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

N. Mikheev
Division of Theoretical Physics, Yaroslavl State University

14th International Seminar ***Quarks-2006*****, Repino, St. Petersburg**
May 24, 2006

In collaboration with A. Kuznetsov

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 fly away from the core leaving no energy to explain the observed luminosity of the supernova.

This process was investigated by many authors. R. Barbieri and R. N. Mohapatra (1988) 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 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, Barbieri and Mohapatra obtained the upper bound for the neutrino magnetic moment: $\mu_\nu < (0.2 - 0.8) \times 10^{-11}\, \mu_{\rm B}\,.$

Neutrino spin-flip in the supernova core

Later on, A. Ayala, J. C. D'Olivo and M. Torres (1999) used the formalism of the thermal field theory to take into account the influence of hot dense astrophysical plasma on the photon propagator. However, those authors considered only the contribution of plasma electrons, and neglected the proton fraction. The upper bound for the neutrino magnetic moment was improved by them in the factor of 2:

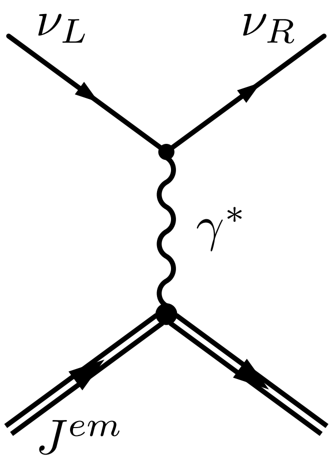
$$\mu_\nu < (0.1 - 0.4) \times 10^{-11} \, \mu_{\rm B} \, .$$

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.

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., shown in the diagram:



Here, 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, neutral atoms, etc.

Photon propagator

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:

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

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.

Integrating the amplitude squared 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.

Neutrino chirality-flip rate

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

$$\Gamma(E) = \frac{\mu_\nu^2}{16\,\pi^2\,E^2} \int\limits_0^\infty k^3\,\mathrm{d}k \int\limits_{-k}^{k} \mathrm{d}\omega\,\theta(2E+\omega-k)\,\frac{(2E+\omega)^2}{1-\mathrm{e}^{-\omega/T}}\,f_\nu(E+\omega)$$

$$\times \left[1-\left(\frac{\omega}{k}\right)^2\right]^2 \left[\rho_\ell(\omega,k) + \left(1-\frac{k^2}{(2E+\omega)^2}\right)\rho_t(\omega,k)\right].$$

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.

We note that our expression for $\Gamma(E)$ is larger by the factor of 2 than the corresponding formula in the paper by A. Ayala et al., and is in agreement with the rate by P. Elmfors et al. (1997).

Photon dispersion

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

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

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.

