Dirac neutrino magnetic moment and a possible time evolution of the neutrino signal from a supernova

Nickolay Mikheev

Yaroslavl State (P.G. Demidov) University, Division of Theoretical Physics

June 11, 2010

16th International Seminar "Quarks-2010", Kolomna, Moscow Region

In collaboration with R. Anikin and A. Kuznetsov

Based on the paper to appear in Astronomy Letters

Outline

1. Neutrino magnetic moment: astrophysical manifestations
2. Neutrino spin rotation in a magnetic field
3. Possible time evolution of the SN neutrino signal

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)*:

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

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: bounds

Several independent bounds were obtained

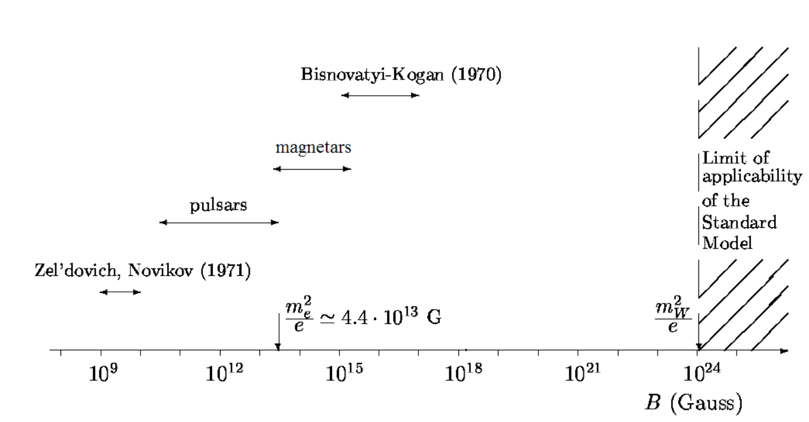
- Solar neutrino physics *(Cisneros, 1971; Voloshin, Vysotsky, Okun, 1986, etc.)*:
  $\mu_\nu < 10^{-10}\, \mu_{\rm B}$,
- Early Universe *(Fukugita, Yazaki, 1987; Elmfors e.a., 1997)*:
  $\mu_\nu < 6.2 \times 10^{-11}\, \mu_{\rm B}$.
- Neutrino energy-loss in low-mass red giants *(Raffelt, 1990)*:
  $\mu_\nu < 3 \times 10^{-12}\, \mu_{\rm B}$.
- Neutrino cooling of hot white dwarfs *(Blinnikov, Dunina-Barkovskaya, 1994)*:
  $\mu_\nu < 10^{-11}\, \mu_{\rm B}$.
- Reactor experiment *(Beda e.a., GEMMA Collab., 2009)*:
  $\mu_\nu < 3.2 \times 10^{-11}\, \mu_{\rm B}$,

Neutrino magnetic moment: bounds from SN1987A

A considerable interest to the neutrino magnetic moment arised after the great event of the $SN1987A$. **Several bounds were obtained:**

- *Barbieri, Mohapatra, 1988*:
  $\mu_\nu < (2 - 8) \times 10^{-12}\, \mu_{\rm B}\,,$
- *Ayala e.a., 1999*:
  $\mu_\nu < (1 - 4) \times 10^{-12}\, \mu_{\rm B}\,,$
- An analysis based on realistic models for radial distributions and time evolution of physical parameters in the SN core, *A. Kuznetsov, N. M., A. Okrugin, 2010*:
  $\mu_\nu < (1.1 - 2.7) \times 10^{-12}\, \mu_{\rm B}\,.$

Evolution of the notion “strong magnetic field” in astrophysics



The natural scale for the field strength: the critical value $B_e = m_e^2/e \simeq 4.41 \times 10^{13}\,\mathrm{G}$.

Neutrino spin rotation in a magnetic field

The equation of the helicity evolution of the neutrino with a magnetic moment in an external uniform magnetic field *(Fujikawa, Shrock, 1980; Voloshin, Vysotsky, Okun, 1986)*

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

μ_ν is the neutrino magnetic moment, $B_\perp$ is the transverse component of the magnetic field.
Voloshin, Vysotsky, Okun (1986) used this mechanism for explaining the Solar neutrino deficit via the transition $\nu_L \to \nu_R$.
Dar (1987, unpublished) considered a double neutrino spin-flip $\nu_L \to \nu_R \to \nu_L$ to solve the supernovae problem, where the 2nd flip was caused by the magnetic field of the SN envelope.

