Neutrino chirality flip in a supernova and the bound on the neutrino magnetic moment

A. V. Kuznetsov[a]*, N. V. Mikheev[a]†
[a] *Yaroslavl State (P.G. Demidov) University*
Sovietskaya 14, 150000 Yaroslavl, Russian Federation

Abstract

The neutrino chirality-flip process under the conditions of the supernova core is investigated in detail with the plasma polarization effects in the photon propagator taken into account. It is shown that the contribution of the proton fraction of plasma is essential. New upper bounds on the neutrino magnetic moment are obtained: $\mu_\nu < (0.5-1.1) \times 10^{-12}\, \mu_{\rm B}$ from the limit on the supernova core luminosity for ν_R emission, and $\mu_\nu < (0.4-0.6) \times 10^{-12}\, \mu_{\rm B}$ from the limit on the averaged time of the neutrino spin-flip. The best astrophysical upper bound on the neutrino magnetic moment is improved by the factor of 3 to 7.

1 Neutrino spin-flip in the supernova core

Nonvanishing neutrino magnetic moment leads to various chirality-flipping processes when the left-handed neutrinos produced inside the supernova core during the collapse could change their chirality becoming sterile with respect to the weak interaction. These sterile neutrinos would escape from the core leaving no energy to explain the observed luminosity of the supernova.

This process was investigated by several authors. R. Barbieri and R. N. Mohapatra [1] considered the neutrino spin-flip via both $\nu_L e^- \to \nu_R e^-$ and $\nu_L p \to \nu_R p$ scattering processes in the inner core of a supernova immediately after the collapse. However, they did not consider the essential plasma polarization effects in the photon propagator, and the photon dispersion was taken in a phenomenolical way, by inserting an *ad hoc* thermal mass into the vacuum photon propagator.

Imposing for the ν_R luminosity Q_{ν_R} the upper limit of 10^{53} ergs/s, the authors [1] obtained the upper bound on the neutrino magnetic moment:

$$\mu_\nu < (0.2-0.8) \times 10^{-11}\, \mu_{\rm B}\,. \tag{1}$$

Later on, A. Ayala, J. C. D'Olivo and M. Torres [2, 3] used the formalism of the thermal field theory to take into account the influence of hot dense astrophysical plasma on the photon propagator. The upper bound on the neutrino magnetic moment was improved by them in the factor of 2:

$$\mu_\nu < (0.1-0.4) \times 10^{-11}\, \mu_{\rm B}\,. \tag{2}$$

However, those authors considered only the contribution of plasma electrons, and neglected the proton fraction. Thus, the reason exists to reconsider the neutrino spin-flip processes in the supernova core more attentively.

We will show in part, that the proton contribution into the photon propagator is essential, as well as the scattering on plasma protons.

---

[*] **e-mail**: avkuzn@uniyar.ac.ru
[†] **e-mail**: mikheev@uniyar.ac.ru

2 Neutrino interaction with background

The neutrino chirality flip is caused by the scattering via the intermediate plasmon on the plasma electromagnetic current presented by electrons, $\nu_L e^- \to \nu_R e^-$, protons, $\nu_L p \to \nu_R p$, etc. It is described by the Feynman diagram shown in Fig. 1, where J^{em} is an electromagnetic current in the general sense, formed by different components of the medium, i.e. free electrons and positrons, free ions, etc.

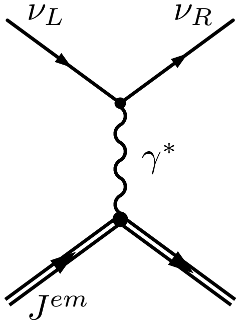

Figure 1: The Feynman diagram for the neutrino spin-flip scattering via the intermediate plasmon γ^* on the plasma electromagnetic current J^{em}.

The technics of calculations of the neutrino spin-flip rate is rather standard. The only principal point is to use the photon propagator with taking account of the plasma polarization effects, see e.g. [4]:

$$G_{\alpha\beta}(q) = \frac{-\mathrm{i}\,\rho^{(t)}_{\alpha\beta}}{q^2 - \Pi_t} + \frac{-\mathrm{i}\,\rho^{(\ell)}_{\alpha\beta}}{q^2 - \Pi_\ell}\,, \tag{3}$$

where $\rho^{(t,\ell)}_{\alpha\beta}$ are the density matrices for the transversal and longitudinal plasmon, and $\Pi_{t,\ell}$ are the corresponding eigenvalues of the photon polarization tensor.

