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Low-energy Anti-neutrinos from the Sun

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Abstract

We consider the sensitivity of future neutrino experiments in the low energy region, such as BOREXINO or HELLAZ, to a solar $\bar{\nu}_e$ signal. We show that, if neutrino conversions within the Sun result in partial polarization of initial solar neutrino fluxes, then a new opportunity arises to observe the $\bar{\nu}_e$'s and thus to probe the Majorana nature of the neutrinos. This is achieved by comparing the slopes of the energy dependence of the differential νe-scattering cross section for different neutrino conversion scenarios. We also show how the $\nu_e \to \bar{\nu}_e$ conversions may take place for low energy solar neutrinos while being unobservable at the Kamiokande and Super-Kamiokande experiments.

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1 Introduction

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 [1]. 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. This applies to all searches for processes such as neutrino-less double beta decay [2], as well as the proposal to search for CP violating effects induced by the so-called Majorana CP phases [3] in neutrino propagation [4]. In this paper we suggest an alternative way in which one might probe for the possibility of L-violation which it is not *directly* induced by the presence of a Majorana neutrino mass. Of course, Majorana masses will be required at some level, as it must be the case due to a general theorem [5], but the quantity which is directly involved is the transition amplitude for a ν_e to convert into an anti-ν_e inside the Sun. One way to achieve this is via a non-zero transition magnetic moment of Majorana neutrinos [6] which may be resonantly enhanced due to the effect of matter in the Sun [7].

In this note we argue that the possible observation of an electron anti-neutrino component in the solar neutrino flux at low energies could provide an indication that neutrinos are Majorana particles. Future real-time neutrino experiments, like HELLAZ [8], BOREXINO [9] or HERON [10], have been proposed to directly measure the fluxes of low-energy solar neutrinos using the neutrino-electron scattering reaction. BOREXINO is designed to take advantage of the characteristic shape of the electron recoil energy spectrum from the ^{7}Be neutrino line. The measurement of the ^{7}Be neutrino flux in BOREXINO will play a key rôle in clarifying the solar neutrino problem and in discriminating which one of all the proposed physical scenarios where neutrinos have non-standard properties is the correct one. For instance, if a very small ratio $R_{Be}^{exp}/R_{Be}^{SSM}$ were measured, as expected in order to reconcile the data from Homestake and Kamiokande/Super-Kamiokande [11], this would point towards the small-mixing MSW solution. On the contrary, if this ratio were found to be larger, there are many ways to explain the deficit, such as the large-mixing MSW solution. The measurement of the ^{7}Be neutrino line at BOREXINO would also test the level of density fluctuations in the solar matter as recently shown in ref. [12]. On the other hand, the HELLAZ and HERON experiments are intended to measure the fundamental neutrinos of the *pp* chain.

It is well-known that if neutrinos are Majorana particles they can not have non-zero magnetic moments. However, they can have transition magnetic moments [6] which may induce chirality-flipping transitions such as

$$\nu_{eL} \to \bar{\nu}_{aR} \tag{1}$$

where a denotes another neutrino flavour, either μ or τ.

In this paper we focus on alternative mechanisms to explain the deficit of solar neutrinos via the conversion to electron anti-neutrinos. 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 above transition in eq. (1) with the standard chirality-preserving MSW conversions [13]

$$\nu_{eL} \to \nu_{\mu L} \tag{2}$$

through cascade conversions like

$$\nu_{eL} \to \bar{\nu}_{\mu R} \to \bar{\nu}_{eR} \qquad \nu_{eL} \to \nu_{\mu L} \to \bar{\nu}_{eR} \tag{3}$$

These conversions arise as a result of the interplay of two types of mixing [14]: 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 interaction of a neutrino transition magnetic moment [7, 15] with the solar magnetic field, and violates the L symmetry by two units ($\Delta L = \pm 2$). This L-violation is an explicit signature of the Majorana nature of the neutrino. The decay of solar neutrinos into a massless (pseudo)-scalar majoron $\nu \to \nu' J$ [16, 17], is another process which violates lepton number [4].

There are however stringent bounds on the presence of solar electron anti-neutrinos in the high energy region (^{8}B). These would interact within the detector through the process $\bar{\nu}_e + p \to n + e^+$. 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 [19, 20, 21], nor in the very recent data from Super-Kamiokande [22]. Also the results from the liquid scintillation detector (LSD) are negative [23]. However, as we show in section 4, 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. This happens, for example, for the specific scenario presented in ref. [14].

