

In the  $L$ -violating processes one has in general all four contributions shown in eq. (1). In contrast, in the case where lepton number is conserved (like in MSW conversions), the solar neutrino flux will consist of *neutrinos*, so only the first and third terms in eq. (1) contribute. It follows that the differential cross section will be *different* in the case where  $\nu_e$ 's from the Sun get converted to electron  $\bar{\nu}_e$ 's. Is it possible to measure this difference in future neutrino experiments?

The relevant quantity to be measured in neutrino scattering experiments is the energy spectrum of events, namely

$$\frac{dN_\nu}{dT} = N_e \sum_i \phi_{0i} \int_{\omega_{min}(T)}^{\omega_{max}} d\omega \lambda_i(\omega) \left\langle \frac{d\sigma}{dT}(\omega, T) \right\rangle \quad (2)$$

where  $d\sigma/dT$  is given in eq. (1) and  $N_e$  is the number of electrons in the fiducial volume of the detector <sup>a</sup>. The sum in the above equation is done over the solar neutrino spectrum, where  $i$  corresponds to the different reactions  $i = pp$ ,  ${}^7\text{Be}$ ,  $pep$ ,  ${}^8\text{B}$  . . . , characterized by an integral flux  $\phi_{0i}$  and a differential spectrum  $\lambda_i(\omega)$  (for neutrinos coming from two-body reactions, one has  $\lambda_i(\omega) = \delta(\omega - \omega_i)$ ). The lower limit for the neutrino energy is  $\omega_{min}(T) = (T + \sqrt{T^2 + 2m_e T})/2$ , while the upper limit  $\omega_{max}$  corresponds to the maximum neutrino energy. In order to take into account the finite resolution in the measured electron recoil energy, we perform a Gaussian average of the cross section, indicated by  $\langle \dots \rangle$  in eq. (2). For further details, see ref. <sup>8</sup>.

We have calculated the averaged energy spectrum of events for the two experiments in the simple case where the parameters  $P_i$  do not depend on the neutrino

<sup>a</sup>For simplicity we take the detector efficiency as unity for energies above the threshold.

