Recent studies (exp. & theor.) of flavour conversion of solar, atmospheric, reactor and accelerator neutrinos have conclusively established that neutrinos have non-zero mass! and they mix among themselves that provides the first evidence of new physics beyond the standard model
Neutrino mass $m_\nu \neq 0$!
Theory (Standard Model with $\nu_R$)

\[ \mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2}, \quad m_e \sim 3 \cdot 10^{-19} \mu_0 \left( \frac{m_{\nu_e}}{\text{GeV}} \right), \quad m_\nu = \frac{e}{2m_e} \]

Lee Shrock, 1977; Fujikawa Shrock, 1980

In the Standard Model: $m_\nu = 0$, there is no $\nu_R \Rightarrow$ $\nu$ magnetic moment $\mu_\nu = 0$.

Thus, $\mu_\nu \neq 0 \leftarrow$ beyond the SM.
0. Introduction

1. magnetic moment in experiments

2. New experimental result on $\mu$

3. electromagnetic properties - theory
   3.1 vertex function
   3.2 $\mu$ (arbitrary masses)
   3.3 relationship between $m$ and $\mu$
   3.4 vertex function in case of flavour mixing
   3.5 dipole moments in case of mixing
   3.6 $\mu$ in left-right symmetry models
   3.7 radiative decay
   3.8 radiative $2\times \pi$- decay
   3.9 astrophysical bounds on $\mu$
   3.10 millicharge (Red Gaints cooling etc)
   3.11 charge radius and anapole moment
   3.12 electromagnetic properties in matter and e.m.f.

4. spin-flavour oscillations

5. Direct-Indirect influence of e.m.f. on

6. Conclusion
Electromagnetic properties of
gauge invariance and anomaly-free constraints of the model

\[ Q_\nu = 0 \Rightarrow \text{interaction with } \gamma \]

entirely from loop effects through weak interactions with charged particles:

\[ e^- e^- \gamma \]

\[ W^+ W^+ \gamma \]
Effective Lagrangian for the spin component of $\nu$ vertex

$$L = \frac{1}{2} \bar{\nu}_j \sigma_{\eta \xi} (\beta_{ij} + \varepsilon_{ij} \gamma_5) \nu_i F^{\eta \xi} + \text{h.c.},$$

**magnetic** and **electric** moments

which couple together mass eigenstates $(\nu_i)_L$ and $(\nu_j)_R$

- $\nu_i = \nu_j$  \quad \text{diagonal moments}
- $\nu_i \neq \nu_j$  \quad \text{transitional moments}

- $\varepsilon_{ii} = \beta_{ii} = 0$  \quad \text{for Majorana}

E.M. properties

\quad a way to distinguish Dirac and Majorana
magnetic moment in experiments

Samuel Ting
(wrote on the wall at Department of Theoretical Physics of Moscow University):

“Physics is an experimental science”
Studies of $\nu$-$e$ scattering - most sensitive method of experimental investigation of $\mu$-$\nu$.

Cross-section:  

\[
\frac{d\sigma}{dT}(\nu + e \rightarrow \nu + e) = \left( \frac{d\sigma}{dT} \right)_{SM} + \left( \frac{d\sigma}{dT} \right)_{\mu\nu},
\]

where the Standard Model contribution

\[
\left( \frac{d\sigma}{dT} \right)_{SM} = \frac{G_F^2 m_e}{2\pi} \left[ (g_V + g_A)^2 + (g_V - g_A)^2 \left( 1 - \frac{T}{E_\nu} \right)^2 + (g_A^2 - g_V^2) \frac{m_e T}{E_\nu^2} \right],
\]

