Dirac neutrino magnetic moment and the dynamics of a supernova explosion

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   - The resonant transition $\nu_R \to \nu_L$

Neutrino magnetic moment

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 convert into **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 the neutrino magnetic moment could be?

Neutrino magnetic moment

In the standard model with the neutrino mass m_ν, the neutrino magnetic moment is unobservably small *(Lee, Shrock, 1977; Fujikawa, Shrock, 1980)*:

$$\mu_\nu^{(SM)} = \frac{3e\, G_{\mathrm{F}}\, m_\nu}{8\pi^2\sqrt{2}} = 3.20 \times 10^{-19} \left(\frac{m_\nu}{1\,\mathbf{eV}}\right) \mu_{\mathrm{B}}\,,$$

where $\mu_{\mathrm{B}} = e/2m_e$ is the Bohr magneton.

Nontrivial extensions of the standard model such as left-right symmetry can lead to more significant values for the neutrino magnetic moment.

Neutrino magnetic moment

Several independent bounds were obtained

- Reactor experiment *(Wong e.a., TEXONO Collab., 2007)*:
  $\mu_\nu < 0.74 \times 10^{-10}\, \mu_{\rm B}$,
- Solar neutrino physics *(Cisneros, 1971; Voloshin, Vysotsky, Okun, 1986, etc.)*:
  $\mu_\nu < 10^{-10}\, \mu_{\rm B}$,
- Early Universe *(Fukugita, Yazaki, 1987)*:
  $\mu_\nu < 6.2 \times 10^{-11}\, \mu_{\rm B}$.
- Neutrino energy-loss in low-mass red giants *(Raffelt, 1990)*:
  $\mu_\nu < 3 \times 10^{-12}\, \mu_{\rm B}$.

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

Neutrino magnetic moment $\Rightarrow$ spin-flipping processes in the supernova core: $\nu_L \longrightarrow \nu_R$

ν_R's being sterile fly away from the core $\Rightarrow$ *leaving no enough energy to explain the observed luminosity of the supernova* $\Rightarrow$ upper bound on the neutrino magnetic moment.

SN1987A, R. Barbieri and R. N. Mohapatra (1988): the neutrino spin-flip via both $\nu_L e^- \longrightarrow \nu_R e^-$ and $\nu_L p \longrightarrow \nu_R p$ processes.

From the ν_R luminosity upper limit $Q_{\nu_R} < 10^{53}$ **erg/s**, the upper bound on the neutrino magnetic moment was established :

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

However, the essential plasma polarization effects in the photon propagator were not considered comprehensively. An **ad hoc** *photon thermal mass was inserted instead.*

Neutrino chirality-flip $\nu_L \longrightarrow \nu_R$ 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.

The upper bound for the neutrino magnetic moment was improved by them in the factor of 2: $\mu_\nu < (0.1 - 0.4) \times 10^{-11}\, \mu_{\rm B}$.

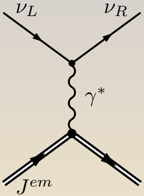
However, looking at the intermediate analytical results by the authors, we conclude that only the contribution of plasma **electrons** *was taken into account there, while the* **proton** *fraction was omitted. Moreover, they took an unrealistic value for the volume* $V \simeq 8 \times 10^{18}\,\mathrm{cm}^3$.

Thus, the reason existed to reconsider the neutrino spin-flip processes in the supernova core more attentively.

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 $\Gamma_{\nu_R}(E)$ of the right-handed neutrino $\nu_L \to \nu_R \pm \gamma^*$ was recalculated in our paper *(JCAP, 2007).*

The function $\Gamma_{\nu_R}(E)$ determines the spectrum of the right-handed neutrino energies, i.e. the number of ν_R's emitted per 1 MeV of the neutrino energy spectrum, per unit time, from the unit volume of the supernova core:

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

The rate of the ν_R creation

The function $\Gamma_{\nu_R}(E)$ also determines the spectral density of the right-handed neutrino luminosity (i.e. the right-handed neutrino emissivity) of the supernova core:

$$\frac{\mathrm{d}L_{\nu_R}}{\mathrm{d}E} = V\,\frac{\mathrm{d}n_{\nu_R}}{\mathrm{d}E}\,E = V\,\frac{E^3}{2\,\pi^2}\,\Gamma_{\nu_R}(E)\,,$$

where V is the volume of the area emitting neutrinos.