In this paper we propose to probe for the possible existence of L-violating processes in the solar interior that can produce an anti-neutrino component in the neutrino flux. We consider neutrino-electron scattering in future underground solar neutrino experiments in

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[4] However the solar neutrino matter-induced decay seems marginally possible as a solution to the solar neutrino problem [18].

the low-energy region, below the threshold for $\bar{\nu}_e + p \to n + e^+$, such as is the case for pp or ^{7}Be neutrinos. These should be measured, respectively, in future experiments such as HELLAZ and BOREXINO, which will have energy thresholds [8, 9] [5]

$$T_{Th}(\text{HELLAZ}) = 100 \text{ keV}, \qquad T_{Th}(\text{BOREXINO}) = 250 \text{ keV} .$$

We show 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, while being unobservable at the Kamiokande and Super-Kamiokande experiments.

2 The Cross-Sections

The complete expression for the differential cross section of the weak process $\nu e \to \nu e$, as a function of the electron recoil energy T, in the massless neutrino limit, can be written as [24],

$$\begin{aligned}
\frac{d\sigma}{dT}(\omega, T) = \quad & \frac{2G_F^2 m_e}{\pi}\{P_e\left[g_{eL}^2 + g_R^2\left(1-\frac{T}{\omega}\right)^2 - g_{eL}g_R\frac{m_eT}{\omega^2}\right] + \\
& +P_{\bar{e}}\left[g_R^2 + g_{eL}^2\left(1-\frac{T}{\omega}\right)^2 - g_{eL}g_R\frac{m_eT}{\omega^2}\right] + \\
& +P_a\left[g_{aL}^2 + g_R^2\left(1-\frac{T}{\omega}\right)^2 - g_{aL}g_R\frac{m_eT}{\omega^2}\right] + \\
& +P_{\bar{a}}\left[g_R^2 + g_{aL}^2\left(1-\frac{T}{\omega}\right)^2 - g_{aL}g_R\frac{m_eT}{\omega^2}\right]\}
\end{aligned} \tag{4}$$

where $g_{eL} = \sin^2\theta_W + 0.5$, $g_{aL} = \sin^2\theta_W - 0.5$ $(a = \mu, \tau)$ and $g_R = \sin^2\theta_W$ are the weak couplings of the Standard Model, and ω is the energy of the incoming neutrino. The different rows in this equation correspond to the contributions of electron neutrinos, electron anti-neutrinos, muon/tau neutrinos and muon/tau anti-neutrinos, respectively.

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 $\nu_{eL} \to \bar{\nu}_{eR}$, $\nu_{eL} \to \nu_{aL}$ or $\nu_{eL} \to \bar{\nu}_{aR}$, respectively. These parameters obey the unitarity condition

$$P_e(\omega) + P_{\bar{e}}(\omega) + P_a(\omega) + P_{\bar{a}}(\omega) = 1 \ , \tag{5}$$

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[5] For BOREXINO an energy threshold of $T_{th} \simeq 25$ keV is expected, but $\epsilon(\omega) \neq 1$ for this region.

In general they are obtained from the complete 4×4 evolution Hamiltonian describing the evolution of the neutrino system [6] after taking into account the effects of matter [7]. They depend, in general, on the neutrino energy ω, on the solar magnetic field through the parameter $\mu_\nu B_\perp$ and on the neutrino mixing parameters Δm^2, $\sin^2 2\theta$.

In the L-violating processes like the conversions in eq. (3), one has in general all four contributions shown in eq. (4). 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 rows in eq. (4) contribute. For $\nu_e \to \nu_{\mu,\tau}$ (active-active conversions) one has the contribution of both terms, since then $P_a = 1 - P_e$, while only the terms proportional to P_e are present in the case of $\nu_e \to \nu_s$ (active-sterile) conversions, as the detector is *blind* to sterile neutrinos. It follows that the differential cross section will be *different* in the case where electron neutrinos from the Sun get converted to electron anti-neutrinos. The question one should answer is the following: is it possible to measure this difference in the present or in future underground neutrino experiments?

