Electromagnetic neutrino properties: present status and future prospects

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&
JINR–Dubna
GEMMA coll.
Outline

1. (short) review of $\nu$ electromagnetic properties
2. experimental constraints on $\mu_\nu$ and $q_\nu$
3. $\nu$ electromagnetic interactions (new effects)
4. two new aspects of $\nu$ spin (flavour) oscillations

consistent treatment of $\nu$ flavour (spin) oscillations in $B$

generation of $\nu$ spin (flavour) new oscillations by $\nu$ interaction oscillations with transversal matter current $j_\perp$

Popov, Pustoshny, AS (2017, 2018)
...2018 anniversaries in $\nu$ oscillation story

1968 - Davis et al. - $\nu_e$

1968 - Gribov & Pontecorvo - $\nu_e \leftrightarrow \nu_\mu$ (theory)

1988 - Resonance Spin-Flavour $\nu$ Precession in matter (Akhmedov + Lim & Marciano)

1998 - Super-Kamiokande - $\nu$ oscillations in $\nu_{\text{atm}}$ flux
Neutrino electromagnetic interactions: A window to new physics

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(published 16 June 2015)

A review is given of the theory and phenomenology of neutrino electromagnetic interactions, which provide powerful tools to probe the physics beyond the standard model. After a derivation of the general structure of the electromagnetic interactions of Dirac and Majorana neutrinos in the one-photon approximation, the effects of neutrino electromagnetic interactions in terrestrial experiments and in astrophysical environments are discussed. The experimental bounds on neutrino electromagnetic properties are presented and the predictions of theories beyond the standard model are confronted.

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+ upgrade:

"-electromagnetic interactions: A window to new physics – II”, arXiv: 1801.18887
Oscillations and exact eigenstates of neutrinos in a magnetic field

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Introduction

Mesonic and baryonic magnetic environments generate a permanent magnetic field of $10^{-15}$ T or less, the density of quark-gluon plasma at the limit of nuclear matter. Neutrino oscillations in this magnetic field were considered in [1-3]. In the case of a stationary magnetic field, the probability of neutrino oscillation $P_{\nu\nu}$ is given by

$$
\frac{d^2 P_{\nu\nu}}{d^2 \theta} = \frac{1}{4} \sin^2 2\theta \cos^2 2\theta \left( 1 + \frac{1}{2} \sin^2 2\theta \right) 
$$

where $\theta$ is the mixing angle and $\Delta m^2$ is the mass difference.

In the case of a magnetic field varying in time, the probability of neutrino oscillation is given by

$$
\frac{d^2 P_{\nu\nu}}{d^2 \theta} = \frac{1}{4} \sin^2 2\theta \cos^2 2\theta \left( 1 + \frac{1}{2} \sin^2 2\theta \right) \cos 2\Delta
$$

where $\Delta = \frac{\Delta m^2 \cos 2\theta}{2 E}$ is the magnetic angle and $E$ is the neutrino energy.

Massive neutrinos in a magnetic field

Consider a magnetic field with a direction opposite to the velocity of massive neutrinos, i.e., $\mathbf{B} \perp \mathbf{v}$. In this case, the magnetic field produces a transverse magnetic force $F_B = q \mathbf{v} \times \mathbf{B}$, which leads to a deviation of the particle trajectory. The magnetic force is

$$
F_B = q \mathbf{v} \times \mathbf{B} = q \mathbf{v} \sin \theta B \cos \phi
$$

where $q$ is the charge, $\theta$ is the angle between the velocity and the magnetic field, and $\phi$ is the angle between the magnetic field and the direction of the magnetic field.

General Formulation

The probability of neutrino oscillation in a magnetic field is given by

$$
\frac{d^2 P_{\nu\nu}}{d^2 \theta} = \frac{1}{4} \sin^2 2\theta \cos^2 2\theta \left( 1 + \frac{1}{2} \sin^2 2\theta \right) \cos 2\Delta \cos 2\theta
$$

where $\Delta = \frac{\Delta m^2 \cos 2\theta}{2 E}$ is the magnetic angle and $E$ is the neutrino energy.

The magnetic force $F_B$ is

$$
F_B = q \mathbf{v} \times \mathbf{B} = q \mathbf{v} \sin \theta B \cos \phi
$$

where $q$ is the charge and $\theta$ is the angle between the velocity and the magnetic field.

The magnetic field $B$ is

$$
B = \frac{\mu_0 I}{2\pi r^2}
$$

where $\mu_0$ is the permeability constant.

The magnetic moment $\mu$ is

$$
\mu = q \mathbf{v} \times \mathbf{B}
$$

where $q$ is the charge.

The magnetic field $B$ is

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B = \frac{\mu_0 I}{2\pi r^2}
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$$

where $q$ is the charge.

