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Matter polarization effect on neutrino spin oscillations

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Abstract

Neutrino electromagnetic properties are of great importance from the point of view of fundamental theory, as well as from the point of view of applications. It is of common knowledge that neutrinos determine to a large extent the dynamics of supernova explosion. In this work we study the effect of matter polarized by external magnetic field on neutrino spin evolution and propagation inside supernovae. Alternatively, the problem of neutrino interaction with such kind of matter can be treated as the interaction of the induced neutrino magnetic moment (IMM) with the magnetic field. Using the corresponding interaction Lagrangian we obtain the effective evolution equation for a neutrino with IMM and on its basis consider neutrino spin oscillations for different cases of Dirac/Majorana neutrino type, absence/presence of neutrino anomalous magnetic moment (AMM). It is shown that due to IMM the neutrino flux from a supernova undergoes additional attenuation. Also, the effects of IMM and AMM when taken together can cancel each other leading to a specific maximum in the neutrino spectrum from supernovae.

Neutrino magnetic moments

Neutrino (anomalous) magnetic moment μ_ν

Within the minimally extended Standard Model (SM) with right-handed neutrino singlets added [1]:

$$\mu = \frac{3eG_F m}{8\sqrt{2}\pi^2} \simeq 3.2\times10^{-19}\mu_B\left(\frac{m}{1\ \text{eV}}\right),$$

$$\mu_B = e/2m_e$$

Dirac neutrinos can have both diagonal and transition μ in flavor basis, Majorana neutrinos can have the transition μ only

Neutrino induced magnetic moment (IMM) μ^{ind}

corresponds to the contribution of pseudovector currents of medium particles into the effective vertex of neutrino interaction.

In a degenerate electron gas [2,3,4]:

$$\mu^{\text{ind}} = -\frac{eG_F p_F}{4\sqrt{2}\pi^2} \simeq -2.2\times10^{-13}\mu_B\left(\frac{p_F}{1\ \text{MeV}}\right),$$

$$p_F = \sqrt{\mu_e^2 - m_e^2} \simeq 130\times\left(\frac{n_e}{10^{37}\ \text{cm}^{-3}}\right)^{1/3}\ \text{MeV}$$

μ_e and n_e are the chemical potential and number density

IMM interpretation:
- interaction of ν with external magnetic field through IMM
- **weak interaction of ν with polarized by magnetic field matter**

Neutrino dynamics

Phenomenological Lagrangian for coherent neutrino interaction with homogeneous non-moving matter composed of e, p and n [4]:

$$\Delta L_{\text{eff}} = -f^\mu\left(\bar\nu\gamma_\mu\tfrac{1}{2}(1+\gamma^5)\nu\right),$$

For e- and μ-types of neutrino in the [5,6] in the limit $eB \ll P_F^2$:

$$f^\mu_{e,\mu} = \left\{V_{e,\mu},\ \mp2\mu^{\text{ind}}\mathbf{B}\right\},$$

$$V_e = \sqrt{2}G_F(n_e - n_n/2),\quad V_\mu = -\sqrt{2}G_F n_n/2$$

Evolution equation

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e^{s=-1}\\ \nu_e^{s=+1}\end{pmatrix} = (H_{\text{vac}} + H_{\text{matt}} + H_M)\begin{pmatrix}\nu_e^{s=-1}\\ \nu_e^{s=+1}\end{pmatrix}$$

where s = ± 1 is the neutrino helicity,
H_{vac} - vacuum oscillation term,
H_M – AMM interaction term,
$H_{\text{matt}} = \langle\nu_\alpha^s|\Delta H_{\text{eff}}|\nu_\beta^{s'}\rangle$, where α, β=e, μ – matter interaction term