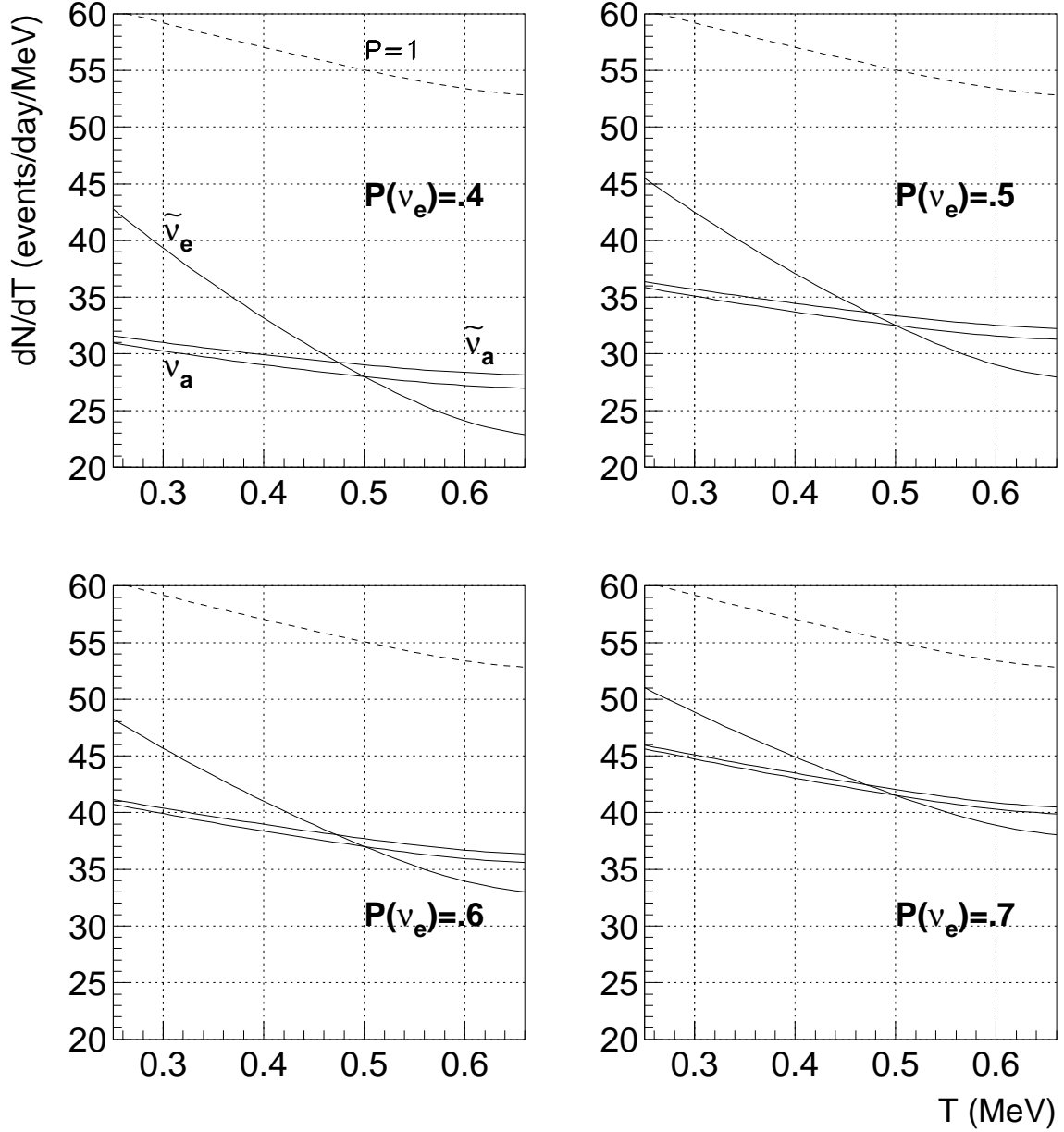


Fig. 1. Energy spectrum of events corresponding to  ${}^7\text{Be}$  solar neutrinos for the BOREXINO experiment. The upper line corresponds to the case where one has no neutrino conversions ( $P_e = 1$ ). When electron anti-neutrinos are present in the solar flux the results are the lines labeled with  $\bar{\nu}_e$ , calculated for the indicated value of  $P_e$  and the corresponding amount of  $\bar{\nu}_a$ . The cases of  $\nu_e \rightarrow \nu_{\mu,\tau}$  and  $\nu_e \rightarrow \bar{\nu}_{\mu,\tau}$  are the lower lines with labels  $\nu_a$  and  $\bar{\nu}_a$ , respectively.

energy. Here we present our results for BOREXINO in figure 1, where one can see that it is possible to distinguish the case with  $\bar{\nu}_e$  considering the behaviour of the cross section for low energies. It is the *slope* of the measured spectrum the key for recognizing the presence of  $\bar{\nu}_e$ 's in the solar neutrino flux, and correspondingly the presence of  $L$ -violating processes which can only exist if neutrinos are Majorana particles.

The shortcoming of the above discussion is that we have neglected the energy dependence of the physical parameters  $P_i$ . One must calculate the averaged  $\nu - e$  cross section using analytical expressions for  $P_i = P_i(\omega)$ . However, since the  ${}^7\text{Be}$  neutrinos are mono-energetic, whatever the mechanism that produces the deficit is, their survival probability will take on a constant value  $P_e(\omega_{Be})$ . Therefore one can apply directly the results we have obtained for constant  $P_i$  for the range of electron recoil energy where the contribution of  ${}^7\text{Be}$  neutrinos dominates. In ref. <sup>8</sup> we give a discussion of the experimental uncertainties.

There are however stringent bounds on the presence of solar  $\bar{\nu}_e$ 's in the high energy region ( ${}^8\text{B}$ ). These would interact within the detector through the process  $\bar{\nu}_e + p \rightarrow n + e^+$ . This process, which has an energy threshold of  $E_\nu = m_n - m_p + m_e \simeq 1.8$  MeV, has not been found to occur in the Kamiokande experiment nor in the very recent data from Super-Kamiokande <sup>9</sup>. Also the results from LSD are negative <sup>10</sup>.

