# Neutrino spin-flavor oscillations in the Sun: Differences between Dirac and Majorana neutrinos

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The study of neutrino electromagnetic interactions provides us a powerful tool to probe various important phenomena that lie within the reach of current neutrino experiments. In the minimally extended SM containing massive neutrinos, both Dirac and Majorana neutrinos acquire non-zero magnetic moment by contributions from higher order loop diagrams [1]. This leads to the phenomena of neutrino spin and spin-flavor oscillations in presence of sufficiently strong electromagnetic fields which exhibits interesting quantum mechanical effects [2]. In addition under $CP$ and $CPT$ both Dirac and Majorana fields transform differently, which results in phenomenological differences in the spin-flavor oscillations of Dirac and Majorana neutrinos. Here we analyze one such situation, where neutrinos undergo spin-flavor transitions due to magnetic field present in the radiative zone inside the Sun.

The standard solar model BP(2000) [3] gives the variation of electron number density in the Sun, which is usually parametrized using an exponential function as shown in Fig 1. However, this parametrization does not fit well near the solar core. So we use a different parametrization: $n_e(x) = n_0(1 - \tanh(x/l_1))$, where $n_0$ is the electron density near the solar core and $l_1$ is the length scale of density variation. Also the variation of magnetic field with distance in the radiative zone of the Sun [4] can be parametrized as: $B(x) = B_0 \,\mathrm{sech}((x-a)/l_2)$, where $B_0$ is the peak magnetic field, $l_2$ is the length scale over which the field varies and $a = 0.25R_\odot$ where $R_\odot$ is the solar Radius. Various solar models give peak magnetic field of upto $10^3$ T in the radiative zone of the Sun [4].

The neutrino spin-flavor Hamiltonian is the sum of vacuum term $H_0$, matter term $H_m$ and magnetic field term $H_b$ and can be written in dimensionless form as

$$H = H_0 + H_m + H_b = \boldsymbol{\omega} \cdot \boldsymbol{\sigma}. \quad (1)$$

Employing the basis $(\nu_L, \nu_R)^T$ containing left and right helicity neutrino components, for a neutrino propagating in a transverse magnetic field we can write $\boldsymbol{\omega} = (l_v/l_b, 0, l_v/l_m - A(\theta))$, where $l_v(\mathrm{km}) = 2.5E(\mathrm{GeV})/\Delta m^2(\mathrm{eV}^2)$ is the neutrino wavelength in vacuum, $E$ is the neutrino energy and $\Delta m^2$ is the mass squared difference for the solar neutrinos, $l_m(\mathrm{km}) = 1.6\times10^4/Y_e^{\mathrm{eff}}\rho(\mathrm{g/cm}^3)$ is the refraction length scale for the medium, $Y_e^{\mathrm{eff}}$ is the electron fraction and $\rho$ is the matter density, $l_b(\mathrm{km}) = 1.1 \times 10^{10}/B(\mathrm{G})$ is the neutrino length scale in magnetic field, $B$ is the magnetic field in gauss, and $A(\theta)$ is a function of vacuum mixing angle. Here we have assumed the neutrino magnetic moment $\mu_\nu = 10^{-11}\mu_B$, where

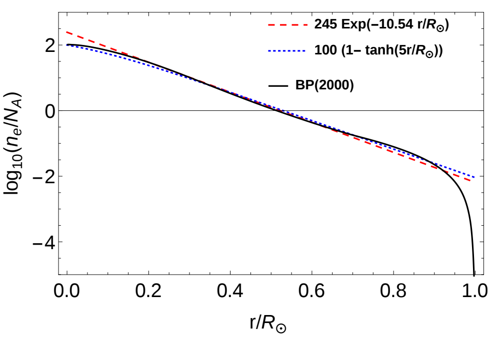


FIG. 1: Electron number density variation vs. radial distance in the Sun. The solid line represent the standard solar model BP(2000) and the dashed curves are analytical parametrization.