3 Neutrino chirality-flip rate

Integrating the amplitude squared of the process, described by the Feynman diagram of Fig. 1, over the states of particles forming the electromagnetic current and over the states of the initial left-handed neutrinos, we obtain the rate $\Gamma(E)$ of creation of the right-handed neutrino with the fixed energy E.

The value $\Gamma(E)$ can be rewritten in the form of double integral over the energy ω and momentum $k \equiv |\vec{k}|$ of the virtual plasmon:

$$\begin{aligned}\Gamma(E) \quad &= \quad \frac{\mu_\nu^2}{16\,\pi^2\,E^2} \int\limits_0^\infty k^3\,\mathrm{d}k \int\limits_{-k}^{k} \mathrm{d}\omega\,\theta(2E+\omega-k)\,\frac{(2E+\omega)^2}{1-\mathrm{e}^{-\omega/T}}\, f_\nu(E+\omega) \\ &\times \quad \left[1-\left(\frac{\omega}{k}\right)^2\right]^2 \left[\rho_\ell(\omega,k) + \left(1-\frac{k^2}{(2E+\omega)^2}\right)\rho_t(\omega,k)\right]. \end{aligned} \tag{4}$$

Here $f_\nu(\varepsilon) = \left(\mathrm{e}^{(\varepsilon-\tilde{\mu}_\nu)/T}+1\right)^{-1}$ is the left-handed neutrino distribution function with the chemical potential $\tilde{\mu}_\nu$, the functions $\rho_{\ell,\,t}(\omega,k)$ are the spectral densities of the longitudinal and transversal plasmons.

It should be noted that the factor $(1-\mathrm{e}^{-\omega/T})^{-1} = 1 + f(\omega)$ when $\omega > 0$, accounting for the Bose—Einstein distribution $f(\omega)$ of photons in the final state, arises automatically in the integration over the states of particles forming the electromagnetic current, independently on the nature of particles. In the region where $\omega < 0$, this factor can be rewritten as $(1-\mathrm{e}^{|\omega|/T})^{-1} = -f(|\omega|)$, and together with the change of sign of the functions $\rho_{\ell,t}$ when $\omega = -|\omega|$ is substituted, it accounts for the distribution of initial photons with the energy $|\omega|$, being captured by a neutrino.

We note that our expression (4) for $\Gamma(E)$ is larger by the factor of 2 than the corresponding formulas in the papers by A. Ayala et al. [2,3]. On the other hand, it is in agreement, to the notations, with the rate obtained by P. Elmfors et al. [5].

4 Photon dispersion

The spectral densities $\rho_{\ell,t}(\omega,k)$ are defined by the photon polarization operator and have the form:

$$\rho_{\ell,t}(\omega,k) = \frac{2\,I_{\ell,t}}{(q^2 - R_{\ell,t})^2 + I_{\ell,t}^2}\,. \tag{5}$$

Here, $R_{\ell,t}$ and $I_{\ell,t}$ are connected with the real and imaginary parts of the eigenvalues of the photon polarization operator $\Pi_{\ell,t} = R_{\ell,t} \pm \mathrm{i}\,I_{\ell,t}$, containing the contributions of all components of the active medium. The functions $\Pi_{\ell,t}$ can be found in [4].

For the supernova conditions, the main contribution comes from the plasma electrons and protons:

$$R_{\ell,t} \simeq R_{\ell,t}^{(e)} + R_{\ell,t}^{(p)}\,, \quad I_{\ell,t} \simeq I_{\ell,t}^{(e)} + I_{\ell,t}^{(p)}\,. \tag{6}$$

It is interesting to note that for the medium where $I_{\ell,t} \to 0$, and simultaneously the dispersion equation $q^2 - R_{\ell,t} = 0$ is fulfilled, the rate $\Gamma(E)$ describes the Cherenkov-like process with emission ($\omega > 0$) and absorption ($\omega < 0$) of the real plasmon (photon), investigated in part by W. Grimus and H. Neufeld [6].

In the Figs. 2 and 3 we illustrate the importance of taking into account the proton contribution into the eigenvalue Π_ℓ for the longitudinal plasmon. For the case of transversal plasmon, the proton contribution is not essential.

