Neutrino magnetic moment and the supernova explosion

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Outline

1. Neutrino chirality-flip $\nu_L \longrightarrow \nu_R$ in the supernova core
2. Could sterile ν_R's stimulate the supernova explosion?

Neutrino chirality-flip $\nu_L \longrightarrow \nu_R$ in the supernova core

Nonvanishing neutrino magnetic moment leads to chirality-flipping processes

$$\nu_L \to \nu_R + \gamma^*, \quad \nu_L + \gamma^* \to \nu_R \, ,$$

where the left-handed Dirac neutrinos produced in the stellar interior become the right-handed ones, i.e. sterile with respect to the weak interaction, and this can be important e.g. for the stellar energy-loss.

How large value of the neutrino magnetic moment could be?

Neutrino chirality-flip $\nu_L \longrightarrow \nu_R$ in the supernova core

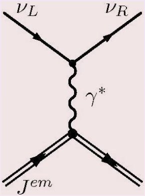
Several independent bounds were obtained.

- Solar neutrino physics:
  $\mu_\nu < 10^{-10}\,\mu_{\rm B}\,,$
  where $\mu_{\rm B} = e/2m_e$ is the Bohr magneton.
- Early Universe:
  $\mu_\nu < 6.2 \times 10^{-11}\,\mu_{\rm B}\,.$
- Neutrino energy-loss in low-mass red giants:
  $\mu_\nu < 3 \times 10^{-12}\,\mu_{\rm B}\,.$
- Supernova explosion SN1987A:
  $\mu_\nu < 1.5 \times 10^{-12}\,\mu_{\rm B}\,.$

Neutrino chirality-flip $\nu_L \to \nu_R$ in the supernova core

How many right-handed neutrinos can be produced in the supernova core?

It is necessary to calculate the rate of creation of the right-handed neutrino in the processes $\nu_L \to \nu_R + \gamma^*$, $\nu_L + \gamma^* \to \nu_R$.



Here, J^{em} is an electromagnetic current in the general sense, formed by different components of the medium.

The technics of calculations is rather standard. The only principal point is to use the photon propagator $G^{\alpha\beta}(q)$ with taking account of the plasma polarization effects.

The rate of the ν_R creation

The rate of creation of the right-handed neutrino $\nu_L(p) \to \nu_R(p') + \gamma^*(Q)$ was recalculated in our paper *(Journal of Cosmology and Astroparticle Physics, 2007)*, and the result was obtained:

$$\Gamma_{\nu_R}(E') = \frac{\mu_\nu^2}{16\,\pi^2\,E'^2} \int\limits_{-E'}^{\infty} \mathrm{d}q_0 \int\limits_{|q_0|}^{2E'+q_0} q^3\,\mathrm{d}q\, f_\nu(E'+q_0)\,(2E'+q_0)^2$$

$$\times \left(1 - \frac{q_0^2}{q^2}\right)^2 [1 + f_\gamma(q_0)] \left[\left(1 - \frac{q^2}{(2E'+q_0)^2}\right) \varrho_t - \varrho_\ell\right].$$

where $p = (E, \mathbf{p})$, $p' = (E', \mathbf{p}')$, $Q = (q_0, \mathbf{q})$.

The rate of the ν_R creation

The plasmon spectral densities:

$$\varrho_\lambda = \frac{-2\, I_\lambda}{(Q^2 - R_\lambda)^2 + I_\lambda^2}\,,$$

which are defined by the eigenvalues $\Pi_{t,\ell}$ of the photon polarization tensor:

$$\Pi_\lambda = R_\lambda + \mathrm{i}\, I_\lambda\,,$$

where R_λ and I_λ are the real and imaginary parts, containing the contributions of all components of the active medium.

The rate of the ν_R creation

The formula for the rate of the ν_R creation was analysed numerically.

The strong domination of the neutrino scattering on protons was found.

This effect was missed in previous investigations. A number of created right-handed neutrinos was underestimated essentially.