Neutrino spin rotation in magnetic field + medium

The equation of the neutrino helicity evolution in magnetic field and medium *(Voloshin, Okun, 1986)*

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

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 $\nu_L \to \nu_R$

The additional energy of left-handed neutrinos C_L:

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

The possibility exists that $C_L = 0$ in the supernova envelope. And this is the condition of the resonant transition $\nu_L \to \nu_R$.

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

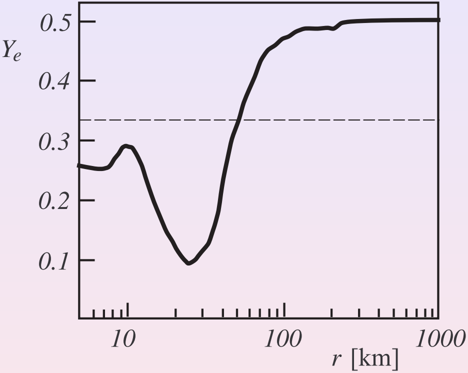
The resonant transition $\nu_L \longrightarrow \nu_R$

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, *Buras et al. (2005)*.

The dashed line: $Y_e = 1/3$.

The probability of the left-handed neutrino survival

A numerical analysis of the evolution equation gives a connection between the field strength and other parameters in the SN envelope with the probability of the left-handed neutrino survival W_{LL}. With the typical values, see e.g. *Bethe (1990); Buras et al. (2005)*

$$\frac{\mathrm{d}Y_e}{\mathrm{d}r} \sim 10^{-7}\,\mathrm{cm}^{-1}\,, \quad \rho \sim 10^{10}\,\mathrm{g}\cdot\mathrm{cm}^{-3}\,,$$

one obtains the approximation formula

$$\frac{B_\perp(t)}{B_e} = f(W_{LL}) \left(\frac{10^{-13}\mu_\mathrm{B}}{\mu_\nu}\right) \left(\frac{\rho(t)}{10^{10}\,\mathrm{g}\cdot\mathrm{cm}^{-3}}\right)^{1/2} \times$$

$$\times \left(\frac{\mathrm{d}Y_e}{\mathrm{d}r}(t) \times 10^{7}\,\mathrm{cm}\right)^{1/2}$$

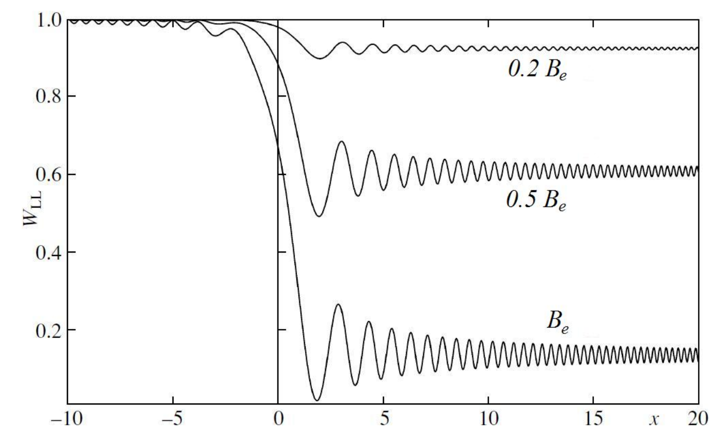
The probability of the left-handed neutrino survival