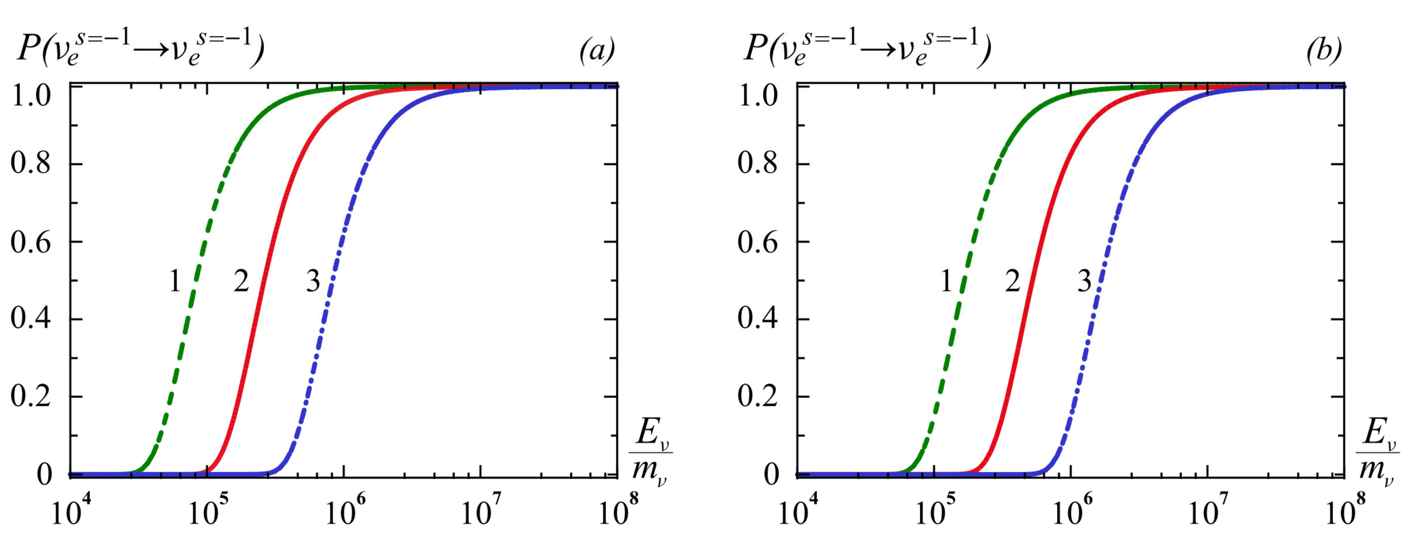

Fig. 1. The survival probability for neutrino with negative helicity as a function of neutrino energy: (a) – for Dirac neutrino, (b) – for Majorana neutrino; Line 1: $dY_e/dr = 10^{-8}$ cm^{-1}, Line 2: $dY_e/dr = 10^{-9}$ cm^{-1}, Line 3: $dY_e/dr = 10^{-10}$ cm^{-1}; $\rho_B = 10^{12}$ g/cm^3, $B = 6.6\times10^{16}$ G, $Y_e = 1/3$.

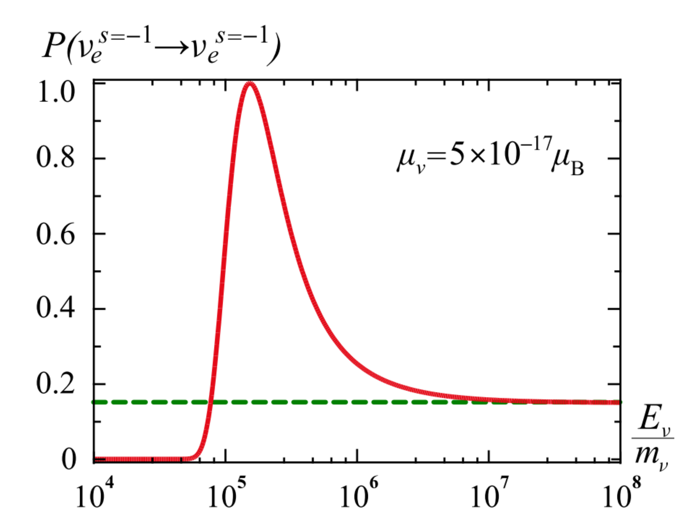

Fig. 2. The survival probability for Dirac neutrino with magnetic moment and with negative helicity depending on the neutrino energy: $dY_e/dr = 10^{-9}$ cm^{-1}, $\rho_B = 10^{12}$ g/cm^3, $B = 6.6\times10^{16}$ G, $Y_e = 1/3$, $\mu_\nu = 5\times10^{-17}\mu_B$. The dashed line corresponds to the conversion due to the magnetic moment only.