We have obtained a new upper bound on the neutrino magnetic moment from the SN1987A neutrino luminosity:

$$\mu_\nu < 1.5 \times 10^{-12} \, \mu_{\rm B} \, .$$

The rate of the ν_R creation with the energy E' at $T = 0$

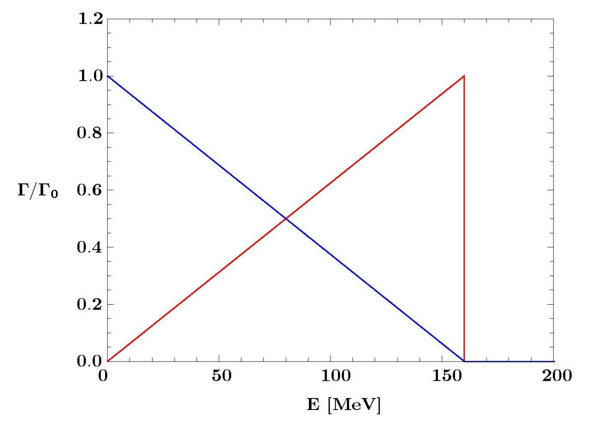
There exists a simple methodical way to illuminate the strong domination of the neutrino scattering on protons.
Taking the zero temperature limit, one can calculate the rate of the ν_R creation analitically.
The contributions of protons and electrons into the rate of the ν_R creation with the energy E' at $T = 0$:

$$\Gamma^{(p)}_{\nu_R}(E') = \frac{\mu_\nu^2\, m_\gamma^2}{2\,\pi}\, E'\; \theta\left(\tilde{\mu}_\nu - E'\right) \;,$$

$$\Gamma^{(e)}_{\nu_R}(E') = \frac{\mu_\nu^2\, m_\gamma^2}{2\,\pi}\, \left(\tilde{\mu}_\nu - E'\right)\; \theta\left(\tilde{\mu}_\nu - E'\right) \;,$$

m_γ is the transversal plasmon mass, $\tilde{\mu}_\nu$ is the neurino chemical potential (typically $\tilde{\mu}_\nu \simeq 160$ MeV).

The rate of the ν_R creation at $T = 0$



The contributions of protons (red line) and electrons (blue line).

$$\Gamma_0 = \mu_\nu^2 \, m_\gamma^2 \, \tilde{\mu}_\nu / (2\,\pi) \, .$$

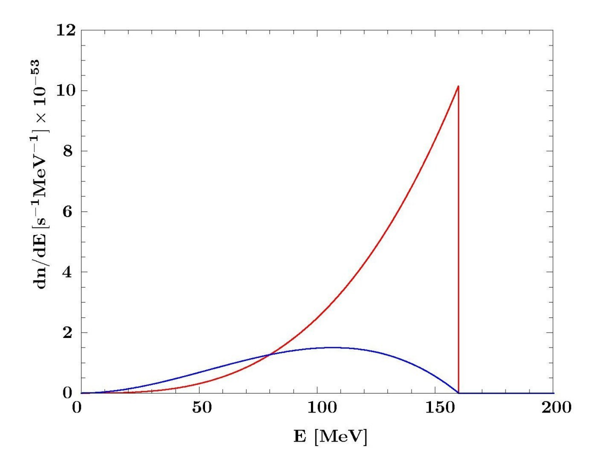
The energy spectrum of the ν_R flux

Given the rate $\Gamma_{\nu_R}(E')$, one can calculate the energy spectrum of the right-handed neutrino flux:

$$\frac{\mathrm{d}n_{\nu_R}}{\mathrm{d}E'} = V \, \frac{E'^2}{2\,\pi^2} \, \Gamma_{\nu_R}(E') \, .$$

Here, V is the volume of the supernova core.

The energy spectrum of the ν_R flux at $T = 0$



The contributions of protons (red line) and electrons (blue line).

The energy spectrum of the ν_R flux

The non-zero temperature leads to a washing out of the sharp peak in the proton contribution, and makes the energy distribution wider.

This gives an additional enhancing of the proton contribution.

Multiplying the energy spectrum of the right-handed neutrino flux by the energy, one obtains the energy spectrum of the ν_R luminosity.

The energy spectrum of the ν_R luminosity at $T = 30$ MeV

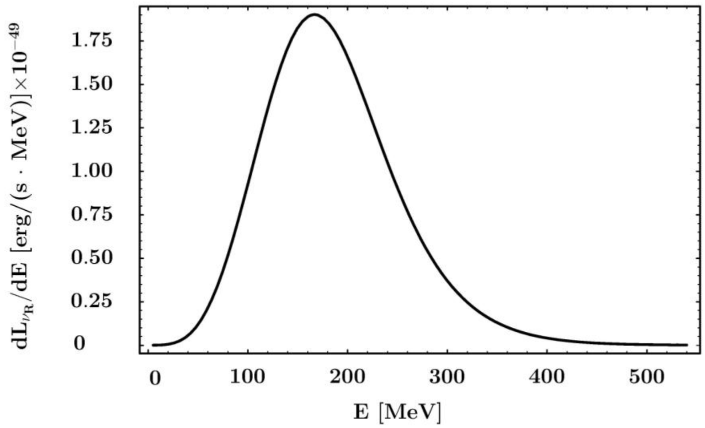


Fig. 1. The energy spectrum of the right-handed neutrino luminosity for the plasma temperature $T = 30$ MeV and for $\mu_\nu = 3 \times 10^{-13}\, \mu_B$.