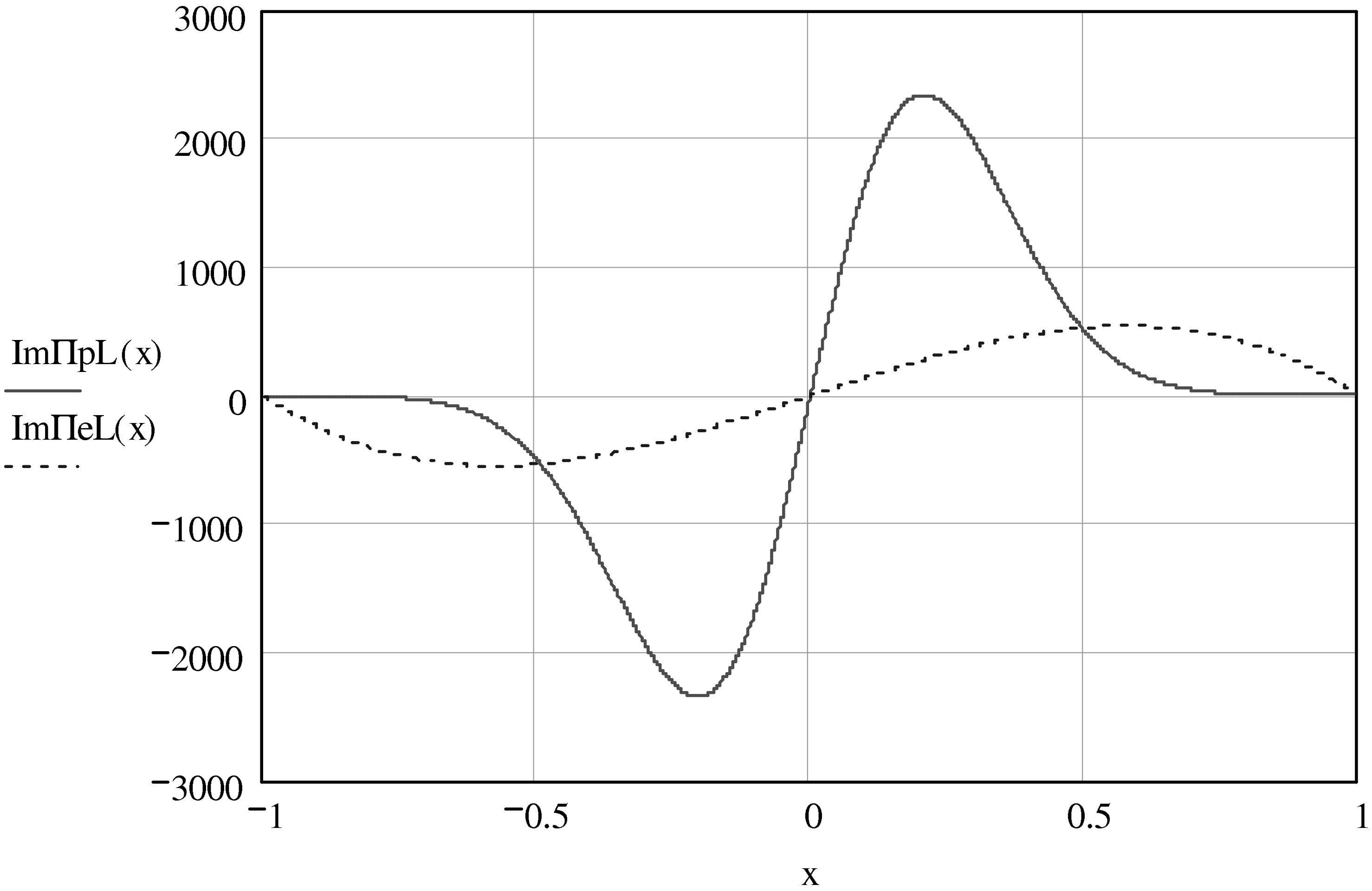
For the supernova conditions, the main contribution comes from the plasma electrons and protons:

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

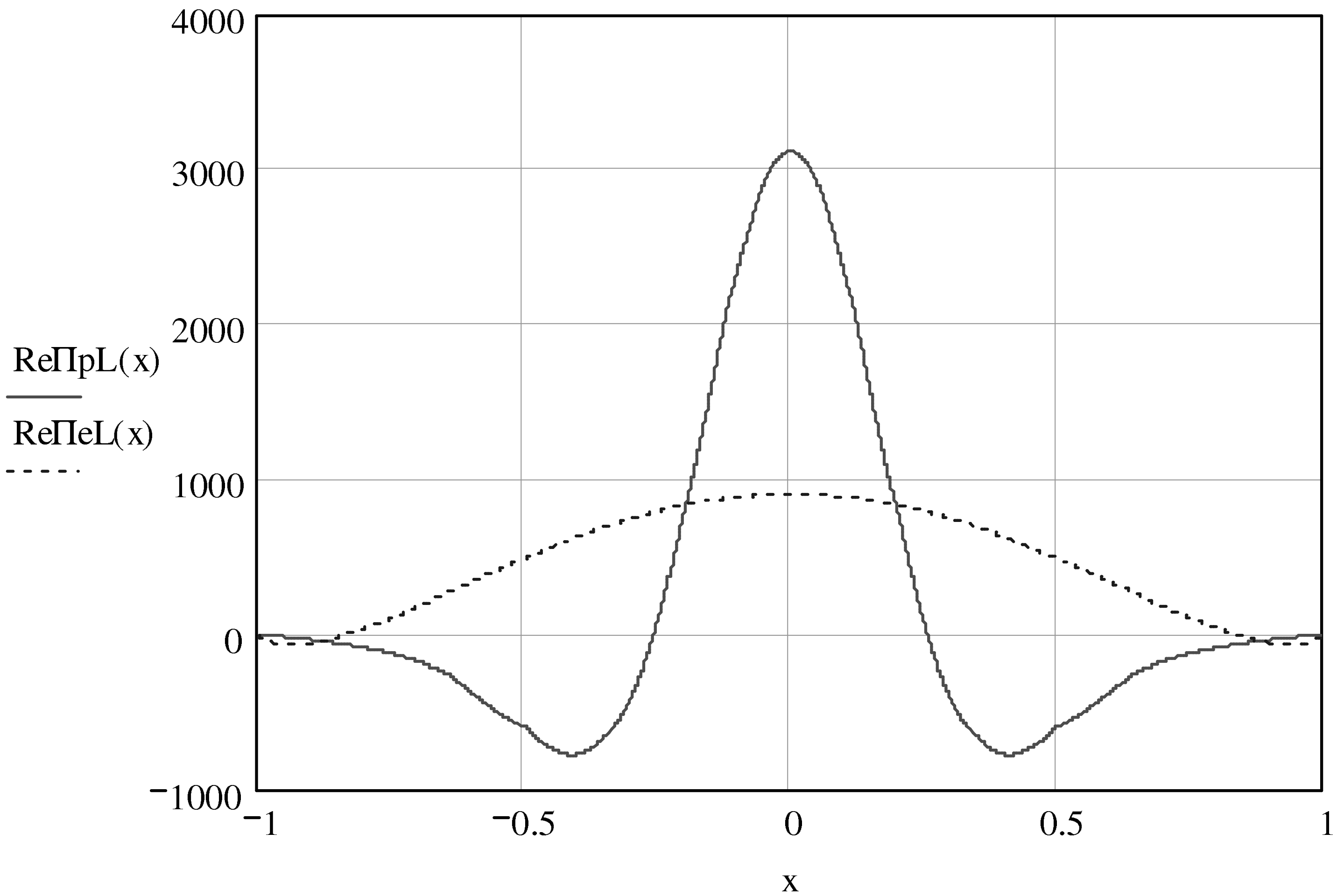
It is interesting to note that for the medium where $I_{\ell,\,t} \to 0$ and simultaneously the dispersion equation $q^2 - R_{\ell,\,t} = 0$ is fulfilled, the rate $\Gamma(E)$ describes the Cherenkov-like process with emission $(\omega > 0)$ and absorption $(\omega < 0)$ of the real plasmon (photon), investigated in part by W. Grimus and H. Neufeld (1993).

Proton and electron contributions into the imaginary part of Π_ℓ

In the next two plots we illustrate the importance of taking into account the proton contribution to Π_ℓ.