$T$ is the electron recoil energy and

\[
g_V = \begin{cases} 
2 \sin^2 \theta_W + \frac{1}{2} & \text{for } \nu_e, \\
2 \sin^2 \theta_W - \frac{1}{2} & \text{for } \nu_\mu, \nu_\tau,
\end{cases} \quad g_A = \begin{cases} 
\frac{1}{2} & \text{for } \nu_e, \\
-\frac{1}{2} & \text{for } \nu_\mu, \nu_\tau 
\end{cases},
\]

g_A \rightarrow -g_A

for anti-neutrinos

to incorporate charge radius: 

\[
g_V \rightarrow g_V + \frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2 \theta_W.
\]
magnetic moment in experiments
(for neutrino produced as $\nu_l$ with energy $E_\nu$
and after traveling a distance $L$)

$$\mu^2_{\nu}(\nu_l, L, E_\nu) = \sum_j \left| \sum_i U_{li} e^{-i E_i L} \mu_{ji} \right|^2$$

where

neutrino mixing matrix $\mu_{ij} \equiv |\beta_{ij} - \epsilon_{ij}|$

Observable $\mu$ is an effective parameter that depends on neutrino
flavour composition at the detector.

Implications of $\mu$ limits from different experiments
(reactor, solar $^8B$ and $^7Be$) are different.
MUNU experiment at Bugey reactor (2005)

\[ \mu_\nu \leq 9 \times 10^{-11} \mu_B \]

TEXONO collaboration at Kuo-Sheng power plant (2006)

\[ \mu_\nu \leq 7 \times 10^{-11} \mu_B \]

GEMMA (2007)

\[ \mu_\nu \leq 5.8 \times 10^{-11} \mu_B \]

GEMMA I 2005 - 2007

BOREXINO (2008)

\[ \mu_\nu \leq 5.4 \times 10^{-11} \mu_B \]

reported at Neutrino’08 Conference (New Zealand),
see also talk of Livia Ludhova

\[ \mu_\nu \leq 8.5 \times 10^{-11} \mu_B \ (\nu_\tau, \nu_\mu) \]

Montanino, Picariello, Pulido, PRD 2008


“The New Result of the Neutrino magnetic Moment measurement in the GEMMA Experiment”


GEMMA I (2008)

Status:
“on” (operation of reactor) 9426 hours
“off” (reactor shutdown) 2965 hours

\[ \mu_\nu \leq 3.1 \times 10^{-11} \mu_B \]

and

\[ \mu_\nu \leq 4.9 \times 10^{-11} \mu_B \]

...obtained with more conservative data analysis method
Astrophysics bounds on $\mu_\nu$

$$\mu_\nu(\text{astro}) < 10^{-10} - 10^{-12} \mu_B$$

Mostly derived from consequences of helicity-state change in astrophysical medium:
- available degrees of freedom in BBN,
- stellar cooling via plasmon decay,
- cooling of SN1987a.

The bounds depend on
- modeling of the astrophysical systems,
- on assumptions on the neutrino properties.

Generic assumption:
- absence of other nonstandard interactions except for $\mu_\nu$.

A global treatment would be desirable, incorporating oscillation and matter effects as well as the complications due to interference and competitions among various channels.
\( \mu \nu \) is presently known to be in the range

\[ 10^{-20} \mu_B \leq \mu \nu \leq 10^{-10} \mu_B \]

\( \mu \nu \) provides a tool for exploration possible physics beyond the Standard Model
… a bit of electromagnetic properties theory
3.1 vertex function

The most general study of the massive neutrino vertex function (including electric and magnetic form factors) in arbitrary $R_5$ gauge in the context of the SM + SU(2)-singlet $Y_R$ accounting for masses of particles in polarization loops.
M. Dvornikov, A. Studenikin

Phys. Rev. D 63, 073004 (2001),
"Electric charge and magnetic moment of massive neutrino."
JETP 116 (2001), N8.1
"Electromagnetic form factors of a massive neutrino."

\[ \Lambda_{\mu}(q) = f_q(q^2) \sigma_{\mu} + f_M(q^2) i \sigma_{\mu \nu} q^\nu - f_E(q^2) i \sigma_{\mu \nu} q^\nu \gamma_5 - f_A(q^2)(q^2 \gamma_{\mu} - q_{\mu} \gamma_5) \gamma_5 \]

charge
magnetic moment

- electric moment
- anapole moment
Calculation of \( \nu \) magnetic moment (massive \( \nu \), arbitrary \( R_\xi \)-gauge)

\[
\Lambda_\mu(q) = f_Q(q^2) \gamma_\mu + f_M(q^2) i \sigma_{\mu \nu} q^\nu - f_E(q^2) \sigma_{\mu \nu} q^\nu \gamma_5
\]
\[
+ f_A(q^2) (q^2 \gamma_\mu - q_\mu \gamma_5) \gamma_5
\]

\[\mu(a,b,\alpha) = f_M(q^2 = 0)\]