3 BOREXINO and HELLAZ

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

$$\frac{dN_\nu}{dT} = N_e \sum_i \phi_{0i} \int_{\omega_{min}(T)}^{\omega_{max}} d\omega \ \lambda_i(\omega)\epsilon(\omega)\langle\frac{d\sigma}{dT}(\omega, T)\rangle \ , T > T_{th} \tag{6}$$

where $d\sigma/dT$ is given in eq. (4), $\epsilon(\omega)$ is the efficiency of the detector (which we take as unity for energies above the threshold, for simplicity), and N_e is the number of electrons in the fiducial volume of the detector. The sum in the above equation is done over the solar neutrino spectrum, where i corresponds to the different reactions $i = pp$, ^{7}Be, pep, ^{8}B ..., characterized by a differential spectrum $\lambda_i(\omega)$ and an integral flux ϕ_{0i}. The lower limit for the neutrino energy is

$$\omega_{min}(T) = \frac{T}{2}\left(1 + \sqrt{1 + \frac{2m_e}{T}}\right) \ .$$

while the upper limit ω_{max} corresponds to the maximum neutrino energy, taken, as $\lambda_i(\omega)$, from the Standard Solar Model [25]. For neutrinos coming from two-body reactions, like ^{7}Be or pep neutrinos, one has $\lambda_i(\omega) = \delta(\omega - \omega_i)$.

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 $\langle \ldots \rangle$ in eq. (6),

$$\langle \frac{d\sigma}{dT}(\omega,T)\rangle = \frac{\int_0^{T_{max}} dT' \ \exp\left[-\frac{(T'-T)^2}{2\Delta_{T'}^2}\right] \frac{d\sigma}{dT'}(\omega,T')}{\int_0^{T_{max}} dT' \ \exp\left[-\frac{(T'-T)^2}{2\Delta_{T'}^2}\right]} \ . \tag{7}$$

Here T' is the *true* recoil electron energy in the cross-section eq. (4), and T the measured recoil energy. The electron recoil energy obeys the following kinematical inequality

$$0 \leq T' \leq T_{max} = \frac{2\omega^2}{m_e + 2\omega} \ ,$$

The finite energy resolution of the experiments has been introduced in the parameter $\Delta_T \equiv \Delta T$. For the corresponding experiments in the energy region below 1 MeV, one has the following electron recoil energy resolutions.

The liquid scintillator in BOREXINO is expected to observe approximately 300 photoelectrons (*phe*) per MeV of deposited electron recoil energy. This gives an estimate of the energy resolution of the order [9]

$$\frac{\Delta T}{T}(\text{BOREXINO}) \simeq \frac{1}{\sqrt{N_{phe}}} \simeq \frac{0.058}{\sqrt{T/\text{MeV}}} \ , \tag{8}$$

This corresponds to 12% for the threshold ($T_{th} \simeq 0.25$ MeV) and 7% for the maximum recoil energy for ^{7}Be neutrinos, $T_{max} \simeq 0.663$ MeV.

In HELLAZ the Multi-Wire-Chamber (MWC) counts the secondary electrons produced by the initial one in helium. It is expected to count 2500 electrons at the threshold recoil energy, $T_{th} \simeq 0.1$ MeV, so in that case [8]

$$\frac{\Delta T}{T}(\text{HELLAZ}) \simeq \frac{1}{\sqrt{N_e}} \simeq \frac{0.02}{\sqrt{T/T_{th}}} \ , \tag{9}$$

or an energy resolution of the order 1.5% for the maximum for *pp* neutrinos $T_{max} \simeq 0.26$ MeV.

First let us focus in the simple case where the parameters P_i do not depend on the neutrino energy. Since the scattering of *pp* neutrinos can not lead to electron recoil energies above 0.26 MeV approximately, we can consider separately the detection of *pp* neutrinos in HELLAZ [6] for the region 0.1 MeV $< T <$ 0.26 MeV and the corresponding of ^{7}Be neutrinos in BOREXINO for 0.26 MeV $< T <$ 0.663 MeV.

We have calculated the averaged energy spectrum of events from eq. (6) for the two experiments. Our results are shown in figures 1 and 2 for BOREXINO and HELLAZ,

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[6] HELLAZ is also intended to measure the contribution from ^{7}Be neutrinos. However it is uncertain how they will separate the contribution of *pp* neutrinos for energies close to $T_{max}^{pp} \simeq 0.26$ MeV

respectively. The upper line in the different figures corresponds to the case where one has no neutrino conversions, so $P_e = 1$. When electron anti-neutrinos are present in the solar flux the results are the lines labelled with $\bar{\nu}_e$, calculated for the indicated value of P_e and $P_{\bar{a}} = 0.05$ (since for the cascade scenario in eq. (3) one needs at least a small amount of $\bar{\nu}_a$). The cases of $\nu_e \to \nu_{\mu,\tau}$ and $\nu_e \to \bar{\nu}_{\mu,\tau}$ are the lower lines with labels ν_a and $\bar{\nu}_a$, respectively.