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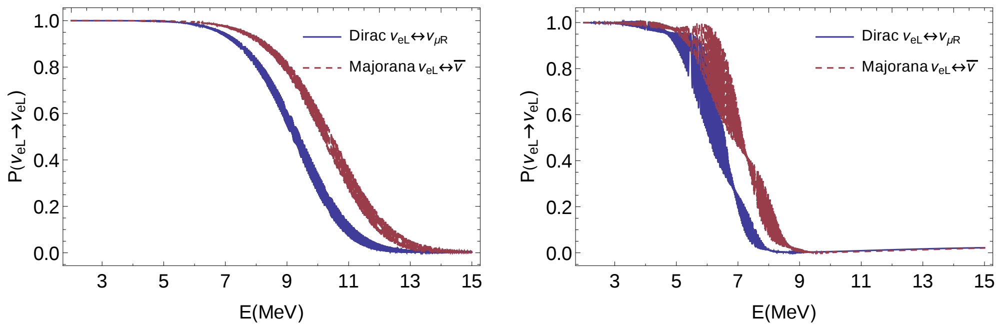


(a)$B_0 = 10^6$ G (b)$B_0 = 5 \times 10^6$ G

FIG. 2: The electron neutrino survival probability at the surface of the Sun as a function of energy of $^8B$ neutrinos. For a given neutrino energy, Dirac neutrinos undergo resonant transition at lower density compared to Majorana neutrinos. Since the magnetic field peaks in the radiative zone, Dirac neutrinos experience stronger magnetic field in the region around resonance and undergo faster depletion with energy compared to Majorana neutrinos.

$\mu_B = 5.78 \times 10^{-8}$GeV fm$^3$ is the Bohr magneton, which is consistent with the current experimental bounds on $\mu_\nu$ [1].

As the electron neutrinos produced in the fusion reactions inside the Sun propagate outward, they may undergo resonant spin-flavor conversion. Numerically the resonance condition is obtained when the diagonal elements of the spin-flavor Hamiltonian cross and for our case is given by

$$\rho(x_R)(\mathrm{g/cm}^3) = 6.577 \frac{\Delta m^2_{\mathrm{sol}}(\mathrm{eV}^2)\cos 2\theta_{12}}{E(\mathrm{MeV})Y_e^{\mathrm{eff}}},$$

where the location of resonance $x_R$ depends on the Dirac or Majorana nature of the neutrino viz.

$$Y_e^{\mathrm{eff}} = \begin{cases} (3Y_e - 1)/2 & \nu_{eL} \leftrightarrow \nu_{\mu_R,\tau_R}(\mathrm{Dirac}) \\ (2Y_e - 1) & \nu_{e_L} \leftrightarrow \bar{\nu}_{\mu,\tau}(\mathrm{Majorana}), \end{cases}$$

where we have taken the electron fraction $Y_e = 5/6$ for the Sun. Clearly for the low energy part of the solar spectrum with $E \leq 2$ MeV, the solar density is not sufficient to produce sizable resonant transitions, so we consider only the case of $^8B$ neutrinos with maximum energy $E_{\mathrm{max}} \approx 15$ MeV. The magnetic field strength determines the region around the resonance where transition probability is sufficient. Stronger magnetic field extends over larger regions and hence affects neutrinos over a broader energy range.

The survival probability for electron neutrinos $P(\nu_{eL} \rightarrow \nu_{eL})$ produced inside the Sun can be found by numerically solving the Schrödinger like equation corresponding to Hamiltonian in Eq. (1). The resulting plot of $P(\nu_{eL} \rightarrow \nu_{eL})$ versus energy clearly show the difference between the Dirac and Majorana cases. Thus a careful measurement of energy of the $^8B$ solar neutrinos is required to analyze the effects of magnetic field in the solar environments and discern the Dirac or Majorana character of neutrinos. In addition, these studies may also allow us to put strong upper bounds on the magnetic fields in solar radiative zone as well as on the magnetic moment of neutrinos.

## References


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