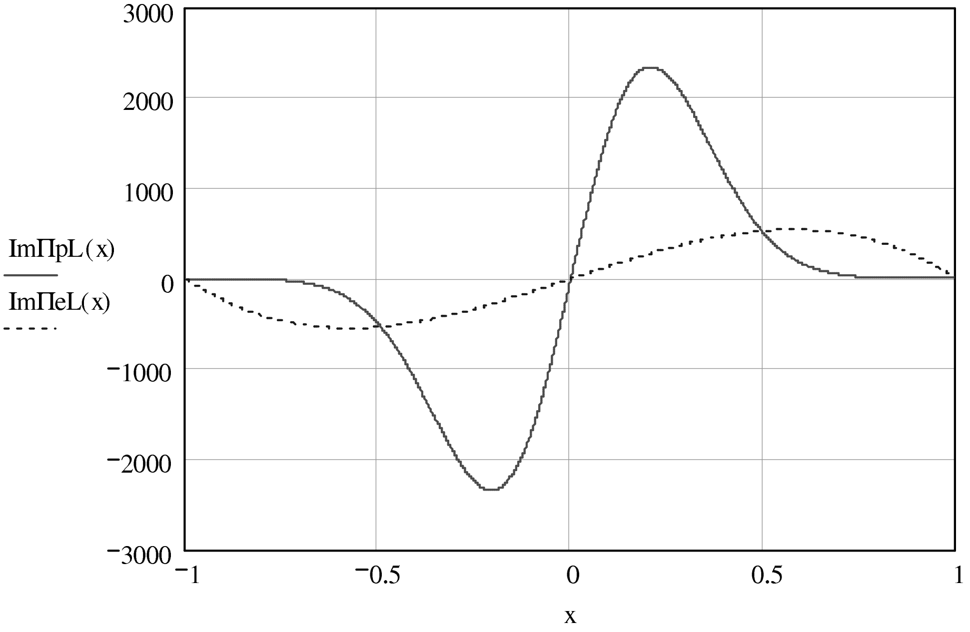

Figure 2: Proton (solid line) and electron (dotted line) contributions to the imaginary part of Π_ℓ.

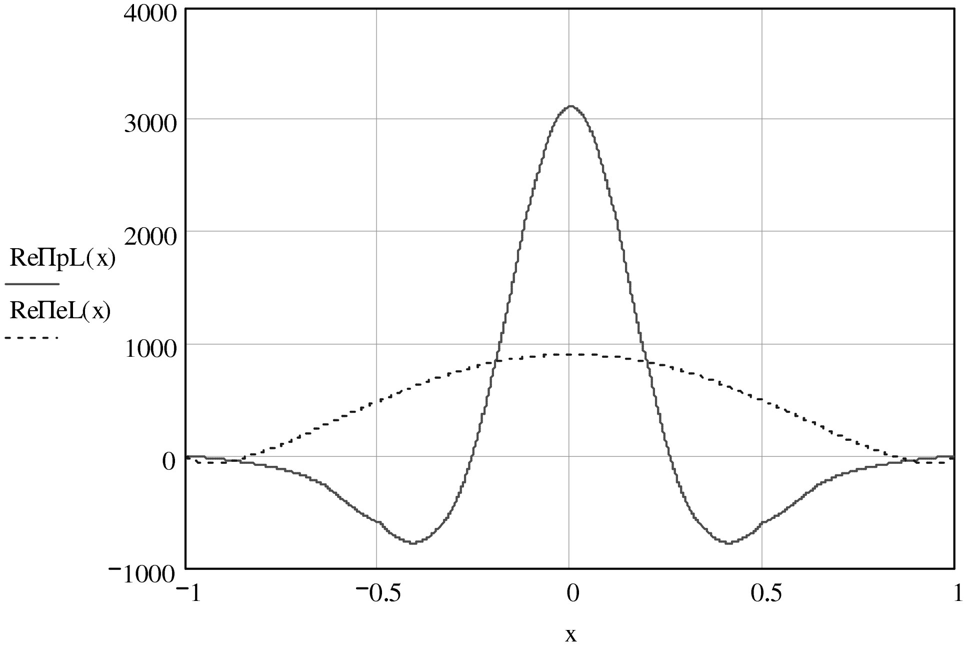

Figure 3: Proton (solid line) and electron (dotted line) contributions to the real part of Π_ℓ.

5 Right-handed neutrino luminosity

The result of our numerical calculation of the neutrino chirality-flip rate $\Gamma(E)$ is presented in the Fig. 4. The plotted function $F(E)$ is defined by the expression

$$\Gamma(E) = \frac{\mu_\nu^2 \, T^3}{32 \, \pi} \, F(E) \, . \tag{7}$$

It is seen from the Fig. 4 that the proton contribution is essential indeed.

The supernova core luminosity for ν_R emission can be computed as

$$Q_{\nu_R} = V \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \, E \, \Gamma(E) \, , \tag{8}$$

where V is the plasma volume.