One can see from figure 1 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 electron anti-neutrinos in the solar neutrino flux, and correspondingly the presence of L-violating processes which can only exist if neutrinos are Majorana particles.

Comparing figures 1 and 2, we conclude that the measurement of ^{7}Be neutrinos in BOREXINO is more efficient for the discrimination, because in contrast to the *pp* case (HELLAZ) the difference in the slope of the process with electron anti-neutrinos with respect to the other cases appears well above the energy threshold.

On the other hand one can also see from the diagrams in figure 1 that the discrimination is possible for a broad range of values for P_e, provided that it is not very close to unity nor to zero.

The shortcoming of the above discussion is of course that physical parameters P_i do depend on the neutrino energy. One must calculate the averaged $\nu - e$ cross section using analytical expressions for $P_i = P_i(\omega)$ for the different processes that have been addressed to solve the Solar Neutrino Problem (SNP). However, since the ^{7}Be neutrinos are mono-energetic, whatever the mechanism that produces the deficit is, their survival probability will be a constant value of $P_e(\omega_{Be})$. 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}Be neutrinos dominates (approx. from $T_{min} = T_{max}(pp\ \nu) \simeq 0.261$ MeV to $T_{max} \simeq 0.665$ MeV). The solar neutrino flux in this region will be measured with good accuracy in the forthcoming experiments BOREXINO and HELLAZ.

Other experimental uncertainties must be incorporated to the differential spectra obtained from eq. (4). For example, in the results shown we have neglected an unknown statistical error, since it will decrease as $\mid \pm\Delta N/N \mid \sim t^{-1/2}$. Thus, after enough running time in the experiment, the statistical error may be assumed to be less than the systematic error. Moreover, for the BOREXINO experiment one expects a small internal background in the low-energy window, $0.25 \leq T/\text{MeV} \leq 0.8$. The main contaminators, such as ^{14}C