The function

$$f(W_{LL}) = 0.88\,\frac{(1 - W_{LL})^{0.62}}{(W_{LL})^{0.13}}$$

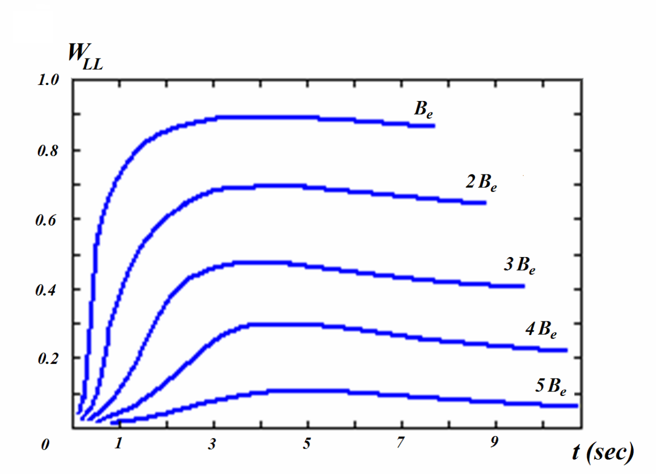
defines the adiabaticity of the conversion process. Real adiabaticity corresponds to the strong enequality $f \gg 1$, when $W_{LL} \ll 1$, and the total conversion of the left-handed neutrinos into the right-handed neutrinos is realised in this case, $W_{LR} = (1 - W_{LL}) \to 1$.

The probability of the left-handed neutrino survival



$$\mu_\nu = 10^{-13}\,\mu_{\rm B},\ \rho = 10^{10}\mathrm{g}\cdot\mathrm{cm}^{-3},\ \mathrm{d}Y_e/\mathrm{d}r \simeq 10^{-7}\mathrm{cm}^{-1}.$$

The probability of the left-handed neutrino survival



$\mu_\nu = 10^{-13}\,\mu_{\rm B}$, $B_e = m_e^2/e \simeq 4.41 \times 10^{13}\,{\rm G}$.

Detecting the time evolution of the SN neutrino flux is needed!

A combined action of a magnetic field and medium in the SN envelope on the outgoing neutrinos could cause the resonant transition $\nu_L \longrightarrow \nu_R$, and thus the neutrino signal could be modified. It could be observable.

A number of neutrino events in the Super-Kamiokande from a SN at the distance $\lesssim$ 10 kpc is estimated as $\sim 10^4$.

This allows to detect the time evolution of the SN neutrino signal.

The SN1987A neutrino signal

The statistics of the SN1987A neutrino events is rather poor.

Kamiokande-II Collab.: 11 events (+ 1 as a background)

IMB Collab.: 8 events

Baksan: 5 events (+ 1 as a background)

The signal detected by LSD Collab. at 4 h 43 min earlier than others, deserves a separate analysis.

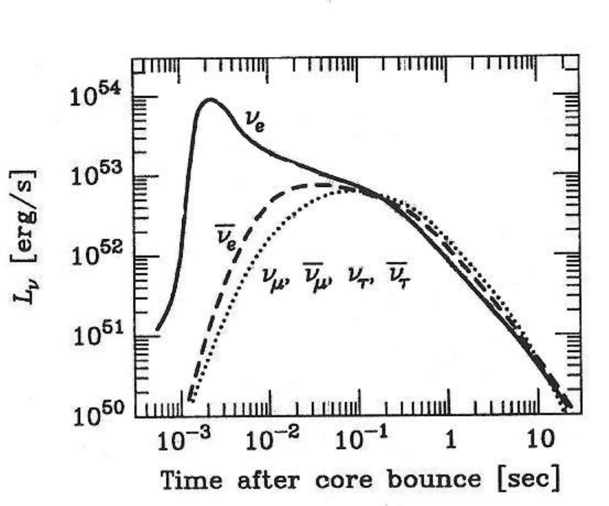
24 events as a total.

The SN1987A neutrino signal

How to synchronize? The synchronism accuracy was: $\pm$ 1 min at Kamiokande-II, $\pm$ 50 ms at IMB, and (+2,-54) s at Baksan.

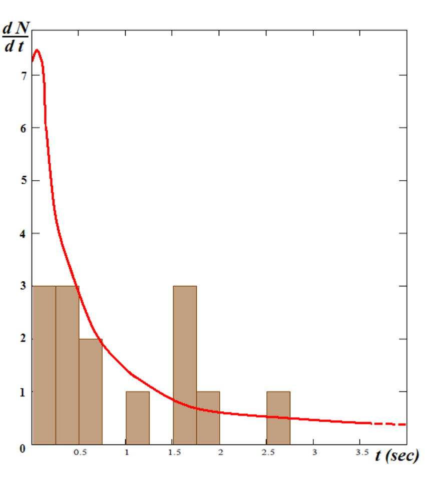
The easiest but not groundless way is *(Alexeyev e.a., 1988)*: to synchronize the first events of the detectors (within the accuracy interval) and to make the time shifts. The reason is in the predicted time evolution of the SN neutrino signal, with the high initial peak.