As we show in ref. <sup>8</sup> for the specific scenario presented in ref. <sup>2</sup>, the co-existence of a suppressed production of high-energy  $\bar{\nu}_e$ 's and a sizeable flux of anti-neutrinos at energies below 1.8 MeV can be easily understood theoretically. The resonance in the  $\nu_{eL} \rightarrow \bar{\nu}_{eR}$  conversions can lie in the energy region below 1 MeV (relevant for HELLAZ or BOREXINO) provided that the neutrino parameters have reasonable values, so that the conversion probability is small for energies  $\omega \gg 1$  MeV. Therefore the anti-neutrino flux would be *hidden* in the background and therefore unobservable in Super-Kamiokande. Our conclusion is that neutrino conversions within the Sun can result in partial polarization of the initial fluxes, in such a way as to produce a sizeable  $\bar{\nu}_e$  component without conflicting present Super-Kamiokande data. The observation of  $\bar{\nu}_e$ 's from the Sun in future neutrino experiments in the low energy region could lead to the conclusion that the neutrinos are Majorana particles.

## 2. Neutrino magnetic moments and low-energy solar neutrino-electron scattering experiments

In this section we are concerned with a particular effect in neutrino-electron scattering for solar neutrinos which possess a Dirac magnetic moment or Majorana transition magnetic moments, that we will note generically as  $\mu_\nu$ . The latter is especially interesting first of all because Majorana neutrinos are more fundamental and they arise in most models of particle physics beyond the standard model <sup>1</sup>, and because its effects can be resonantly enhanced in matter <sup>3</sup>, providing one of the most attractive solutions to the solar neutrino problem <sup>11</sup>. Another practical advantage in favour

of Majorana transition moments is that, in contrast to Dirac-type  $\mu_\nu$ 's, these are substantially less stringently constrained by astrophysics<sup>12</sup>.

For *longitudinally polarized neutrinos* the weak interaction and the electromagnetic interaction amplitudes on electrons do not interfere, since the weak interaction preserves neutrino helicity while the electromagnetic does not. As a result the cross section depends quadratically on  $\mu_\nu$ . However if there exists a process capable of converting part of the initially fully polarized  $\nu_e$ 's, then an *interference term* arises proportional to  $\mu_\nu$ , as pointed out e.g. in ref.<sup>13</sup>. This term depends on the angle between the component of the neutrino spin transverse to its momentum and the momentum of the outgoing recoil electron. Therefore the number of events measured in an experiment exhibits an *asymmetry* with respect to the above defined angle. The asymmetry will not show up in terrestrial experiments even with stronger magnetic fields, since only in the Sun the neutrino depolarization would be resonant and only in the solar convective zone one will find a magnetic field  $\vec{B}_\odot$  extended over such a wide region ( $\sim$  a tenth of the solar radius). At earth-bound experiments the helicity-flip could be caused only by the presence of a neutrino mass and is therefore small.

Barbieri and Fiorentini considered<sup>13</sup> the conversions  $\nu_{eL} \rightarrow \nu_{eR}$  as a result of the spin-flip by a toroidal magnetic field in the solar convective zone. They showed that the azimuthal asymmetry could be observable in a real time solar  $^8\text{B}$ -neutrino experiment and as large as 20% for an electron kinetic energy threshold of 5 MeV, fixing the  $\nu_e$  survival probability  $P_e = 1/3$  (as was suggested by the Homestake experiment) and the maximal Dirac magnetic moment allowed by laboratory experiments,  $\mu_\nu \simeq 10^{-10} \mu_B$ . On the other hand, Vogel and Engel<sup>14</sup> emphasized that if an asymmetry in the scattering of transversally polarized neutrinos exists, recoil electrons will be emitted copiously along the direction of the neutrino polarization in the plane orthogonal to the neutrino momentum. However both<sup>13</sup> and<sup>14</sup> *overestimated* the asymmetry by an approximate factor two. First, the weak term in eq. (11a) of ref.<sup>13</sup> is a factor 2 less than our eq. (3) and the interference term coincides with ours, while in ref.<sup>14</sup> the interference term (their eq. (A9)) is a factor 2 bigger than our eq. (4).

Here we show the sensitivity of planned solar neutrino experiments in the *low energy region* ( $\omega \lesssim 1$  MeV) to the azimuthal asymmetries that are expected in the number of neutrino events, arising from the electromagnetic-weak interference term.