Could sterile ν_R's stimulate the supernova explosion?

We will show that the obtained ν_R luminosity is large enough to influence essentially on the supernova explosion dynamics.

In a modelling of the supernova explosion, two main problems arise.

- The mechanism of the damped shock wave stimulation has not been developed completely yet.

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In a modelling of the supernova explosion, two main problems arise.

- The mechanism of the damped shock wave stimulation has not been developed completely yet.
- Even in the case of the "successful" theoretical supernova explosion, the energy release turns out to be essentialy less than the observed kinetic energy of the envelope $\sim 10^{51}$ erg (FOE problem).

Could sterile ν_R's stimulate the supernova explosion?

It is necessary for the self-consistent description of the explosion dynamics, that the neutrino flux, outgoing from the supernova core, could transfer by some mechanism the energy $\sim 10^{51}$ erg to the supernova envelope.

Could sterile ν_R's stimulate the supernova explosion?

The mechanism first proposed by *A. Dar, 1987*, with the neutrino magnetic moment being not too small.

A part of left-handed electron neutrinos ν_e produced in the collapsing supernova core could convert into right-handed neutrinos due to the interaction of the neutrino magnetic moment with plasma electrons and protons.

These ν_{eR}'s (sterile to the weak interaction), freely escape from the central part of the supernova, if the neutrino magnetic moment is not too large, $\mu_\nu < 10^{-11}\,\mu_{\rm B}$.

Could sterile ν_R's stimulate the supernova explosion?

In the supernova envelope, a part of these neutrinos can flip back to ν_{eL}'s due to the interaction of the neutrino magnetic moment with a magnetic field, which could achieve the critical value $B_e = m_e^2/e \simeq 4.41 \times 10^{13}$ G.

These ν_{eL}'s being absorbed in beta-processes, $\nu_e n \to e^- p$, can transfer an additional energy to the supernova envelope.

The equation of the neutrino helicity evolution

The equation of the helicity evolution of the neutrino with a magnetic moment in an external uniform magnetic field (Voloshin, Okun, 1986)

$$\mathrm{i}\,\frac{\partial}{\partial t}\begin{pmatrix}\nu_R\\ \nu_L\end{pmatrix} = \left[\hat{E}_0 + \begin{pmatrix}0 & \mu_\nu B_\perp\\ \mu_\nu B_\perp & C_L\end{pmatrix}\right]\begin{pmatrix}\nu_R\\ \nu_L\end{pmatrix},$$

μ_ν is the neutrino magnetic moment, $B_\perp$ is the transverse component of the magnetic field, C_L is the additional energy of ν_{eL} in medium:

$$C_L = \frac{3\,G_{\mathrm{F}}}{\sqrt{2}}\,\frac{\rho}{m_N}\left(Y_e + \frac{4}{3}\,Y_{\nu_e} - \frac{1}{3}\right).$$

$\rho/m_N = n_B$ is the nucleon density,
$Y_e = n_e/n_B = n_p/n_B$, $Y_{\nu_e} = n_{\nu_e}/n_B$,
n_{e,p,ν_e} are the densities of electrons, protons and neutrinos.

Could sterile ν_R's stimulate the supernova explosion?

The additional energy of left-handed neutrinos C_L deserves a special analysis

$$C_L = \frac{3\,G_{\mathrm{F}}}{\sqrt{2}}\,\frac{\rho}{m_N}\left(Y_e + \frac{4}{3}\,Y_{\nu_e} - \frac{1}{3}\right)\,.$$

The possibility exists for this value to be zero just in the region of the supernova envelope between the neutrinosphere and the shock-wave stagnation area, $R_\nu < R < R_s$. And this is the condition of the resonant transition $\nu_R \to \nu_L$.

The neutrino density Y_{ν_e} in the supernova envelope can be neglected, and the condition of the resonance takes the form $Y_e = 1/3$.