The time evolution of the SN neutrino luminosity



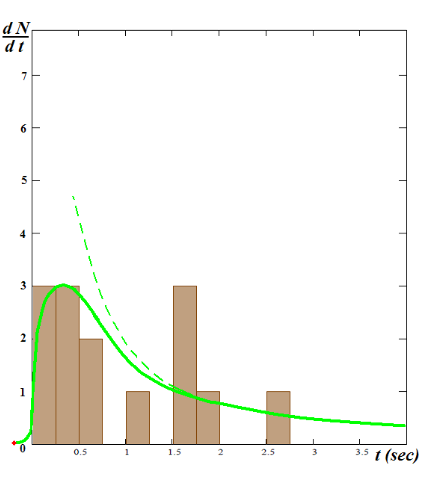
Janka, 1993.

The SN1987A neutrino signal



Histogram of the synchronized neutrino signal (14 of 24 events). The solid red line shows the estimated time evolution of the SN1987A neutrino signal *(Janka, 1993)*, normalized to the same number of events.

The SN1987A neutrino signal



The solid green line shows the estimated time evolution of the SN1987A neutrino signal with taking account of the signal screening due to the helicity oscillations, normalized to the same number of events. The dashed line shows the time evolution without the discussed effect.

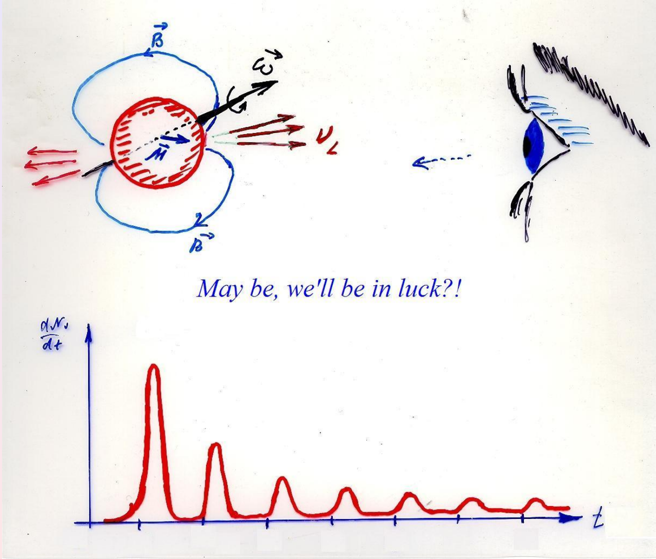
The neutrino pulsar

We believe that slowly rotating neutron stars with superstrong magnetic fields, magnetars, could be born in some supernova explosions.

We remind that the probability of the neutrino chirality survival/conversion depends on the transversal component $B_\perp$ of the magnetic field with respect to the neutrino momentum. This means that strong magnetic poloidal field of a new-born magnetar could collimate the neutrino outflow, forming neutrino beams from the magnetic poles.

If the magnetic pole axis does not coinside with the rotation axis, and if we are in luck with the orientation of the axes, we could watch a pulsating neutrino signal: a neutrino pulsar!

The neutrino pulsar



Conclusions

- A resonant transition $\nu_L \to \nu_R$ is possible in the magnetic field of a supernova envelope.

Conclusions

- A resonant transition $\nu_L \to \nu_R$ is possible in the magnetic field of a supernova envelope.
- A time evolution of the neutrino signal from a supernova at the distance $\lesssim$ 10 kpc is possible which can be detected by the Super-Kamiokande.

Conclusions

- A resonant transition $\nu_L \to \nu_R$ is possible in the magnetic field of a supernova envelope.
- A time evolution of the neutrino signal from a supernova at the distance $\lesssim$ 10 kpc is possible which can be detected by the Super-Kamiokande.
- If we are in luck with the orientation of the new-born pulsar rotation axis, we could watch a pulsating neutrino signal: a neutrino pulsar!

Thank you for your attention!

The neutrino pulsar