Two mass parameters:
\[
a = \left( \frac{m_\ell}{M_W} \right)^2, \quad b = \left( \frac{m_\nu}{M_W} \right)^2
\]

and gauge-fixing parameter:
\[
\alpha = \frac{1}{\xi}
\]

\[\xi = 0\] - unitary gauge, \( \xi = 1 \) - 't Hooft-Feynman gauge

\[
\mu(a,b,\alpha) = \sum_{i=1}^{6} \mu^{(i)}(a,b,\alpha)
\]

Proper vertices:

(a) \hspace{2cm} (b) \hspace{2cm} (c) \hspace{2cm} (d) \hspace{2cm} (e) \hspace{2cm} (f)
magnetic moment
(heavy massive neutrino)

LEP data

only 3 light $\nu$s coupled to $Z^0$, for any additional neutrino

\[ m_\nu \geq 45 \text{ Gev} \]
\[ \mu_\nu = \frac{eG_F}{4\pi^2\sqrt{2}} m_\nu \frac{3}{4(1-a)^3} (2 - 7a + 6a^2 - 2a^2 \ln a - a^3), \quad a = \left( \frac{m_e}{M_W} \right)^2 \]

**Light**

- \( m_e \ll m_\nu \ll M_W \)

**Intermediate**

- \( m_e \ll m_\nu \ll M_W \)

**Heavy**

- \( m_e \ll M_W \ll m_\nu \)

References:

Naïve relationship between the size of $m$ and $\mu$.

If $\mu$ is generated by physics beyond the SM at energy scale $\Lambda$, then $\mu \sim \frac{eG}{\Lambda}$, according to P.Vogel e.a., 2006.

The contribution to $m$ given by the quadratic divergence appearing in renormalization of the dimension four neutrino mass operator is

$$m \sim \frac{\Lambda^2}{2m_e \mu_B} \sim \frac{\mu}{10^{-18} \mu_B} [\Lambda(\text{TeV})]^2 \text{ eV}$$

from quadratic divergence appearing in renormalization of dimension four neutrino mass operator.
large magnetic moment

In the $L-R$ symmetric models $(SU(2)_L \times SU(2)_R \times U(1))$

M. Voloshin (ITEP),


... there may be $SU(2)_\nu$ symmetry that forbids $m_\nu$ but not $\mu_\nu$

- supersymmetry
- extra dimensions

considerable enhancement of $\mu_\nu$ to experimentally relevant range
3.5 Neutrino dipole moments
(+ transition moments)

- **Dirac neutrino**

\[
\begin{align*}
\mu_{ij} & = \frac{e G_F m_i}{8 \sqrt{2} \pi^2} \left(1 \mp \frac{m_j}{m_i}\right) \sum_l \sigma_{l e, \mu, \tau}^l U_{ij} U_{il}^* \\
\epsilon_{ij} & = \frac{e G_F (1 \mp \frac{v}{\pi})}{8 \sqrt{2} \pi^2} \sum_l \sigma_{l e, \mu, \tau}^l U_{ij} U_{il}^* 
\end{align*}
\]

- \(m_i, m_j \ll m_l, m_W\)

\[f(r_l) \approx \frac{3}{2} \left(1 - \frac{1}{2} r_l\right), \quad r_l \ll 1\]

- **Majorana neutrino**

only for \(i \neq j\)

\[\mu_{ij}^M = 2 \mu_{ij}^D \quad \text{and} \quad \epsilon_{ij}^M = 0\]

or

\[\mu_{ij}^M = 0 \quad \text{and} \quad \epsilon_{ij}^M = 2 \epsilon_{ij}^D\]

\[m_e = 0.5 \text{ MeV}, \quad m_\mu = 105.7 \text{ MeV}, \quad m_\tau = 1.78 \text{ GeV}, \quad m_W = 80.2 \text{ GeV}\]

transition moments vanish because unitarity of \(U\) implies that its rows or columns represent orthogonal vectors