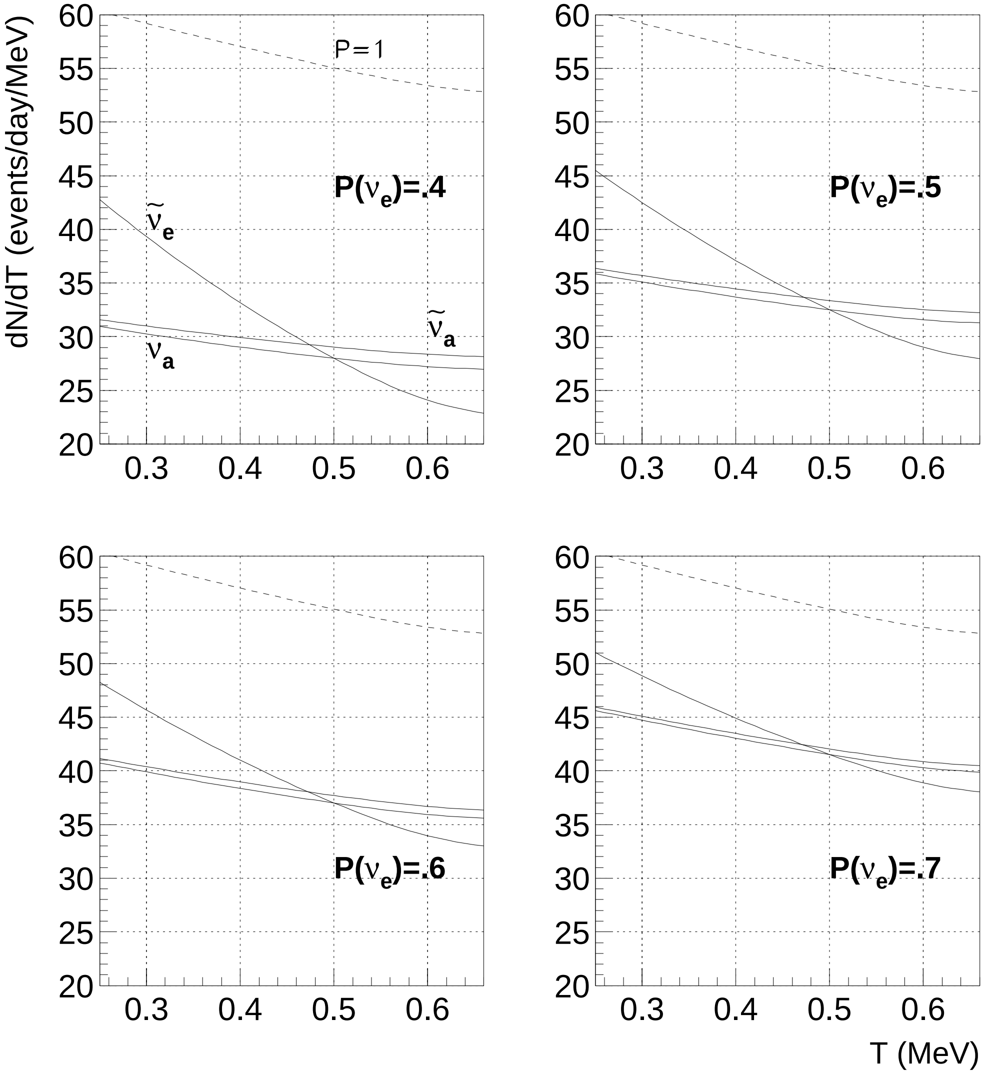

Figure 1: Energy spectrum of events corresponding to ^{7}Be solar neutrinos for the BOREXINO experiment. Different cases are shown, where the solar neutrino flux consists of: only electron neutrinos (label $P_e = 1$), electron neutrinos and electron anti-neutrinos ($\bar{\nu}_e$), electron and muon/tau neutrinos (ν_a) and finally electron and muon/tau anti-neutrinos ($\bar{\nu}_a$). The electron neutrino survival probability P_e (except for the upper line) takes the value as indicated.

