A Bound On The Dirac Neutrino Magnetic Moment From The Supernova Neutrino Luminosity

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Outline

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Neutrino magnetic moment

Nonvanishing **neutrino magnetic moment** leads to helicity-flipping processes

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

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)*:

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

where $\mu_{\rm B} = e/2m_e$ 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)*: $\mu_\nu < 0.74 \times 10^{-10}\, \mu_{\mathrm{B}}$,
- Solar neutrino physics *(Cisneros, 1971; Voloshin, Vysotsky, Okun, 1986, etc.)*: $\mu_\nu < 10^{-10}\, \mu_{\mathrm{B}}$,
- Early Universe *(Fukugita, Yazaki, 1987)*: $\mu_\nu < 6.2 \times 10^{-11}\, \mu_{\mathrm{B}}$.
- Neutrino energy-loss in low-mass red giants *(Raffelt, 1990)*: $\mu_\nu < 3 \times 10^{-12}\, \mu_{\mathrm{B}}$.

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

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

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

The essential plasma polarization effects in the photon propagator were not considered comprehensively.

A. Ayala, J. C. D'Olivo and M. Torres (1999): the formalism of the **Thermal Field Theory** was used to take into account the influence of the hot dense plasma on the photon propagator. The upper bound for the neutrino magnetic moment was improved by them in the factor of 2: $\mu_\nu < (0.1 - 0.4) \times 10^{-11}\, \mu_{\mathrm{B}}$.

The rate of the ν_R creation

The rate of creation $\Gamma_{\nu_R}(E)$ in the processes $\nu_L \to \nu_R \pm \gamma^*$ was recalculated in the paper *(JCAP, 2007 V. 11, P. 031).*

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

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

This effect was missed in previous investigations, where **a number of created right-handed neutrinos was underestimated essentially.**

Uniform ball model

The rate of creation $\Gamma_{\nu_R}(E)$ 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, m_γ is the mass of a transverse plasmon,

$$m_\gamma^2 = \frac{2\,\alpha}{\pi}\left(\eta_e{}^2 + \frac{\pi^2 T^2}{3}\right).$$

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

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

Magnetic moment matrix

We consider a general case of the magnetic moment matrix $\mu_{\nu_i \nu_j} \equiv \mu_{ij}$, where ν_i, ν_j are the neutrino mass eigenstates.

$$\nu_\ell = \sum_i U^*_{\ell i}\, \nu_i \,,$$

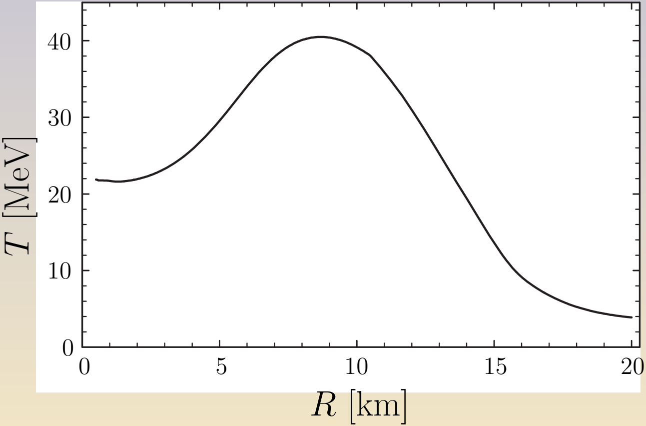
$U_{\ell i}$ is the unitary leptonic mixing matrix by Pontecorvo–Maki–Nakagawa–Sakata.

The value of the magnetic moment squared should be considered as an effective value.
For the processes with the initial electron neutrino:

$$\mu_\nu^2 \to \mu_{\nu_e}^2 \equiv \sum_i \left| \sum_j \mu_{ij} U_{ej} \right|^2$$

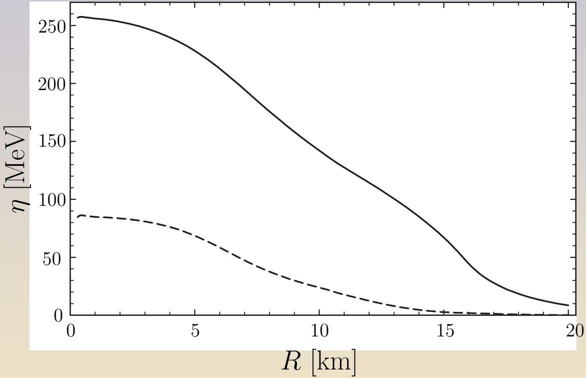
and similarly for the muon and tau initial neutrinos.