- transition moments are suppressed, Glashow-Iliopoulos-Maiani cancellation, for diagonal there is no GIM cancelation

\[P.Pal, 1982\]

L.Wolfenstein, 3.5
The first nonzero contribution from neutrino transition moments is very slow.

$$
\mu_{ij} \overline{\epsilon}_{ij} = \frac{3eG_F m_i}{32\sqrt{2}\pi^2} \left( 1 \pm \frac{m_j}{m_i} \right) \left( \frac{m_\tau}{m_W} \right)^2 \sum_{l=e, \mu, \tau} \left( \frac{m_l}{m_\tau} \right)^2 U_{lj} U_{li}^* 
$$

$$
\mu_{ij} \overline{\epsilon}_{ij} = 4 \times 10^{-23} \mu_B \left( \frac{m_i \pm m_j}{1\text{ eV}} \right) \sum_{l=e, \mu, \tau} \left( \frac{m_l}{m_\tau} \right)^2 U_{lj} U_{li}^* 
$$

Dirac \( \forall \) diagonal \((i=j)\) magnetic moment

$$
\mu_{ii} = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \left( 1 - \frac{1}{2} \sum_{l=e, \mu, \tau} r_l |U_{li}|^2 \right) \approx 3.2 \times 10^{-19} \left( \frac{m_i}{1\text{ eV}} \right) \mu_B 
$$

Lee, Shrock, Fujikawa, 1977

- no GIM cancellation
- \( \mu_{ii}^D \) - to leading order - independent on \( U_{li} \) and \( m_l = e, \mu, \tau \)
- \( \mu_{ii}^M = \epsilon_{ii}^M = 0 \)
- \( \mu_{ii}^D = 0 \) for massless \( \forall \) (in the absence of right-handed charged currents)
3.6 Neutrino magnetic moment in left-right symmetric models

\[ SU_L(2) \times SU_R(2) \times U(1) \]

Gauge bosons
- \( W_1 = W_L \cos \xi - W_R \sin \xi \)
- \( W_2 = W_L \sin \xi + W_R \cos \xi \)

with mixing angle \( \xi \) of gauge bosons \( W_{L,R} \) with pure \((V \pm A)\) couplings

\[ \mu_{\nu_i} = \frac{eG_F}{2\sqrt{2}\pi^2} \left[ m_\ell \left( 1 - \frac{m_{W_1}^2}{m_{W_2}^2} \right) \sin 2\xi + \frac{3}{4} m_{\nu_i} \left( 1 + \frac{m_{W_1}^2}{m_{W_2}^2} \right) \right] \]

Due to smallness of neutrino-mass-induced magnetic moments,

\[ \mu_{\nu_i} \approx 3.2 \times 10^{-19} \left( \frac{m_i}{1 \text{ eV}} \right) \mu_B \]

any indication for non-trivial electromagnetic properties of \( \nu \), that could be obtained within reasonable time in the future, would give evidence for interactions beyond extended Standard Model

Kim, 1976; Marciano, Sanda, 1977; Beg, Marciano, Ruderman, 1978
3.7 Neutrino radiative decay

$\nu_i \rightarrow \nu_j + \gamma$

$m_i > m_j$

$\mathcal{L}_{\text{int}} = \frac{1}{2} \bar{\psi}_i \sigma_{\alpha\beta}(\sigma_{ij} + \epsilon_{ij} \gamma_5) \psi_j F^{\alpha\beta} + h.c.$

Radiative decay rate

$$\Gamma_{\nu_i \rightarrow \nu_i + \gamma} = \frac{\mu_{\text{eff}}^2}{8\pi} \left( \frac{m_i^2 - m_j^2}{m_i^2} \right)^3$$

$$\approx 5 \left( \frac{\mu_{\text{eff}}}{\mu_B} \right)^2 \left( \frac{m_i^2 - m_j^2}{m_i^2} \right)^3 \left( \frac{m_i}{1 \text{ eV}} \right)^3 \text{s}^{-1}$$