The magnetic field $B$ is

$$
B = \frac{\mu_0 I}{2\pi r^2}
$$

where $\mu_0$ is the permeability constant.
Spin-light of neutrino in astrophysical environments

K. Stankevich, AS
T_9 poster # 662

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Neutrino decoherence in matter

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1 Introduction

In this report, we present the study of the neutrino decoherence effect in the presence of a magnetic field. The phenomenon of neutrino decoherence, a key concept in the theory of quantum mechanics, has been a subject of intense research in recent years. It is a process by which a system's quantum coherence is lost due to interactions with the environment. In this work, we investigate the decoherence effects for the neutrino states in the presence of a magnetic field, which is a fundamental property of the universe.

2 Formulation

We start by considering the Hamiltonian of the neutrino state in the presence of a magnetic field. The Hamiltonian is given in the following equation:

\[ H = \sum_{\alpha} E_{\alpha} |\alpha\rangle \langle \alpha| + \sum_{\alpha} \sum_{\beta \neq \alpha} V_{\alpha\beta} |\alpha\rangle \langle \beta| + H_{\text{magnetic field}} \]

where \( |\alpha\rangle \) represents the neutrino state, \( E_{\alpha} \) is the energy of the state, \( V_{\alpha\beta} \) is the interaction between the states, and \( H_{\text{magnetic field}} \) is the Hamiltonian of the magnetic field in the presence of the neutrino.

3 Neutrino radiative decay

The radiative decay of a neutrino is a process by which a neutrino transitions to another state via the emission of a particle. The decay rate for the neutrino is given by:

\[ \Gamma = \frac{G_F^2 m_{\nu}^5}{48 \pi^3} \frac{1}{E_{\nu}^2} \left| V_{\nu e} \right|^2 \]

where \( G_F \) is the Fermi constant, \( m_{\nu} \) is the neutrino mass, \( E_{\nu} \) is the energy of the neutrino, and \( V_{\nu e} \) is the neutrino mixing parameter.

4 Neutrino decoherence parameter

The decoherence parameter is a measure of the extent to which a system's quantum coherence is lost. It is given by:

\[ \delta = \frac{\Gamma}{\Gamma_0} \]

where \( \Gamma \) is the decay rate and \( \Gamma_0 \) is the decay rate in the absence of the magnetic field.

5 Suppression environment

The environment in which a neutrino is moving can affect its decoherence. In this part, we consider the effects of a strong magnetic field on the neutrino decoherence.

6 Conclusion

We conclude that the magnetic field can have a significant effect on the neutrino decoherence. The results of this study can be used to further understand the behavior of neutrinos in the presence of a magnetic field.

References

electromagnetic properties

... in spite of ...

- results of terrestrial lab experiments on \( m \) (and \( \nu \) EM properties in general)
- as well as data from astrophysics and cosmology

are in agreement with "zero" \( \nu \) EM properties
Nobel Prizes

2013 & 2015

1833 - 1896
Observation of Higgs boson confirms the symmetry breaking mechanism by Brout-Englert-Higgs (BEH) provides final glorious triumph of Standard Model ... new division in particle physics with special name BEH Physics
The Nobel Prize in Physics 2015

«for the discovery of neutrino oscillations, which shows that neutrinos have mass»
... a tool for studying physics

**Beyond Extended Standard Model...**

Theory (Standard Model with νR)

\[ \mu_\nu = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \sim 3 \times 10^{-19} \mu_B \left( \frac{m_\nu}{3\text{eV}} \right) \]

\[ M_8 = \frac{\epsilon}{2m_e} \]

magnetic moment

\[ a_e = \frac{\alpha_{QED}}{2\pi} \sim 10^{-3} \]

... much greater values are desired

for astrophysical or cosmology

visualization of \( \mu_\nu \)

... hopes for physics BESM...
v electromagnetic properties

(flash on theory)

m_0 

\neq 0
electromagnetic vertex function

\[ \langle \psi(p') | J_{\mu}^{EM} | \psi(p) \rangle = \bar{u}(p') \Lambda_{\mu}(q, l) u(p) \]

Matrix element of electromagnetic current is a Lorentz vector

\[ \Lambda_{\mu}(q, l) \] should be constructed using

matrices \( \hat{1}, \gamma_5, \gamma_\mu, \gamma_5 \gamma_\mu, \sigma_{\mu\nu}, \)
tensors \( g_{\mu\nu}, \epsilon_{\mu\nu\sigma\gamma}, \)
vectors \( q_{\mu} \) and \( l_{\mu} \)

\[ q_{\mu} = p'_{\mu} - p_{\mu}, \quad l_{\mu} = p'_{\mu} + p_{\mu} \]