The recent model of the O-Ne-Mg core collapse SN



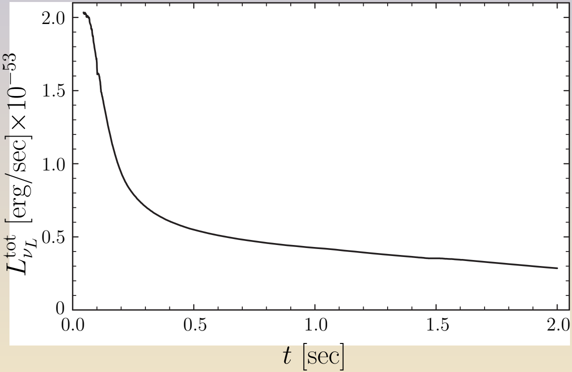
The radial distribution for the temperature within the SN core at the moment $t = 1.0$ sec after the bounce.

The recent model of the O-Ne-Mg core collapse SN



The radial distributions for the chemical potentials of electrons (solid line) and electron neutrinos (dashed line) within the SN core at the moment $t = 1.0$ sec after the bounce.

The recent model of the O-Ne-Mg core collapse SN



The time evolution of the total luminosity of all active neutrino species.

The recent model of the O-Ne-Mg core collapse SN

Instead of multiplying by the volume of the neutrino-emitting region V, we integrate over this volume to obtain the spectral density of the energy luminosity of a supernova core via right-handed neutrinos:

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

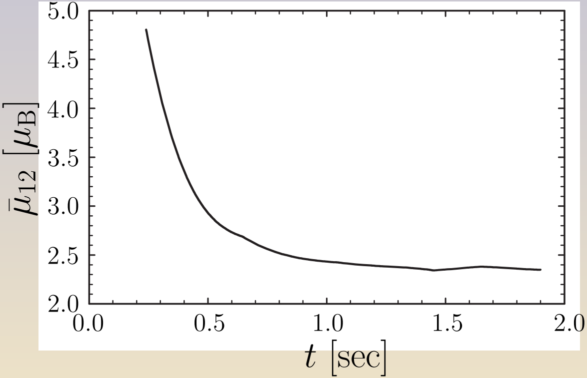
Integrating over the neutrino energy, one obtains the time evolution of the right-handed neutrino luminosity:

$$L_{\nu_R}(t) = \frac{2}{\pi} \int \mathrm{d}r \, r^2 \int\limits_0^\infty \mathrm{d}E \, E^3 \, \Gamma_{\nu_R}(E,t)\,.$$

The observed $SN1987A$ signal duration indicates that a novel energy-loss via right-handed neutrinos is bounded by

$$L_{\nu_R} < L_{\nu_L}\,.$$

The recent model of the O-Ne-Mg core collapse SN



The time evolution of the upper bound on the neutrino magnetic moment within the time interval until 2 sec after the bounce (in assumption that the effective magnetic moments of electron, muon and tau neutrinos are equal); $\bar{\mu}_{12} = \bar{\mu}_\nu / (10^{-12}\, \mu_{\rm B})$.

The recent model of the O-Ne-Mg core collapse SN

The averaged upper bound tends to some value, providing the limit

$$\bar{\mu}_\nu < 2.4 \times 10^{-12} \, \mu_\mathrm{B} \, .$$

In a general case the combined limit on the effective magnetic moments of the electron, muon and tau neutrinos is

$$\left[\mu^2_{\nu_e} + 0.71 \left(\mu^2_{\nu_\mu} + \mu^2_{\nu_\tau}\right)\right]^{1/2} < 3.7 \times 10^{-12} \, \mu_\mathrm{B} \, .$$

Bounds On The Neutrino Magnetic Moment From The SN Neutrino Luminosity

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

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

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

Conclusions

- We have analysed **quantitatively** the conversion of the neutrino helicity, $\nu_L \to \nu_R$, under real supernova conditions.
- We make the estimation of the Dirac neutrino magnetic moment from the limit on the supernova core luminosity for ν_R emission by a more consistent way, taking some radial distributions and time evolution of physical parameters from some realistic models of the supernova core.
- The upper bounds on the flavor- and time-averaged magnetic moment of the Dirac type neutrino are obtained in those models, from the condition of not-affecting the total cooling time scale significantly:

  $$\bar{\mu}_\nu < (1.1 - 2.7) \times 10^{-12}\, \mu_{\rm B}\,,$$

  depending on the explosion model.