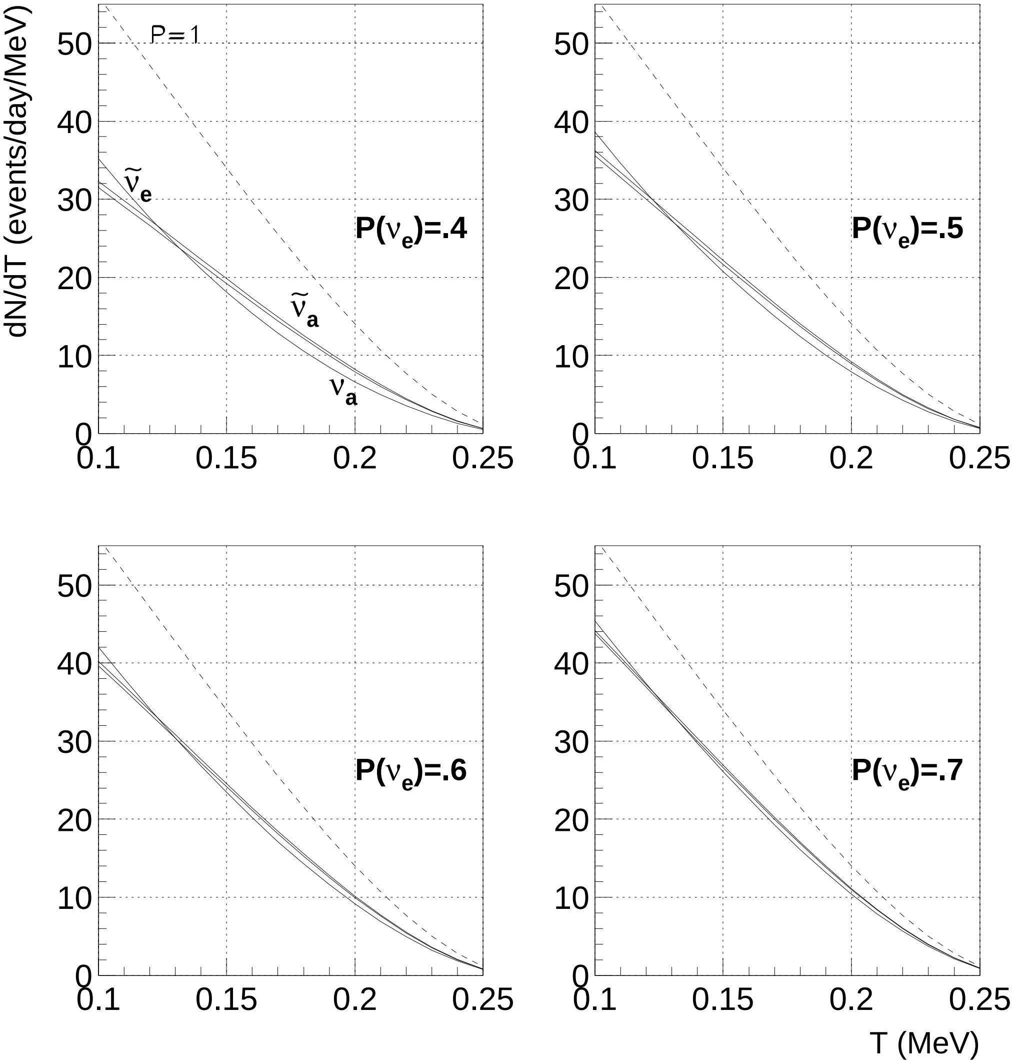

Figure 2: Same as figure 1 for *pp* neutrinos and the HELLAZ experiment.

and ^{246}Pa, will be well discriminated in the liquid scintillator (see fig. 15 in ref. [9]). External background is estimated to be less than 0.1 events per day, mainly from muons of cosmic rays, therefore expected to be negligible. Finally, our assumption of constant P_i requires that the value of the solar magnetic field is fixed for a long period.

4 Kamiokande and Super-Kamiokande Limits

In this section we show that the conversion of solar neutrinos to electron anti-neutrinos can be suppressed in the high-energy region of ^{8}B neutrinos, while being sizeable for neutrinos with energies below 1 MeV.

The differential spectrum of electron anti-neutrinos in the $\omega \gg 1$ MeV region, $\lambda_{\bar\nu}(\omega)$, is the corresponding one of ^{8}B solar neutrinos distorted due to multiplication by the conversion probability

$$\lambda_{\bar\nu}(\omega) = \lambda_\nu^B(\omega) P_{\nu_{eL}\to\bar\nu_{eR}}(\omega) \tag{10}$$

We choose as a particular model the one presented in reference [14]. In this model the $\nu_{eL} \to \bar\nu_{eR}$ conversions occur in a twisting magnetic field [26] in the triple resonance case with a probability given as

$$P_{\bar e}(\omega) \simeq A(\omega)\sin^4\frac{(\mathcal{F}t)}{2} \tag{11}$$

where the oscillation depth A and the oscillation frequency $\mathcal{F}$ take the form

$$A(\omega) = \frac{4(\delta\sin 2\theta)^2(\mu B_\perp)^2}{[(\delta\sin 2\theta)^2 + (\mu B_\perp)^2]^2} \leq 1 \tag{12}$$

$$\mathcal{F} = \sqrt{(\delta\sin 2\theta)^2 + (\mu B_\perp)^2} \simeq \frac{\mu}{2\times 10^{-11}\mu_B}\frac{B_\perp}{10^4\mathrm{G}}\sqrt{1 + \left(\frac{\delta\sin 2\theta}{\mu B_\perp}\right)^2} \times 10^{-15}\mathrm{eV} \tag{13}$$

These parameters depend on the value of the magnetic field in the solar convective zone $B_\perp$, the neutrino transition magnetic moment μ, the neutrino vacuum mixing angle θ and, finally, the neutrino non-degeneracy parameter $\delta = \Delta m^2/4\omega$.

The oscillation length, $l_{osc} = 2\pi/\mathcal{F}$, must be much less than the width of the convective zone $L_{conv} \simeq 3\times 10^{10}$ cm $= 1.5\times 10^{15}$ eV^{-1}, otherwise $\sin\mathcal{F}t/2 \sim \mathcal{F}t/2$ and the conversion probability in eq. (11) is small. In such a case the maximum value of $P_{\bar e}$ is obtained at the resonance energy, where

$$\delta_{res}\sin 2\theta = \frac{\Delta m^2}{4\omega_{res}}\sin 2\theta = \mu B_\perp$$

Then one can average $\langle \sin^4(\mathcal{F}t/2)\rangle = 3/8$ [7], and this is the maximum value of the conversion probability.

The resonance can lie in the energy region below 1 MeV, provided that the neutrino parameters have reasonable values. In such a case the conversion probability is small for energies $\omega \gg 1$ MeV. For instance, if the resonant energy coincides with the neutrino ^{7}Be line, $\omega_{res} \simeq 0.862$ MeV, one can estimate that the conversion probability for neutrino energies above 8 MeV is

$$P_{\bar{\nu}_e}(8\ \mathrm{MeV}) \simeq \frac{3}{2}\left(\frac{\delta(8\ \mathrm{MeV})}{\delta(\omega_{res})}\right)^2 = \frac{3}{2}\left(\frac{0.862\ \mathrm{MeV}}{8\ \mathrm{MeV}}\right)^2 \simeq 0.015\ . \tag{14}$$

i.e, only a few percent of the initial electron neutrinos in the high energy range convert to electron anti-neutrinos.