The rate of the ν_R creation

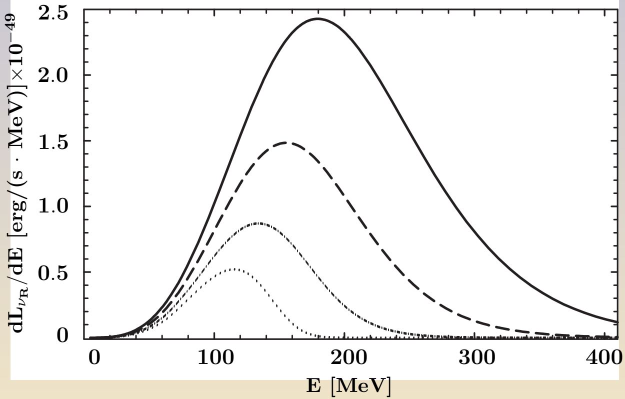
The **strong domination** of the neutrino scattering on **protons** was found.

This effect was missed in previous investigations, where **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:

$$\mu_\nu < (0.7 - 1.5) \times 10^{-12}\,\mu_{\rm B}\,.$$

The energy spectrum of the ν_R luminosity



The energy spectra of the right-handed neutrino luminosity for the plasma temperatures $T = 35$ MeV (bold), 25 MeV (dashed), 15 MeV (dash-dotted), 5 MeV (dotted), and for $\mu_\nu = 3 \times 10^{-13}\,\mu_{\rm B}$.

Bounds On The Neutrino Magnetic Moment From The SN Neutrino Luminosity

Uniform ball model for th SN core:
$\mu_\nu < (0.7 - 1.5) \times 10^{-12} \mu_B$.

The recent model of the O-Ne-Mg core collapse SN:
$\bar{\mu}_\nu < 2.4 \times 10^{-12} \mu_B$ *(H.-Th. Janka with collaborators, 2009)*.

Earlier models of the SN explosion:
$\bar{\mu}_\nu < 2.7 \times 10^{-12} \mu_B$ *(R. Buras et al., 2006)*;
$\bar{\mu}_\nu < 1.2 \times 10^{-12} \mu_B$ *(J. A. Pons et al., 1999)*;
$\bar{\mu}_\nu < 1.1 \times 10^{-12} \mu_B$ *(W. Keil and H.-Th. Janka, 1995)*.

(See poster: *A. Kuznetsov, N. Mikheev, A. Okrugin.*

Reexamination Of A Bound On The Dirac Neutrino Magnetic Moment From The Supernova Neutrino Luminosity.)

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.

In fact, the known mechanisms do not fill the deficit $\sim (\text{several}) \times 10^{50}$ erg.

Two-step conversion of the neutrino helicity $\nu_L \longrightarrow \nu_R \longrightarrow \nu_L$

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, $\mu_\nu < 10^{-11}\,\mu_B$.

Two-step conversion of the neutrino helicity $\nu_L \to \nu_R \to \nu_L$

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.

The resonant transition $\nu_R \to \nu_L$

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

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

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 $Y_e = 1/3$.

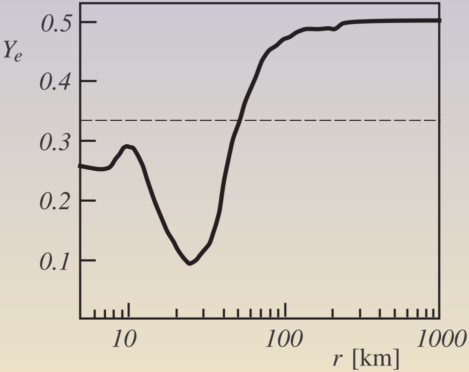
The resonant transition $\nu_R \to \nu_L$

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 dip** 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 dip** caused by the "short" neutrino outburst, see e.g. *Buras et al. (2005)*. The dashed line corresponds to the value $Y_e = 1/3$.

The resonant transition $\nu_R \to \nu_L$

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)*:

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

The resonant transition $\nu_R \longrightarrow \nu_L$

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

$$B_\perp \gtrsim 2.6 \times 10^{12}\,\mathbf{G} \left(\frac{10^{-12}\mu_{\rm B}}{\mu_\nu}\right) \left(\frac{\rho}{10^{10}\mathbf{g{\cdot}cm}^{-3}}\right)^{1/2} \left(\frac{{\rm d}Y_e}{{\rm d}r} \times 10^8\,\mathbf{cm}\right)^{1/2} .$$

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

The resonant transition $\nu_R \to \nu_L$

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

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

and under the condition that the magnetic field of the scale $(10^{12} \div 10^{13})$ **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

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

which is just enough for the problem solution.

Conclusions

- We have analysed **quantitatively** the two-step conversion of the neutrino helicity, $\nu_L \to \nu_R \to \nu_L$, under the supernova conditions.

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