- Radiative decay has been constrained from absence of decay photons:
  1) reactor $\bar{\nu}_e$ and solar $\nu_e$ fluxes,
  2) SN 1987A $\nu$ burst (all flavours),
  3) spectral distortion of CMBR

Raffelt 1999
Kolb, Turner 1990;
Ressell, Turner 1990
Neutrino radiative two-photon decay

$\nu_i \rightarrow \nu_j + \gamma + \gamma$

$m_i > m_j$

fine structure constant

$\Gamma_{\nu_i \rightarrow \nu_j + \gamma + \gamma} \sim \frac{\alpha_{QED}}{4\pi} \frac{\Gamma_{\nu_i \rightarrow \nu_j + \gamma}}{F(B)}$

... there is no GIM cancellation...

$f(r_i) \approx \frac{3}{2} \left( 1 - \frac{1}{2} \left( \frac{m_i}{m_W} \right)^2 \right) \rightarrow \left( \frac{m_i}{m_i} \right)^2$

... can be of interest for certain range of masses...

Nieves, 1983; Ghosh, 1984
The tightest astrophysical bound on $\mu$ comes from cooling of red giant stars by plasmon decay $\gamma^* \rightarrow \nu \bar{\nu}$

\[ L_{int} = \frac{1}{2} \sum_{a,b} \left( \mu_{a,b} \bar{\psi}_a \sigma_{\mu\nu} \psi_b + \epsilon_{a,b} \bar{\psi}_a \sigma_{\mu\nu} \gamma_5 \psi_b \right) \]

Matrix element

\[ |M|^2 = M_{\alpha\beta} p^\alpha p^\beta, \quad M_{\alpha\beta} = 4\mu^2 \left( 2k_\alpha k_\beta - 2k^2 \epsilon_\alpha \epsilon_\beta - k^2 g_{\alpha\beta} \right), \]

Decay rate

\[ \Gamma_{\gamma \rightarrow \nu \bar{\nu}} = \frac{\mu^2}{24\pi} \frac{(\omega^2 - k^2)^2}{\omega} \]

In the classical limit $\gamma^*$ - like a massive particle with $\omega^2 - k^2 = \omega_{pl}^2$

Energy-loss rate per unit volume

\[ Q_\mu = g \int \frac{d^3k}{(2\pi)^3} \omega f_{BE} \Gamma_{\gamma \rightarrow \nu \bar{\nu}} \]

distribution function of plasmons
Magnetic moment **plasmon decay** enhances the Standard Model photo-neutrino cooling by photon polarization tensor

\[ Q_\mu = g \int \frac{d^3k}{(2\pi)^3\omega} f_{BE} \Gamma_{\gamma \rightarrow \nu \bar{\nu}} \]

more fast cooling of the star.

- In order not to delay helium ignition ( \( \leq 5\% \) in \( Q \) )

\[ \mu \leq 3 \times 10^{-12} \mu_B \]

\[ \mu^2 \rightarrow \sum_{a,b} \left( |\mu_{a,b}|^2 + |\epsilon_{a,b}|^2 \right) \]

G. Raffelt, PRL 1990
Constraints on neutrino millicharge from red giants cooling

Interaction Lagrangian

\[ L_{int} = -i q_\nu \bar{\nu} \gamma^\mu \psi_\nu A^\mu \]

Decay rate

\[ \Gamma_{q_\nu} = \frac{q_\nu^2}{12\pi} \omega_{pl} \left( \frac{\omega_{pl}}{\omega} \right) \]

- \( q_\nu \leq 2 \times 10^{-14} e \) ... to avoid helium ignition in low-mass red giants

- \( q_\nu \leq 3 \times 10^{-17} e \) ... absence of anomalous energy-dependent dispersion of SN1987A signal, most model independent

- ... from “charge neutrality” of neutron...