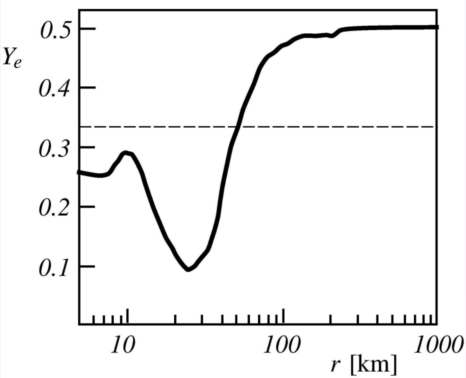
Could sterile ν_R's stimulate the supernova explosion?

The values Y_e in the supernova envelope, typical for the collapsing matter, are: $Y_e \sim 0.4$–0.5.

The shock wave causes the nuclei dissociation and makes the substance to be more transparent for neutrinos.
This leads to the so-called "short" neutrino outburst and consequently to the significiant matter deleptonization in this region.

A typical gap arises in the radial distribution of the value Y_e, where Y_e may fall down to the value ~ 0.1, see e.g. *Bethe (1990); Buras et al. (2005)*.

The dependence $Y_e(r)$



The dependence $Y_e(r)$ about 0.1 to 0.2 s after the shock formation, with the typical gap caused by the "short" neutrino outburst, see e.g. *Buras et al. (2005)*. The dashed line corresponds to the value $Y_e = 1/3$.

Could sterile ν_R's stimulate the supernova explosion?

A point necessarily exists where $Y_e = 1/3$. Only one such point appears, with $\mathrm{d}Y_e/\mathrm{d}r > 0$.

The condition $Y_e = 1/3$ is the necessary but not the sufficient one for the resonant conversion $\nu_R \to \nu_L$.

The adiabatic condition: the diagonal element C_L should not exceed the nondiagonal element $\mu_\nu B_\perp$, when the shift is made from the resonance point at the distance $\sim$ oscillations length.

This leads to the condition *(Voloshin, 1988)*:

$$\mu_\nu B_\perp \gtrsim \left(\frac{\mathrm{d}C_L}{\mathrm{d}r}\right)^{1/2} \simeq \left(\frac{3\,G_\mathrm{F}}{\sqrt{2}}\,\frac{\rho}{m_N}\,\frac{\mathrm{d}Y_e}{\mathrm{d}r}\right)^{1/2}.$$

Could sterile ν_R's stimulate the supernova explosion?

The magnetic field value, providing the realization of the resonance condition:

$$B_\perp \gtrsim 2.6 \times 10^{13}\text{G} \left(\frac{10^{-13}\mu_B}{\mu_\nu}\right) \left(\frac{\rho}{10^{10}\text{g}\cdot\text{cm}^{-3}}\right)^{1/2} \left(\frac{\mathrm{d}Y_e}{\mathrm{d}r} \times 10^8\,\text{cm}\right)^{1/2} .$$

where the typical values for ρ and $\mathrm{d}Y_e/\mathrm{d}r$ in the considered area are taken.

Thus, the Dar scenario of the two-step conversion of the neutrino helicity, $\nu_L \to \nu_R \to \nu_L$, can be realized, if the value of the neutrino magnetic moment is in the interval

$$10^{-13}\,\mu_B < \mu_\nu < 10^{-12}\,\mu_B\,,$$

and under the condition that the magnetic field of the scale 10^{13} G exists in the region $R_\nu < R < R_s$.

During the shock wave stagnation time $\Delta t \sim 0.2$–0.4 sec the additional energy can be injected into this region, of the order of

$$\Delta E \simeq L_{\nu_R}\,\Delta t \sim 10^{51}\,\text{erg}\,,$$

which is just enough for the problem solution.

Conclusions

- We have analysed quantitatively the two-step conversion of the neutrino helicity, $\nu_L \rightarrow \nu_R \rightarrow \nu_L$, under the supernova conditions. This process could provide an additional energy $\sim 10^{51}$ erg to be injected into the region between the neutrinosphere and the shock-wave stagnation area, $R_\nu < R < R_s$, during the typical stagnation time of the order of some tenths of a second. This energy could be sufficient for stumulation of the damped shock wave.

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- The conditions for the realization of this scenario appear to be not very rigid. The Dirac neutrino magnetic moment should belong to the interval $10^{-13}\,\mu_{\rm B} < \mu_\nu < 10^{-12}\,\mu_{\rm B}$, and the magnetic field $\sim 10^{13}$ G should exist in the region $R_\nu < R < R_s$.