We consider the neutrino–electron scattering process  $\nu_e(k_1) + e(p_1) \rightarrow \nu_e(k_2) + e(p_2)$  when the initial flux of neutrinos is not completely polarized due to transitions induced by non-zero transition magnetic moments in the Sun. This includes both conventional Dirac-type magnetic moments as well as Majorana transition moments. The differential cross section  $d\sigma/dTd\phi$ , where  $T$  is the recoil energy of electrons and  $\phi$  the azimuthal angle (see fig. 2), can be written as a sum of three terms: weak, electromagnetic and interference. Let us first assume that only the Dirac  $\nu_e$  magnetic moment exists,  $\mu_{\nu_e}$ . For ultra-relativistic neutrinos the expressions for the weak,

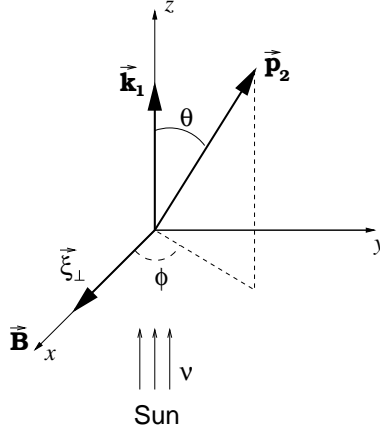


Fig. 2. Coordinate system conventions.

electromagnetic and interference terms are

$$\left(\frac{d\sigma}{dTd\phi}\right)_{weak} = P_e \frac{G_F^2 m_e}{\pi^2} h(g_{eL}, g_R) \quad \left(\frac{d\sigma}{dTd\phi}\right)_{em} = \frac{\alpha^2}{2m_e^2} \left(\frac{\mu_{\nu_e}}{\mu_B}\right)^2 \left[\frac{1}{T} - \frac{1}{\omega}\right] \quad (3)$$

$$\left(\frac{d\sigma}{dTd\phi}\right)_{int} = -\frac{\alpha G_F}{2\sqrt{2}\pi m_e T} \left(\frac{\mu_{\nu_e}}{\mu_B}\right) \left[g_{eL} + g_R \left(1 - \frac{T}{\omega}\right)\right] \vec{p}_2 \cdot \vec{\xi}_\perp \quad (4)$$

where all parameters are the same as in eq. (1). The *interference term* is proportional to  $\mu_\nu$ <sup>13</sup>, and  $\vec{\xi}_\perp$  is the transverse component of the neutrino polarization spin vector with respect to its momentum. It has the value  $|\vec{\xi}_\perp| = 2(P_e(1 - P_e))^{1/2}$ . This interference term depends on the azimuthal angle  $\phi$  as defined in figure 2, since eq. (4) may be rewritten using

$$\vec{p}_2 \cdot \vec{\xi}_\perp = |\vec{p}_2| \sin \theta |\vec{\xi}_\perp| \cos \phi = \sqrt{2m_e T \left(1 - \frac{T}{T_{max}}\right)} |\vec{\xi}_\perp| \cos \phi \quad (5)$$

where  $T_{max} = 2\omega^2/(m_e + 2\omega)$  is the maximum electron recoil energy.

If neutrinos are Majorana particles they can only possess transition magnetic moments, that we will denote  $\mu_{12}$ . For simplicity we assume the case of CP conservation. For definiteness, moreover, we consider the case of two neutrino species,  $\nu_e$  and  $\nu_\mu$ , with positive relative CP-parity<sup>4</sup>. The three terms of the differential cross section will include an electromagnetic term (same as in eq. (3) with  $\mu \rightarrow \mu_{12}$ ), a weak term that consists of the first and fourth terms in eq. (1), and an interference term which differs from eq. (4),

$$-\frac{\alpha G_F}{4\sqrt{2}\pi m_e T} \left(\frac{\mu_{12}}{\mu_B}\right) \left[(g_{eL} + g_{\mu L} + 2g_R) \left(2 - \frac{T}{\omega}\right) + (g_{eL} - g_{\mu L}) \frac{T}{\omega}\right] \vec{p}_2 \cdot \vec{\xi}_\perp^{e\bar{\mu}} \quad (6)$$

since in the Majorana case there are two active neutrino species. Here the mixed transversal polarization vector is given<sup>7</sup> by  $|\vec{\xi}_\perp^{e\bar{\mu}}| = 2\sqrt{P_e(1 - P_e)}$ .