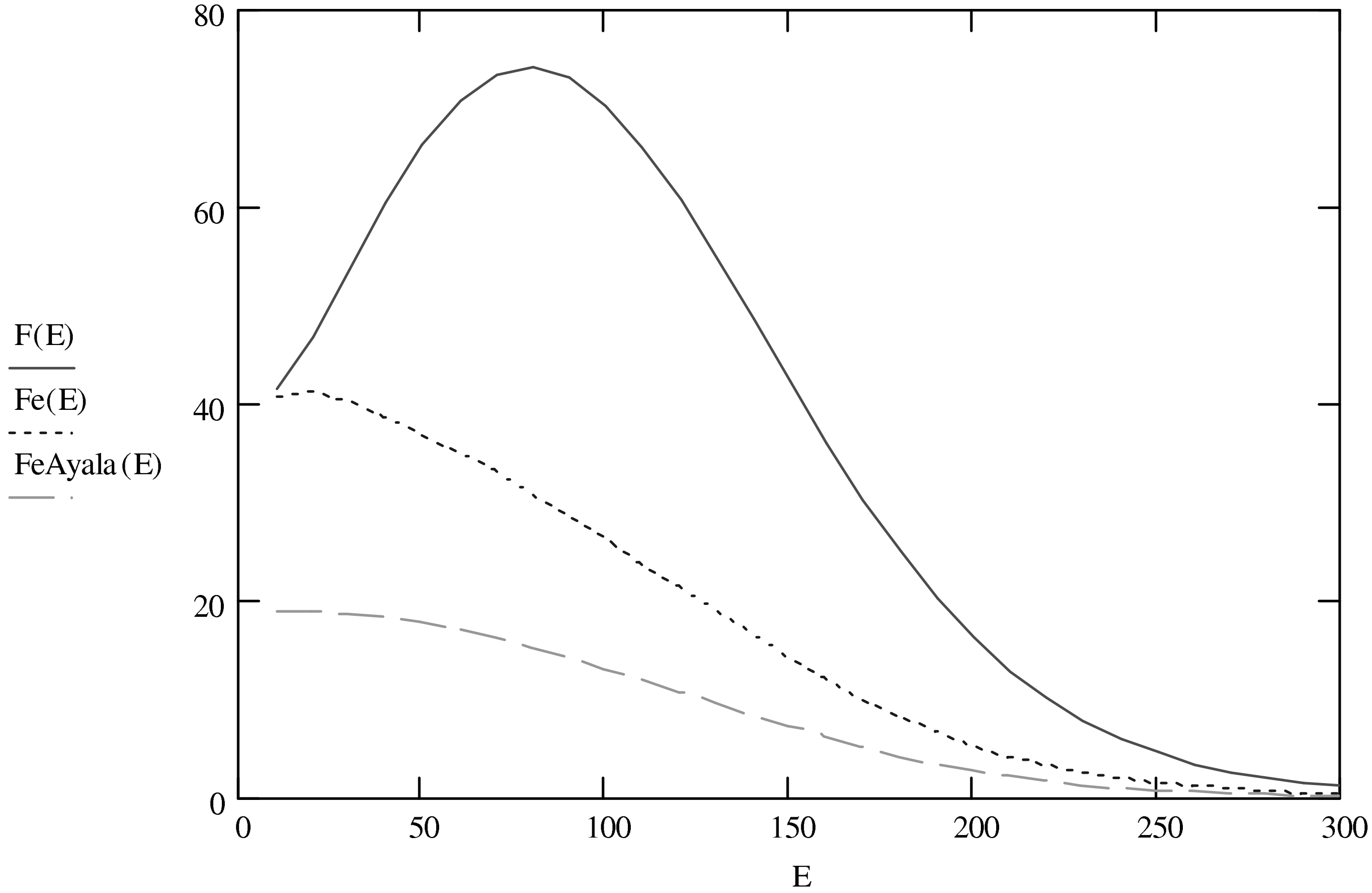
Proton and electron contributions into the real part of Π_ℓ



For the case of transversal plasmon, the proton contribution is not essential.

Neutrino chirality-flip rate

The production rate of ν_R with the proton contribution (solid line) and without it (dotted line). The proton contribution is seen to be essential.



The dashed line shows the result by A. Ayala et al.

Right-handed neutrino luminosity

The supernova core luminosity for ν_R emission can be computed as

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

where V is the plasma volume.