\[ q_\nu \leq 3 \times 10^{-21} e \]
Although it is usually assumed that are electrically neutral (charge quantization implies $Q \sim \frac{1}{3}e$), can dissociates into charged particles so that $f_Q(q^2) \neq 0$ for $q^2 \neq 0$:

$$f_Q(q^2) = f_Q(0) + q^2 \frac{df_Q}{dq^2}(0) + \cdots,$$

where the massive charge radius

$$a_\nu = f_A(q^2) = \frac{1}{6} \langle r_\nu^2 \rangle$$

Interpretation of charge radius as an observable is rather delicate issue: $\langle r_\nu^2 \rangle$ represents a correction to tree-level electroweak scattering amplitude between and charged particles, which receives radiative corrections from several diagrams (including exchange) to be considered simultaneously calculated CR is infinite and gauge dependent quantity. For massless, $a_\nu$ and $\langle r_\nu^2 \rangle$ can be defined (finite and gauge independent) from scattering cross section.
Direct calculation of $\gamma - Z$ and proper-vertex diagrams contribution

\[ \mathbf{\vee} \text{ anapole moment is infinite and gauge dependent} \]

$\mathbf{m=0, \quad Lucio, Rosado, Zepeda, 1985}$
$\mathbf{m\neq 0, \quad Dvornikov, Studenikin, 2004}$

is not a static quantity,

can’t be measured with external field

Physical definition of anapole moment:

- through diagrams contributing to $\nu_l l' \rightarrow \nu_l l'$
- with inclusion of all $\mathbf{\vee}$ anapole diagrams
- finite and gauge independent
- does not depend on charged lepton $l'$.
e.m. form factors are affected by matter and $B$

magnetic moment $\mu_N = \mu_N(B)$

induced electric charge of

in magnetized matter

Egorov, Studenikin, 1983

Borisov, Zhukovsky, Kunitsin, Ternov, 1985

Oraevsky, Semikoz, Smorodinsky, 1986

Bhattacharaya, Cangul, Konar, 2002

Nieves, 2003
Neutrino magnetic moment

\[ \frac{\mu_{\nu}(B)}{\mu_{\nu}(0)} \]

\[ \mu_0 = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e} \]

\[ B_0 = \frac{m_w^2}{e} = 1.1 \times 10^{-4} G \]

Borishov, Zhukovskiy, Kurilin, Ternov, 1985;

Masood, Perez Rojas, Gaitan, Rodrigues-Romo, 1999
“effective electric charge” in magnetized plasma

- Neutrinos do not couple with photons in vacuum,
- However, when in thermal medium ($e^-$ and $e^+$)

V. Oraevsky, V. Semikoz, Ya. Smorodinsky, JETP Lett. 43 (1986) 709;
K. Bhattacharya, A. Ganguly, 2002

...different interactions in astrophysical and cosmological media
Consider two different neutrinos: \( \nu_{eL}, \nu_{\mu_R}, m_L \neq m_R \)

Twisting magnetic field \( B = |B_\perp| e^{i \phi(t)} \) for solar etc ...

Evolution equation

\[
H = \begin{pmatrix}
E_L & \mu_{e\mu} B e^{-i\phi} \\
\mu_{e\mu} B e^{+i\phi} & E_R
\end{pmatrix} = \cdots \begin{pmatrix}
1 & 0 \\
0 & 1
\end{pmatrix} + \tilde{H}
\]

\[
\tilde{H} = \begin{pmatrix}
-\frac{\Delta m^2}{4E} \cos 2\theta + \frac{V_{\nu e}}{2} & \mu_{e\mu} B e^{-i\phi} \\
\mu_{e\mu} B e^{+i\phi} & \frac{\Delta m^2}{4E} - \frac{V_{\nu e}}{2}
\end{pmatrix}
\]
Probability of $\nu_{eL} \leftrightarrow \nu_{\mu R}$ oscillations in $B = |B_\perp| e^{i\phi(t)}$ and matter

$$P_{\nu_L \nu_R} = \sin^2 \beta \sin^2 \Omega z, \quad \sin^2 \beta = \frac{(\mu_{e\mu} B)^2}{(\mu_{e\mu} B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2}$$

$$\Delta_{LR} = \frac{\Delta m^2}{2}(\cos 2\theta + 1) - 2EV_{\nu_e} + 2E\dot{\phi}$$

$$\Omega^2 = (\mu_{e\mu} B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2$$

Resonance amplification of oscillations in matter:

$\Delta_{LR} \rightarrow 0 \quad \rightarrow \quad \sin^2 \beta \rightarrow 1$

Akhmedov, 1988
Lim, Marciano

In magnetic field

$\nu_{eL} \nu_{\mu R}$

$$i \frac{d}{dz} \nu_{eL} = -\frac{\Delta_{LR}}{4E} \nu_{eL} + \mu_{e\mu} B \nu_{\mu R}$$

$$i \frac{d}{dz} \nu_{\mu L} = \frac{\Delta_{LR}}{4E} \nu_{\mu L} + \mu_{e\mu} B \nu_{eR}$$
Spin-flavour oscillations in early universe – strong population of wrong-helicity states (r.h.) would accelerate expansion of universe (???)