The relevant quantity to be measured in neutrino-electron scattering experiments capable (like HELLAZ) of measuring directionality of the outgoing  $e^-$  is the azimuthal distribution of the number of events, namely

$$\frac{dN}{d\phi} = N_e \sum_i \Phi_{0i} \int_{T_{Th}}^{T_{max}} dT \int_{\omega_{min}(T)}^{\omega_{max}} d\omega \lambda_i(\omega) \frac{d\sigma}{dT d\phi}(\omega, T) = n^w + n^{em} + n^{int} \cos \phi \quad (7)$$

where  $d\sigma/dT d\phi$  is the total cross section and all parameters are the same as in eq. (2). It has been written as a sum of three terms, where  $n^w$ ,  $n^{em}$  and  $n^{int}$  account for the weak, electromagnetic and interference contributions, respectively. The differential azimuthal asymmetry is defined as

$$\left. \frac{dA}{d\phi} \right|_{\phi'} = \frac{\left. \frac{dN}{d\phi} \right|_{\phi'} - \left. \frac{dN}{d\phi} \right|_{\phi'+\pi}}{\left. \frac{dN}{d\phi} \right|_{\phi'} + \left. \frac{dN}{d\phi} \right|_{\phi'+\pi}} = \frac{n^{int}}{n^w + n^{em}} \cos \phi' \quad (8)$$

where  $\phi'$  is measured with respect to the direction of  $\vec{B}_\odot$ , which we will assume to be along the positive  $x$ -axis. One can also define an integrated asymmetry

$$\mathcal{A}(\phi') = \frac{\int_{\phi'}^{\phi'+\pi} \frac{dN}{d\phi} d\phi - \int_{\phi'+\pi}^{\phi'+2\pi} \frac{dN}{d\phi} d\phi}{\int_{\phi'}^{\phi'+\pi} \frac{dN}{d\phi} d\phi + \int_{\phi'+\pi}^{\phi'+2\pi} \frac{dN}{d\phi} d\phi} = -\frac{2n^{int}}{\pi(n^w + n^{em})} \sin \phi' \equiv -A \sin \phi' \quad (9)$$

Here we have defined  $A$ , the maximum integrated asymmetry measurable by the experiment, which is manifestly positive.

It is important to emphasize that HELLAZ will be the first experiment potentially sensitive to azimuthal asymmetries since the directionality of the outgoing  $e^-$  can be measured. The angular resolution is expected to be  $\Delta\theta, \Delta\phi \sim 30 \text{ mrad} \sim 2^\circ$ , substantially better than that of Super-Kamiokande. Notice also that the Cerenkov cone defined by the angle  $\theta$  is very narrow for high-energy boron neutrinos, as one can see from eq. (5). In contrast, for  $pp$  neutrino energies accessible at HELLAZ ( $T_{max} \simeq 0.26 \text{ MeV}$ ,  $T_{th} \simeq 0.1 \text{ MeV}$ ) we estimate that  $\theta$  can be as large as  $48^\circ$ .

Let now discuss how the measurement of the azimuthal asymmetry could be carried out considering that  $\vec{B}_\odot$  is constant over a given period of time but its direction is unknown. One should collect events in every  $\phi$ -bin, where  $\phi$  is defined with respect to some arbitrarily chosen axis, and then take for different  $\phi'$ s the ratio  $\mathcal{A}(\phi')$  which should show a  $\sin \phi'$  dependence with a maximum equal to  $A$ . This maximum will show us the angle  $\phi_0$  which corresponds to the direction of  $\vec{B}_\odot$  ( $\phi_0 = 0$  if  $\vec{B}_\odot$  goes along the positive  $x$  axis). Then the direction of  $\vec{B}_\odot$  is measured together with  $A$ . Since this direction may change in time the experiment should accumulate events until the maximum  $\sin \phi$ -like correlation in  $\mathcal{A}(\phi)$  is found and then start a new event