Bounds on the solar $\bar{\nu}_e$ flux were obtained from the analysis of the isotropic background in the Kamiokande [20] and Super-Kamiokande [22] experiments. A similar bound has been derived from the analysis of the experimental data obtained on the liquid scintillation detector (LSD) [23].

Assuming that the anti-neutrino spectrum has the same shape as that characterizing ^{8}B solar neutrinos, one has the following bound on the anti-neutrino flux [22]

$$\Phi_{\bar{\nu}}(\omega_{\bar{\nu}} > E_0 = 8.3\ \mathrm{MeV}) < 6 \cdot 10^4\ \mathrm{cm}^{-2}\mathrm{sec}^{-1} \tag{15}$$

This bound sets an upper limit to the presence of electron anti-neutrino in the ^{8}B region, since it must be less than 3.5% of the solar neutrino flux predicted by the Standard Solar Model in the corresponding energy range.

We have calculated the expected flux of high energy electron anti-neutrinos in the case that the conversion occurs through eq. (11). The product of neutrino parameters $\Delta m^2 \sin 2\theta$ has been fixed at 10^{-8} eV^2, whereas the product $\mu B_\perp$ has been varied so as to have the resonant conversion energy in the region below 2 MeV, relevant for *pp* or ^{7}Be neutrinos. Since no positron signal from inverse β decay has been observed in (Super)Kamiokande, its contribution must lie below the flat background. We follow the analysis of reference [20] and its updated version for the Super-Kamiokande data [22].

Using (11) as the conversion probability, the flux of $\bar{\nu}_e$ will be

$$\Phi_\nu^{B,SSM}(\omega_\nu > E_0 = 8.3\ \mathrm{MeV}) \times \frac{\int_{E_0}^{\infty} d\omega\ \lambda_\nu^B(\omega)\sigma_{\bar{\nu}}(\omega)P_{\bar{\nu}_e}(\omega,\omega)}{\int_{E_0}^{\infty} d\omega\ \lambda_\nu^B(\omega)\sigma_{\bar{\nu}}(\omega)} \tag{16}$$

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[7] Note that here we correct eq. 7 of ref. [24] in which $\sin^2$ should be substituted for the averaged propagation factor $\langle \sin^4(\mathcal{F}t)/2\rangle = 3/8$.