For the same supernova core conditions as in the papers [2, 3] (plasma volume $V \sim 8 \times 10^{18} \mathrm{cm}^3$, temperature range $T = 30 - 60$ MeV, electron chemical potential range $\mu_e = 280 - 307$ MeV), we found

$$Q_{\nu_R} = \left(\frac{\mu_\nu}{\mu_\mathrm{B}} \right)^2 (0.76 - 4.4) \times 10^{77} \ \mathrm{ergs/s} \, . \tag{9}$$

Assuming that $Q_{\nu_R} < 10^{53}$ ergs/s, we obtain the upper limit on the neutrino magnetic moment

$$\mu_\nu < (0.5 - 1.1) \times 10^{-12} \, \mu_\mathrm{B} \, . \tag{10}$$

6 Left-handed neutrino washing away

An additional method can be used to put a bound on the neutrino magnetic moment. Together with the supernova core luminosity Q_{ν_R}, a number of right-handed neutrinos emitted per 1 sec per 1 cm^3 can be defined via the rate $\Gamma(E)$ as

$$n_{\nu_R} = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \, \Gamma(E) \, . \tag{11}$$

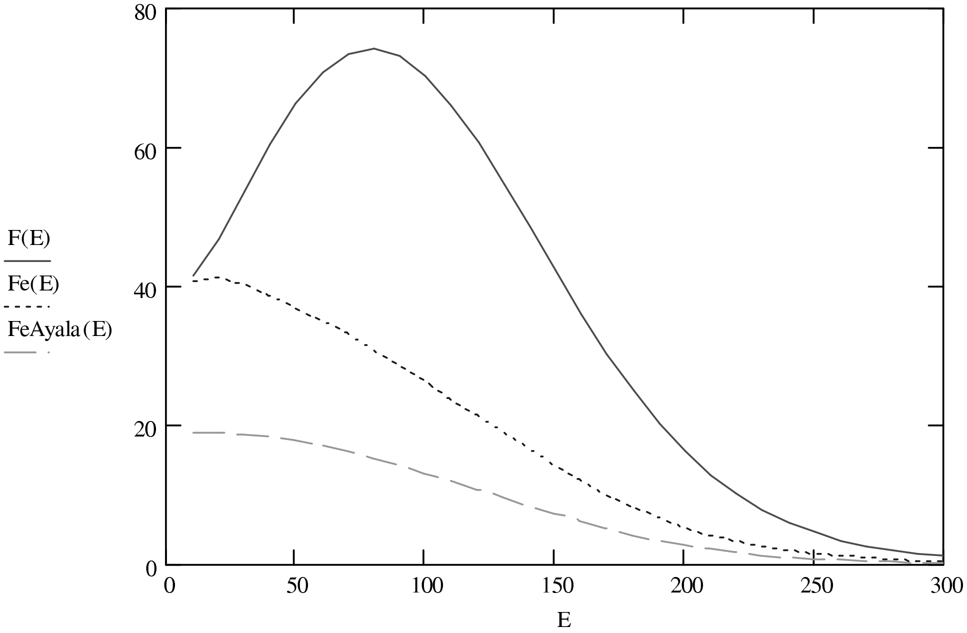

Figure 4: The function $F(E)$ defining the production rate of ν_R with the proton contribution (solid line) and without it (dotted line). The dashed line shows the result by A. Ayala et al. [3].

The right-handed neutrino energy spectrum, i.e. a number of right-handed neutrinos emitted per 1 sec per 1 MeV from the unit volume:

$$\Delta n = \frac{\mathrm{d}n_{\nu_R}}{\mathrm{d}E} \tag{12}$$

can be also evaluated numerically. In the Fig. 5 we show, taking for definitness $\mu_\nu = 10^{-12}\,\mu_{\mathrm{B}}$, the result of this calculation for two values of the plasma temperature.

Integrating the value Δn over all energies, one obtains the number of right-handed neutrinos emitted per 1 cm^3 per 1 sec. Dividing this to the initial left-handed neutrino number density n_{ν_L} , one can estimate the averaged time of the left-handed neutrino washing away, i.e. of the total conversion of left-handed neutrinos to right-handed neutrinos. For the temperature range $T = 30 - 60$ MeV, and for the electron chemical potential $\mu_e \sim 300$ MeV, we obtain

$$\tau \simeq \left(\frac{10^{-12}\,\mu_{\mathrm{B}}}{\mu_\nu}\right)^2 (0.14 - 0.36)\ \mathrm{sec}\,. \tag{13}$$

In order not to spoil the Kelvin—Helmholtz stage of the protoneutron star cooling ($\sim$ 10 sec), this averaged time of the neutrino spin-flip should exceed a few seconds. Taking the conservative limit $\tau > 1$ sec, we obtain the bound on the neutrino magnetic moment:

$$\mu_\nu < (0.4 - 0.6)\ \times 10^{-12}\,\mu_{\mathrm{B}}\,. \tag{14}$$

By this means, we improve the best astrophysical upper bound on the neutrino magnetic moment by A. Ayala et al. [2]. by the factor of 3 to 7.

