PROPAGATION AND OSCILLATIONS OF NEUTRINOS WITH MAGNETIC MOMENT INSIDE THE SUN

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Abstract

The VVO mechanism suggests that the existence of a neutrino magnetic moment would lead to variations of the observed flux of solar neutrinos correlated with the magnetic activity of the Sun. The MSW mechanism suggests neutrino oscillations while propagating in the dense plasma interior of the Sun. Assuming a nonvanishing neutrino magnetic moment and a magnetic field gradient increasing towards the solar core as required in some dynamo models, the combined effect of the oscillation and the flipping on neutrino propagation in the solar interior is studied. If large magnetic fields ($\approx 10^5$G) are present in the solar interior the oscillation parameters could be significantly altered. The effect of charge screening in scattering cross-section are also considered. The considerations are extended to supernovae neutrinos and constraints put on relevant neutrino parameters.

INTRODUCTION

Voloshin, Vysotsky and Okun [Voloshin 1986] have recently suggested that a neutrino magnetic moment μ of the order of $\sim 10^{-10}\mu_B$ (where $\mu_B = e\hbar/2m_e c$ is the Bohr magneton), would be sufficient to flip a substantial part of the left-handed neutrinos into sterile right-handed ones, over a length L in a magnetic field B such that BL $\sim 10^8$Tm, eg L $\approx 10^8$m for B $\approx$ 300 G. This would result in a semiannual variation in the observed solar neutrino flux and may possibly resolve the apparent discrepancy between observed and theoretical fluxes. However existing data of Bahcall is not enough to test this prediction. The value of $10^{-10}\mu_B$ is just below experimental bound from neutrino scattering [Kyuldjiev 1984]. Constraints from SN 1987A appear to rule out such a large value of μ.
Again we have the MSW mechanism which invokes neutrino oscillations (with length $\sim 2\pi E/\Delta m^2$), with a desity dependent oscillation length to to explain resonant conversion of electron neutrinos above a certain threshold energy to muon neutrinos so that the Davis experiment does not register the higher energy neutrinos from B^8 decay. However if in addition to an electron density varying with depth in the solar interior we have a magnetic field gradient increasing towards the solar core as required in some dynamo models then the combined effect of the varying density and magnetic field in

the solar interior on the neutrino propagation has to be studied. For instance a large magnetic field ($\approx 10^5$G) if present in the solar core would cause the neutrinos to flip helicity over a distance of ~ $3\cdot10^5$m only if they had a μ as high as in the VVO mechanism. So actually one would detect only about half of the neutrino flux emerging out of the core. Moreover the effect of charge screening in the solar interior could be significant in modifying scattering cross sections of neutrinos. So all these effects have to be combined, in understanding neutrino propagation in the solar interior.

Neutrino propagation in solar interior with varying density and magnetic field The effective Hamiltonian describing neutrino evolution in flavour space (e,μ) in the presence of B along ν spin is of the form:

$$H_{e\mu} = H_{\mu e} = -(1/2)\Big[(m_1^2 - m_2^2)/2E - (\mu_{11}/\gamma_1 - \mu_{22}/\gamma_2)\sin 2\theta + (\mu_{12}/\gamma_{12})B\cos 2\theta\Big]$$

θ is the vacuum mixing angle $\gamma_1 = E/m_1$, $\gamma_2 = E/m_2$, $\gamma_{12} = 2E/(m_1 + m_2)$. The neutrino mixing angle in presence of a magnetic field B is

$$\theta_B = \theta + \tan^{-1}\mu_{12}B\Big\{m_1 - m_2 - \Big[\mu_{11} - \mu_{22} + [(m_1 - m_2)/(m_1 + m_2)]\cdot(\mu_1 + \mu_2)\Big]\,B\Big\}^{-1}$$

Mixing in presence of a field is maximal when $\tan 2\alpha = \cot 2\theta$ where α is the second term in above expression. Resonance phenomenon occurs only when $|m_1 - m_2|/(m_1 + m_2) \ll |\mu_{11} - \mu_{22}|/|\mu_{11} + \mu_{22}|$ or $\tan 2\alpha = x\,B/(B_o - B)$ where $x = 2\mu_{12}/(\mu_{11} - \mu_{22})$.
In region $B \gg B_o$ mixing is small; it increases with decreasing B and is maximum at $B = B_o$ when $\alpha = \pm\,\pi/4$ and decreases to 0 for $B \to 0$. Similar to case of matter oscillations. B above is a function of radius R. For combined presence of varying electron density and magnetic field, the oscillationlength in a given region is:

$$l_{osc} = 2\pi/\Big[(\mu_{12}B_\perp)^2 + \Big((2m_2^2 - m_1^2)/2E - (2)^{1/2}G_F N\,Y_e f\Big)^2\Big]^{1/2}$$

N is the particle density, Y_e is the electron fraction, G_F is Fermi constant, $f = 1 - N_n - N_e$

$$\tan 2\theta = 2\mu_{12}H_\perp/\Big[(m_2^2 - m_1^2)/2E - (2)^{1/2}G_F Y_e N_e f\Big].$$

For B = 0, we have the usual MSW condition

$$(2)^{1/2} G_F N_e f = (m_1^2 - m_2^2)/2E.$$

The quantities N and B are defined in the radial sense in the above equations,

$$\langle N \rangle = (1/R)\int_0^R dr\ n(r), \quad \langle B \rangle = (1/R)\int_0^R dr\ B(r),$$

where the gradients in the particular region are taken into account. The adiabacity condition takes the form:

$$[2\pi E/(m_1 + m_2)](1/|\mu_{12}|B_o) < L(\Delta B/B_o).$$

Estimates give:

$B_o \approx 10^8(\Delta m/\Delta\mu)G$, Δm is in ev and $\Delta\mu$ is in units of $\mu_B$ev/G. and sets a lower bound on dimensions of region in which $B \geq B_o$. Again charge screening takes place in the solar plasma where the virtual photon acquires a mass

$m_\gamma = \left[(4\pi\alpha/\langle KT\rangle)\Sigma_i n_i\right]$, n_i is the species present and the spin flip scattering cross section is of the form

$$\sigma_e = \pi\ \mu^2(\alpha/m)^2\int_0^{T_e}[dT_e/(T_e + m_\gamma^2/2m^2)][T_e - T_e^2/\bar{E}_\nu]\cdot$$
$$\cdot\left[1-\left\{\exp\left((T_e - k)/KT\right) + 1\right\}^{-1}\right]$$

(k is the chemical potential)
The neutrino mean free path is then:

$\langle l \rangle = \left[\Sigma_i \sigma_i \langle m_i \rangle\right]^{-1}$. This has to be compared with the oscillation length l_{osc} above. The possibility for spin flip event in a distance R is $(1 - \exp(-x)\cosh(x))$, $x = R/\langle l \rangle$. Result is $\langle l \rangle \gg l_{osc}$. For supernova neutrinos with neutrino scattering on Fe-56 nuclei, we have $(Ze)^2$ dependence of c.s., and $\langle l \rangle \approx 10^8$cm, for $\mu \approx 10^{-10}$. This is much smaller than spin flip in presence of magnetic field i.e. $\langle l_B \rangle \sim 10^2$cm, for neutron star magnetic fields. Thus spin flip probability by scattering on nuclei is only ~ 0.1, whereas it is ~ 1 in presence of large magnetic field ~ 10^8G in the collapsing core even for $\mu < 10^{-21}\mu_B$ [Sivaram 1989].

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