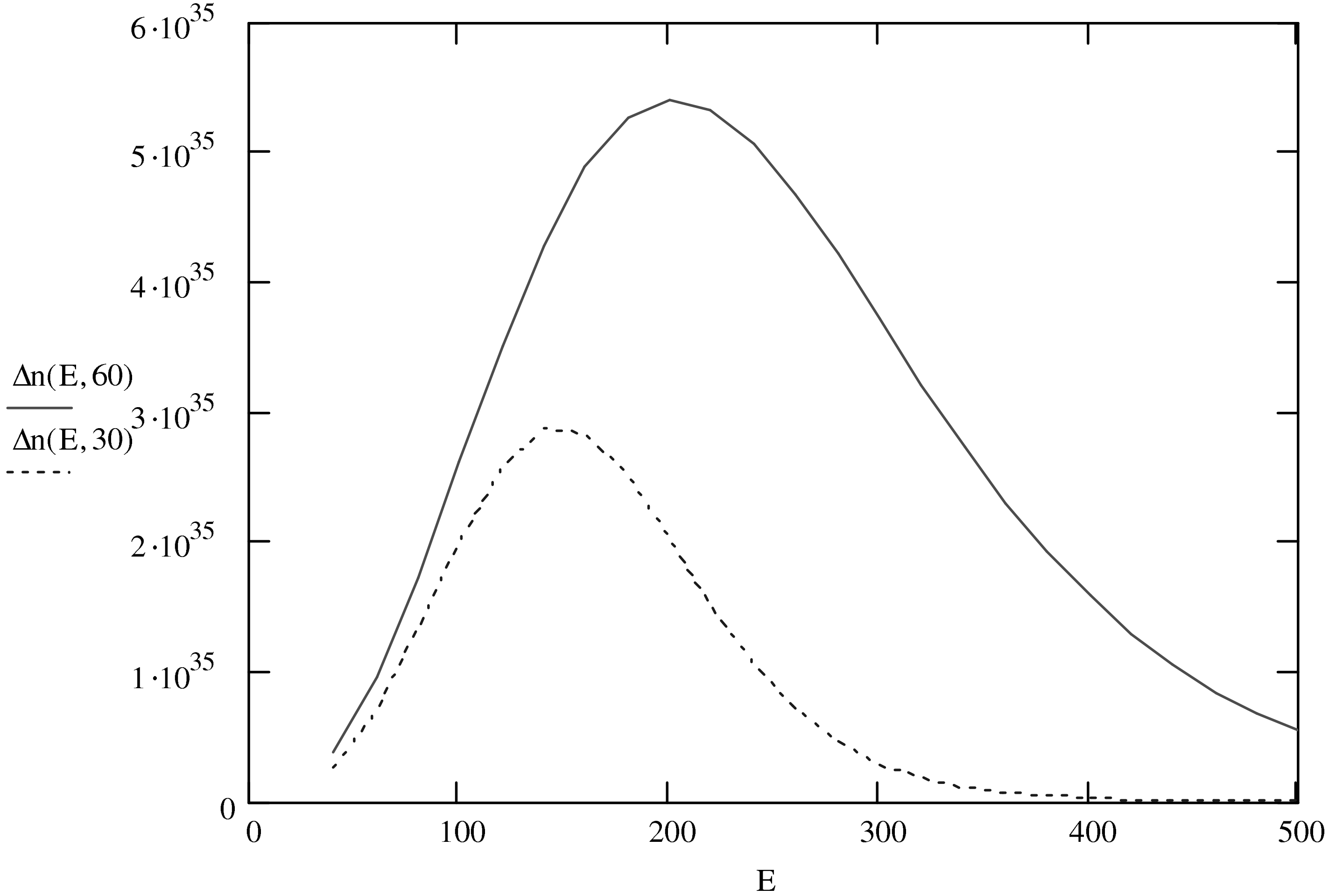
For the same supernova core conditions as in the paper by Ayala et al. (plasma volume $V \sim 8 \times 10^{18} \mathrm{cm}^3$, temperature range $T = 30 - 60$ MeV, electron chemical potential range $\mu_e = 280 - 307$ MeV), we obtain

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

Assuming that $Q_{\nu_R} < 10^{53}$ ergs/s, we obtain the upper limit on the neutrino magnetic moment $\mu_\nu < (0.5 - 1.1) \times 10^{-12} \, \mu_{\mathrm{B}}$.

Right-handed neutrino spectrum

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).



Left-handed neutrino washing out

An additional method can be used to put a bound on the neutrino magnetic moment. Integrating the above-plotted value 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, one can estimate the averaged time of the 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

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

In order not to spoil the Kelvin—Helmholtz stage of the protoneutron star cooling ($\sim$ 10 sec), this 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: $\mu_\nu < (0.4 - 0.6)\, \times 10^{-12}\, \mu_{\rm B}\,.$

By this means, we improve the best astrophysical upper bound on the neutrino magnetic moment by A. Ayala et al. (1999)

by the factor of 3 to 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.
- 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.