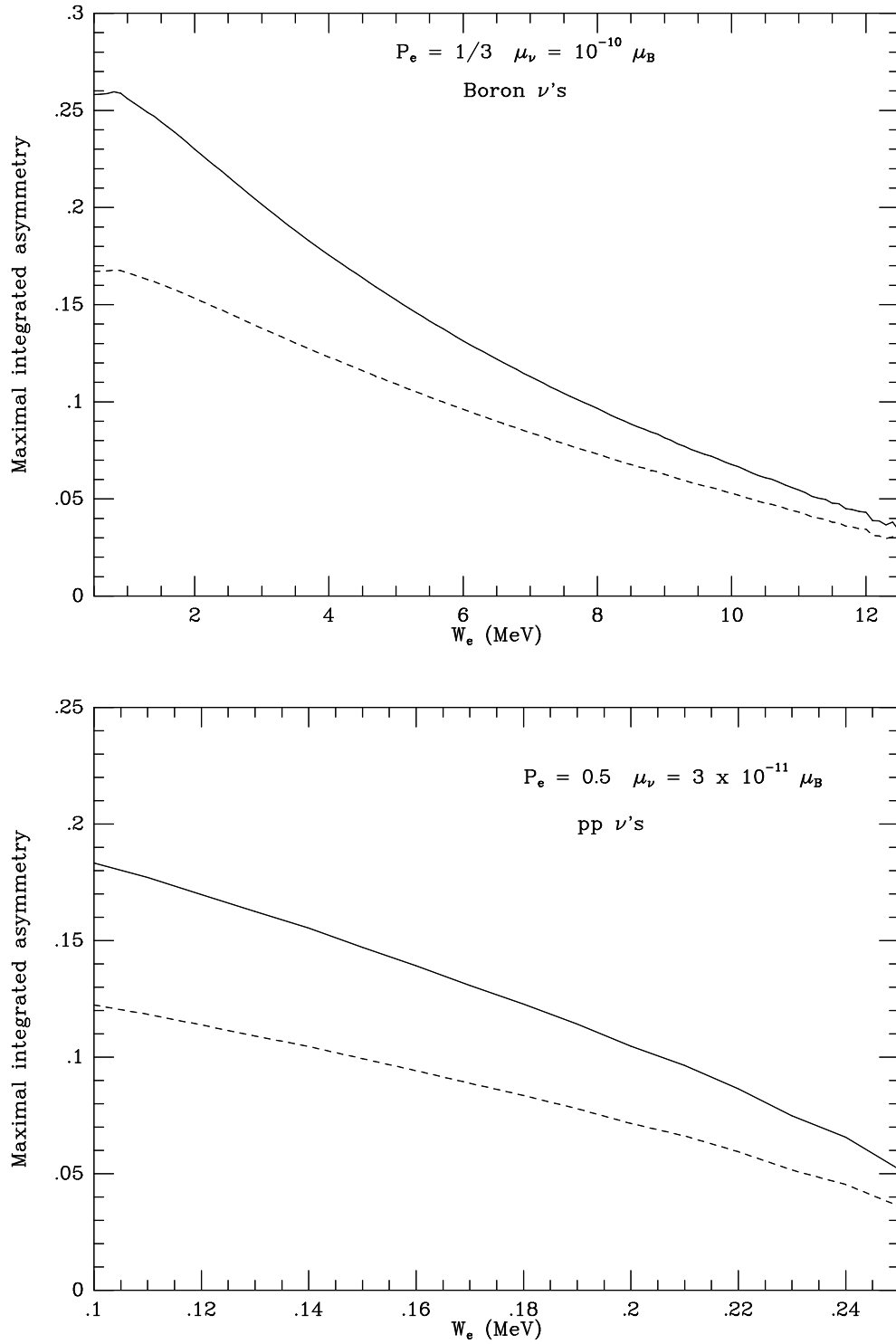


Fig. 3. Maximal integrated azimuthal asymmetry  $A$  for Boron neutrinos and  $pp$  neutrinos, respectively, as a function of the electron recoil energy threshold  $W_e$  for the parameters shown. Solid line: Dirac case ( $\nu_{eL} \rightarrow \nu_{eR}$ ). Dashed line: Majorana case ( $\nu_e \rightarrow \bar{\nu}_\mu$ )



counting period when such correlation goes away due to the changing  $\vec{B}_\odot$ . Therefore the value of  $A$  could be extracted by performing a series of such measurements.