One flavor, Dirac ν_e

$$H_{\text{matt}} = \begin{pmatrix}V_e + 2\mu^{\text{ind}}B_\parallel & -\mu^{\text{ind}}\gamma^{-1}B_\perp\\ -\mu^{\text{ind}}\gamma^{-1}B_\perp & 0\end{pmatrix},\quad H_M = \begin{pmatrix}\mu_\nu\gamma^{-1}B_\parallel & -\mu_\nu B_\perp\\ -\mu_\nu B_\perp & -\mu_\nu\gamma^{-1}B_\parallel\end{pmatrix},$$

$$\gamma = E_\nu/m_\nu$$

The survival probability (transition $\nu^{s=-1}\to\nu^{s=+1}$):

$$P(t) = \frac{\left(2(\mu_\nu^{\text{ind}}\gamma^{-1}+\mu_\nu)B_\perp\right)^2}{\left(2(\mu_\nu^{\text{ind}}\gamma^{-1}+\mu_\nu)B_\perp\right)^2 + \left(V_e + 2(\mu_\nu^{\text{ind}}+\mu_\nu\gamma^{-1})B_\parallel\right)^2}\ \sin^2\left\{\sqrt{D}\,\frac{t}{2}\right\}$$

where D is the denominator of the pre-sine factor.

The resonance condition corresponds to minimal D. However, for effective conversion of neutrinos at the resonance point, the adiabatic condition must be satisfied, requiring that the width of the resonance is of the order of or greater than half of the oscillation length. In our case it reads as:

$$\varkappa_M = \frac{2(2(\mu_\nu^{\text{ind}}\gamma^{-1}+\mu_\nu)B_\perp)^2}{|dV_e/dr|} \gtrsim 1$$

When the adiabaticity condition is violated P can be estimated by the Landau-Zener formula:

$$P_{\nu_e^{s=-1}\to\nu_e^{s=-1}} = \exp\left(-\frac{\pi}{2}\varkappa\right).$$

Negligible μ_ν

The resonance condition

$$V_e = \frac{G_F}{\sqrt{2}}\frac{\rho_B}{m_N}(3Y_e - 1) \to 0 \Rightarrow Y_e \approx 1/3$$

where ρ_B is the mass density and Y_e is the number of electrons per baryon. In the resonance ρ_B~10^9-10^{12} g/cm^3.

Since Y_e has a characteristic dip during the neutronization pulse (and some time after) varying from 0,1 to 0,5 the resonance do exist at some point.

$$\varkappa = \frac{2(2\mu_\nu^{\text{ind}}\gamma^{-1}B_\perp)^2}{|dV_e/dr|} \gtrsim 1$$

The adiabaticity requires that dY_e/dr is small. This condition at a point Y_e=1/3 is fulfilled at a level of ~10^{-9}-10^{-8} cm^{-1} for times up to 500 ms after the core bounce. The derivative dY_e/dr also determines the conversion energy range, see Fig.1.

Attenuation of the low-energy part of the neutrino signal from the supernova for some limited time after collapse

Sizable μ_ν

Disappearance of oscillations upon the condition

$$\mu_\nu^{\text{ind}}\gamma^{-1} = -\mu_\nu$$

A characteristic maximum in the spectrum of electron neutrinos from supernova (see Fig. 2) at relatively low energies less ~1 MeV, if neutrinos possess a sufficiently large magnetic moment (for the conditions chosen, $\mu_\nu \geq 10^{-17}\mu_B$).

Majorana ν

$$H_{\text{matt}} = \begin{pmatrix}V_e + 2\mu_\nu^{\text{ind}}B_\parallel & -2\mu_\nu^{\text{ind}}\gamma^{-1}B_\perp\\ -2\mu_\nu^{\text{ind}}\gamma^{-1}B_\perp & -V_e - 2\mu_\nu^{\text{ind}}B_\parallel\end{pmatrix}$$

The same amplitude of oscillations $\nu_e^{s=-1}\to\nu_e^{s=+1}$ (i.e. $\nu_e\to\bar\nu_e$) as in the Dirac case.

Distortion of the low-energy part of the neutrino signal from the supernova

Effects of neutrino mixing

$$H^e_{\text{matt}} = \begin{pmatrix}V_e + 2\mu_{ee}^{\text{ind}}B_\parallel & -\mu_{ee}^{\text{ind}}\gamma^{-1}B_\perp\\ -\mu_{ee}^{\text{ind}}\gamma^{-1}B_\perp & 0\end{pmatrix},$$

where appears the shift $\mu^{\text{ind}}\to\mu_{ee}^{\text{ind}} = \mu^{\text{ind}}(1+\sin2\theta)$

With $\sin 2\theta \approx 0.93$ we have almost twofold increase in the IMM value for ν_e. For ν_μ: $\mu_{\mu\mu}^{\text{ind}} = -\mu^{\text{ind}}(1-\sin2\theta)$ we have instead a decrease. Due to the sign, no effect of oscillation disappearance takes place for ν_μ.

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