7 Conclusions

- We have investigated in detail the neutrino chirality-flip process under the conditions of the supernova core. The plasma polarization effects caused both by electrons and protons were taken into account in the photon propagator. The rate $\Gamma(E)$ of creation of the right-handed neutrino with the fixed energy E, the energy spectrum, and the luminosity have been calculated.

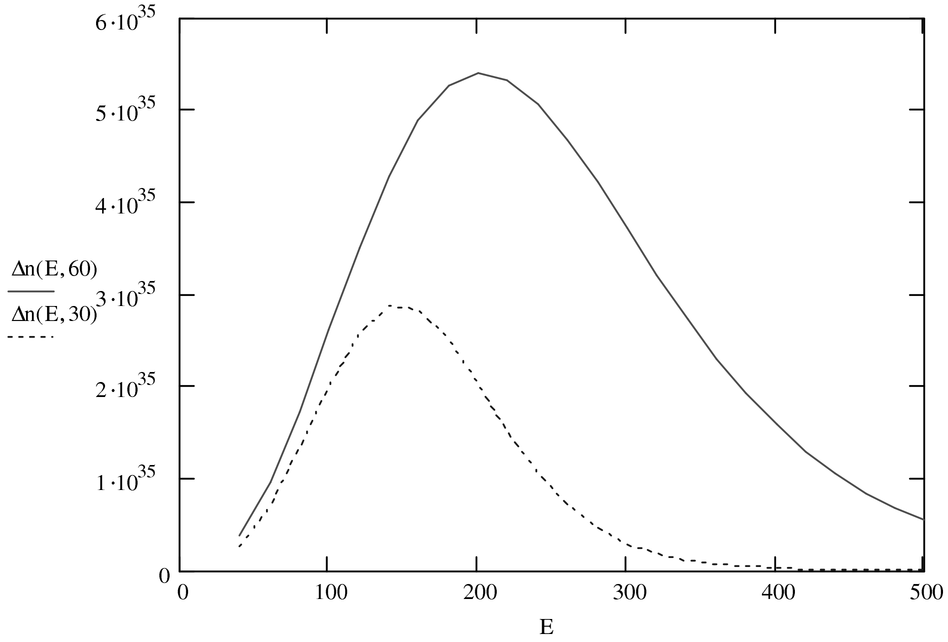

Figure 5: The number of right-handed neutrinos (for $\mu_\nu = 10^{-12}\,\mu_{\rm B}$) emitted per 1 cm^3 per 1 sec per 1 MeV of the energy spectrum for the plasma temperature T =60 MeV (solid line) and for T =30 MeV (dotted line).

- From the limit on the supernova core luminosity for ν_R emission, we have obtained the upper bound on the neutrino magnetic moment $\mu_\nu < (0.5 - 1.1) \times 10^{-12}\,\mu_{\rm B}$.
- From the limit on the averaged time of the neutrino spin-flip, we have obtained the upper bound $\mu_\nu < (0.4 - 0.6) \times 10^{-12}\,\mu_{\rm B}$.
- We have improved the best astrophysical upper bound on the neutrino magnetic moment by the factor of 3 to 7.

Acknowledgements

We express our deep gratitude to the organizers of the Seminar "Quarks-2006" for warm hospitality.

The work was supported in part by the Russian Foundation for Basic Research under the Grant No. 04-02-16253, and by the Council on Grants by the President of Russian Federation for the Support of Young Russian Scientists and Leading Scientific Schools of Russian Federation under the Grant No. NSh-6376.2006.2.

References

[1] R. Barbieri and R. N. Mohapatra, Phys. Rev. Lett. **61**, 27 (1988).

[2] A. Ayala, J. C. D'Olivo and M. Torres, Phys. Rev. D **59**, 111901 (1999).

[3] A. Ayala, J. C. D'Olivo and M. Torres, Nucl. Phys. B **564**, 204 (2000).

[4] E. Braaten, D. Segel, Phys. Rev. D **48**, 1478 (1993).

[5] P. Elmfors, K. Enqvist, G. Raffelt and G. Sigl, Nucl. Phys. B **503**, 3 (1997).

[6] W. Grimus and H. Neufeld, Phys. Lett. B **315**, 129 (1993).