...for recent analysis see

J. Pulido, 2006
A. Balantekin, C. Volpe, 2005
Conclusion
Neutrino – photon couplings (I)

ν decay, Cherenkov radiation

ν decay in plasma

ν → ν

e / N

Scattering

ν_L → ν_R

Spin precession

external source
spin evolution in presence of general external fields

M. Dvornikov, A. Studenikin,
JHEP 09 (2002) 016

General types non-derivative interaction with external fields

\[-\mathcal{L} = g_s s(x) \bar{\nu} \nu + g_p \pi(x) \bar{\nu} \gamma^5 \nu + g_v V^\mu(x) \bar{\nu} \gamma_\mu \nu + g_a A^\mu(x) \bar{\nu} \gamma_\mu \gamma^5 \nu + \frac{g_H}{2} T^{\mu\nu} \bar{\nu} \sigma_{\mu\nu} \nu + \frac{g'_t}{2} \Pi^{\mu\nu} \bar{\nu} \sigma_{\mu\nu} \gamma_5 \nu,\]

scalar, pseudoscalar, vector, axial-vector, tensor and pseudotensor fields:

\[s, \pi, V^\mu = (V^0, \vec{V}), A^\mu = (A^0, \vec{A}), T_{\mu\nu} = (\vec{a}, \vec{b}), \Pi_{\mu\nu} = (\vec{c}, \vec{d})\]

Relativistic equation (quasiclassical) for spin vector:

\[\dot{\zeta}_\nu = 2g_a \left\{ A^0 [\zeta_\nu \times \beta] - \frac{m_\nu}{E_\nu} [\zeta_\nu \times \vec{A}] - \frac{E_\nu}{E_\nu + m_\nu} (\vec{A} \beta) [\zeta_\nu \times \beta] \right\} + 2g_t \left\{ [\zeta_\nu \times \vec{b}] - \frac{E_\nu}{E_\nu + m_\nu} (\vec{b} \beta) [\zeta_\nu \times \beta] + [\zeta_\nu \times [\vec{a} \times \beta]] \right\} + 2ig'_t \left\{ [\zeta_\nu \times \vec{c}] - \frac{E_\nu}{E_\nu + m_\nu} (\vec{c} \beta) [\zeta_\nu \times \beta] - [\zeta_\nu \times [\vec{d} \times \beta]] \right\}.\]

Neither \(S\) nor \(\pi\) nor \(V\) contributes to spin evolution

Electromagnetic interaction

\[T_{\mu\nu} = F_{\mu\nu} = (\vec{E}, \vec{B})\]

SM weak interaction

\[G_{\mu\nu} = (-\vec{P}, \vec{M})\]

\[\vec{M} = \gamma (A^0 \beta - \vec{A}), \quad \vec{P} = -\gamma [\beta \times \vec{A}],\]
New mechanism of electromagnetic radiation
We predict the existence of a **new mechanism** of the electromagnetic process stimulated by the presence of matter, in which a neutrino with **non-zero magnetic moment** emits light.

- A.Lobanov, A.S., PLB 2003
- A.S., A.Ternov, PLB 2004
- A.Grigoriev, Studenikin, Ternov, PLB 2005


A. Shinkevich, A. Studenikin,  *Pramana* 64 (2005) 124


Experimental and theoretical studies of electromagnetic properties is a tedious task.

This has an important impact on understanding of fundamentals of particle physics (Dirac ↔ Majorana etc) and applications in astrophysics.
14th Lomonosov Conference on Elementary Particle Physics

Moscow, August 19-25, 2009

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