The first plot of fig. 3 corresponds to the values of  $A$  in the situation described in refs. <sup>13,14</sup>. From our calculations the asymmetry in the Dirac case is in fact approximately a factor two smaller than predicted by <sup>13</sup>. The asymmetry in the Majorana case for equivalent  $\mu$ , as expected, is smaller since there are two active neutrino species so that the weak term in the denominator in eq. (9) becomes larger. The second plot shows the same kind of analysis for  $pp$ -neutrinos, which will be measured by an experiment like HELLAZ <sup>5</sup>, where both the recoil electron energy  $T$  and the recoil electron scattering angle  $\theta$  should be measured with good precision. The Multi-Wire-Chamber in HELLAZ should be sensitive to the azimuthal angle  $\phi$ , measuring the number of events in  $\phi$ -bins. We use a more realistic survival probability for Resonant Spin-Flavour Precession (RSFP) in the Sun ( $P_e = 0.5$ ) and for  $\mu_\nu = 3 \times 10^{-11} \mu_B$ . This gives the maximum expected asymmetry and seems phenomenologically reasonable in order to convert the initial solar  $\nu_{eL}$ 's via the RSFP scenario.

The dependence of  $A$  on the value of  $\mu_\nu$  deserves a more detailed analysis. It follows that  $A$  is maximized when the pure weak term is equal to the electromagnetic contribution. This fact favours  $pp$ -neutrinos with respect to high energy neutrinos, since such a maximum is reached for lower  $\mu_\nu$  values precisely due to the lower energies considered. In fact, for an energy threshold of recoil electrons  $W_e = 0.1$  MeV (HELLAZ) the maximal asymmetry is reached for  $\mu_\nu \simeq 3 \times 10^{-11} \mu_B$  in contrast to Boron neutrinos, for which it is reached for  $\mu_\nu \simeq 10^{-10} \mu_B$ . This way one sees that figs. 3 describe approximately the most favourable situation for measuring  $A$ .

The fact that  $dA/d\mu_\nu = 0$  is reached for equal number of weak and electromagnetic events seems to suggest that the measurement of the total number of events would be enough to rule out the values of  $\mu_\nu$  to which the asymmetry is sensitive. However, it is not so if one bears in mind that background events from other processes always increase the total number of events and one needs to perform a good background subtraction to get some information on the  $\mu_\nu$  term. In addition if the background is isotropic in the azimuthal plane, it should be absent in the numerator of  $A$  and then if some asymmetry is measured one can ascribe it to an effect of  $\mu_\nu$ . Note also that the asymmetry is a ratio of event numbers. Thus global normalization uncertainties (e.g. total neutrino fluxes) completely drop out from the asymmetry, and energy-dependent uncertainties will be reduced since the same integrations appear in the numerator and in the denominator. For all these reasons the asymmetry measurement is preferred. It suffers of course from the dependence on the unknown magnetic field direction, but sensitivity to that information is also of potential astrophysical interest.

We have considered<sup>15</sup> how the above results are affected by the energy dependence expected in the conversion probability in the simplest realization of the RSFP scenario <sup>3</sup> where vacuum mixing is neglected. It can be shown that the dependence of  $P_e$  on the neutrino energy leads to somewhat smaller azimuthal asymmetries, but qualitatively

very similar to those obtained if the energy dependence is neglected.

We conclude that measuring azimuthal asymmetries in future low-energy solar neutrino-electron scattering experiments with good angular resolution should be a feasible and illuminating task. It should provide useful information on non-standard neutrino properties such as magnetic moments, as well as on solar magnetic fields.

Note we have assumed  $\nu_e$  magnetic moments of the order  $10^{-11}\mu_B$ , which is consistent with present laboratory experiments and, apart from possible effects in red giants, is also compatible with astrophysical limits<sup>12</sup>, given the present uncertainties in these considerations. Finally, note that the future ITEP-Minnesota experiment is planned for searching  $\mu_\nu/\mu_B$  down to  $3 \times 10^{-11}$  with reactor anti-neutrinos<sup>16</sup>, while the LAMA experiment<sup>17</sup> will use a powerful isotope neutrino source.

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