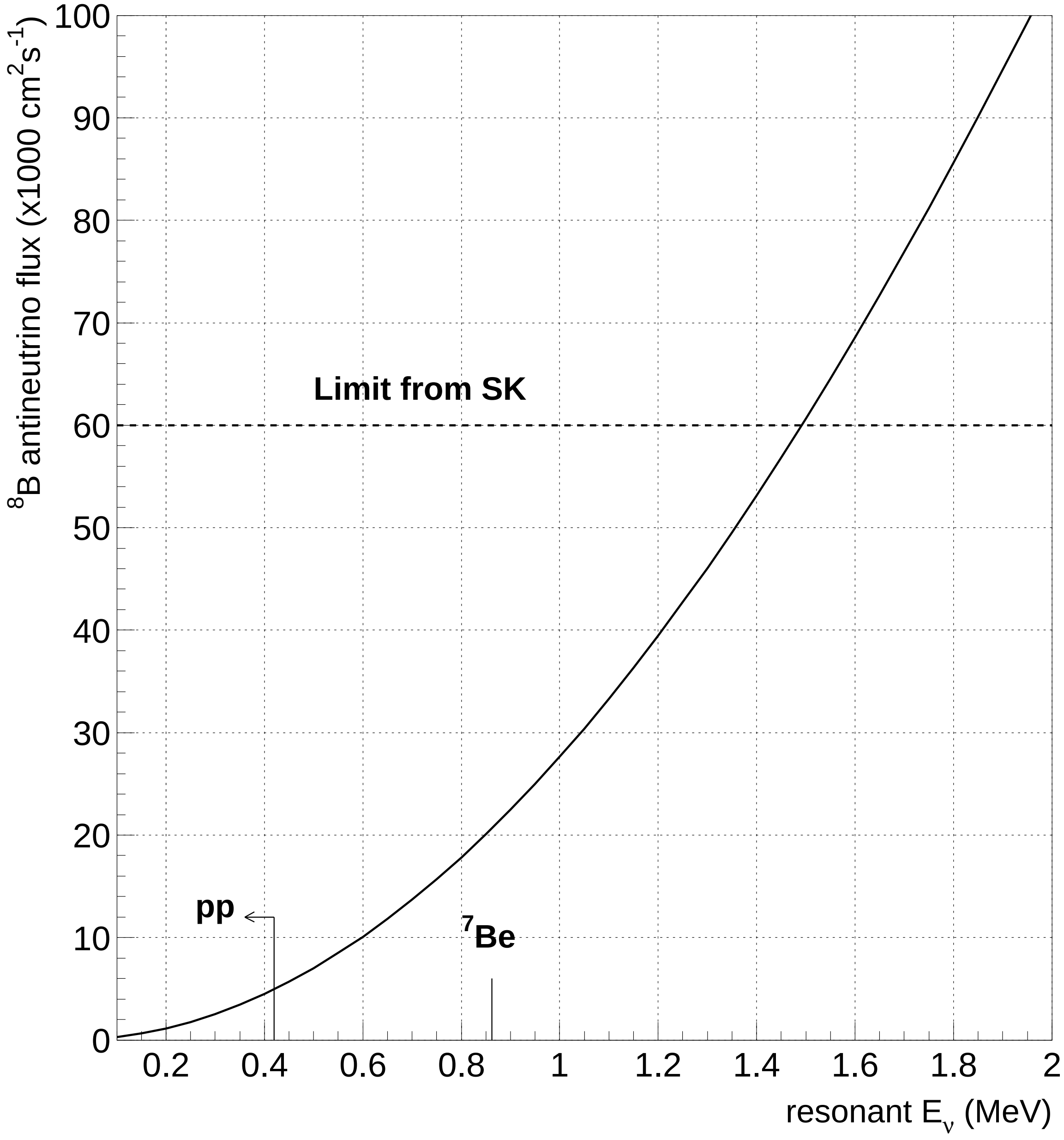

Figure 3: Flux of electron anti-neutrinos in the ^{8}B region according to the conversion mechanism of ref. [14]. We have fixed the value of $\Delta m^2 \sin 2\theta$ at 10^{-8} eV^2 and varied $\mu B_\perp$ so as to have the resonant conversion energy in the region below 2 MeV. The horizontal line corresponds to the limit derived from Super-Kamiokande.

The above expression is plotted in figure (3) as a function of the neutrino energy where the resonance takes place. The bound derived in [22] corresponds to the horizontal line. One can see from this example that the anti-neutrino flux would be *hidden* in the background and therefore unobservable in Super-Kamiokande if ω_{res} lies in the region of pp or ^{7}Be solar neutrinos, relevant for the HELLAZ or BOREXINO experiments, as we discussed in the previous section.

5 Conclusions

In this paper we have argued that the observation of electron low-energy anti-neutrinos from the Sun could lead to the conclusion that the neutrinos are Majorana particles, without conflicting present Kamiokande or Super-Kamiokande data. It is important to emphasize that in the conversions we assume, either given by eq. (3) or presumably caused by ν_e decay, the violation of total lepton number is not produced *directly* by the a Majorana neutrino mass. This is in contrast to the case of laboratory experiments, where the differences between Dirac and Majorana neutrinos can only arise via a neutrino mass insertion and are therefore helicity-suppressed [4]. This is because the neutrino beams produced in laboratory are *fully-polarized.* This applies to neutrinos produced by the weak decay of mesons from accelerators or in reactor or isotope neutrino sources.

The Sun, however, can possess a large-scale magnetic field in the convective zone ($L_{conv} \simeq 3 \times 10^{10}$ cm) with a relatively modest value $B_\perp \sim 10^4$ G. This would effectively cause a neutrino spin-flip if $\mu_\nu B_\perp L \sim 1$ for experimentally acceptable values of the neutrino transition magnetic moment, $\mu_{ij} \sim 10^{-11}\mu_B$. This way one can obtain a flux of neutrinos from the Sun which is *partially-polarized*, in the sense that both neutrinos and anti-neutrinos are present.

Notice that in order to have the conversions in eq. (3), one must require the presence of the Resonant Spin–Flavour Precession (RSFP) mechanism as an intermediate step. As recently discussed in a nice review by Akhmedov [27], this mechanism is not in contradiction with the non-observation of time variations in Kamiokande or GALLEX–SAGE neutrino experiments.

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