Lorentz covariance (1) and electromagnetic gauge invariance (2)
Matrix element of electromagnetic current between neutrino states

\[ \langle \nu(p')| J_{\mu}^{EM} |\nu(p) \rangle = \bar{u}(p') \Lambda_{\mu}(q) u(p) \]

where vertex function generally contains 4 form factors

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

1. electric dipole
2. magnetic
3. electric
4. anapole

Hermiticity and discrete symmetries of EM current \( J_{\mu}^{EM} \) put constraints on form factors

**Dirac**

1) CP invariance + Hermiticity \( \Rightarrow f_E = 0 \),
2) at zero momentum transfer only electric Charge \( f_Q(0) \) and magnetic moment \( f_M(0) \) contribute to \( H_{int} \sim J_{\mu}^{EM} A^\mu \)
3) Hermiticity itself \( \Rightarrow \) three form factors are real: \( \text{Im} f_Q = \text{Im} f_M = \text{Im} f_A = 0 \)

**Majorana**

1) from CPT invariance (regardless CP or CP)
   \( f_Q = f_M = f_E = 0 \)

...as early as 1939, W.Pauli...

EM properties a way to distinguish Dirac and Majorana
In general case matrix element of $J_{\mu}^{EM}$ can be considered between different initial $\psi_i(p)$ and final $\psi_j(p')$ states of different masses $p^2 = m_i^2$, $p'^2 = m_j^2$:

$$< \psi_j(p') | J_{\mu}^{EM} | \psi_i(p) > = \bar{u}_j(p') \Lambda_{\mu}(q) u_i(p)$$

and

$$\Lambda_{\mu}(q) = \left( f_Q(q^2)_{ij} + f_A(q^2)_{ij} \gamma_5 \right) (q^2 \gamma_\mu - q_\mu \gamma_5) + f_M(q^2)_{ij} i \sigma_{\mu \nu} q^\nu + f_E(q^2)_{ij} \sigma_{\mu \nu} q^\nu \gamma_5$$

Form factors are matrices in mass eigenstates space.

Dirac (off-diagonal case $i \neq j$)

1) Hermiticity itself does not apply restrictions on form factors,

2) CP invariance + Hermiticity $f_Q(q^2), f_M(q^2), f_E(q^2), f_A(q^2)$ are relatively real (no relative phases).

Majorana

1) CP invariance + hermiticity

$$\mu_{ij}^M = 2 \mu_{ij}^D \text{ and } \epsilon_{ij}^M = 0$$

or

$$\mu_{ij}^M = 0 \text{ and } \epsilon_{ij}^M = 2 \epsilon_{ij}^D$$

... quite different EM properties ...
Dipole magnetic $f_M(q^2)$ and electric $f_E(q^2)$ are most well studied and theoretically understood among form factors.

...because in the limit $q^2 \rightarrow 0$ they have nonvanishing values.

$\mu_\nu = f_M(0)$

$\epsilon_\nu = f_E(0)$
3.5 Neutrino (beyond SM) dipole moments
(+ transition moments)

- **Dirac neutrino**

\[
\begin{align*}
\mu_{ij} \\
\epsilon_{ij}
\end{align*}
\right\} = \frac{e G_F m_i}{8 \sqrt{2} \pi^2} \left(1 \pm \frac{m_j}{m_i}\right) \sum_{l=e, \mu, \tau} f(r_l) U_{lj} U_{li}^*
\]

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

\[r_l = \left(\frac{m_l}{m_W}\right)^2\]

- **Majorana neutrino** only for \(i \neq j\)

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

or

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

- 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 moments there is no GIM cancellation**

... depending on relative CP phase of \(\nu_i\) and \(\nu_j\).
magnetic moment in experiments

(most easily understood and accessible for experimental studies are dipole moments)
Studies of $\nu - e$ scattering: most sensitive method for experimental investigation of $\mu$ of $\nu$.

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

$$\left(\frac{d\sigma}{dT}\right)_{\mu\nu} = \frac{\pi\alpha_{em}^2}{m_e^2} \left[ 1 - \frac{T}{E_{\nu}} \right] \mu_{\nu}^2$$

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

$$\mu_{ij} \rightarrow |\mu_{ij} - \epsilon_{ij}|$$

for anti-neutrinos

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

$g_A = \begin{cases} \frac{1}{2} & \text{for } \nu_e, \\ -\frac{1}{2} & \text{for } \nu_\mu, \nu_\tau. \end{cases}$

for anti-neutrinos $g_A \rightarrow -g_A$

To incorporate charge radius:

$$g_V \rightarrow g_V + \frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2\theta_W$$
Electromagnetic properties of massive neutrinos in low-energy elastic neutrino-electron scattering

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(Received 11 February 2017; published 14 March 2017)

A thorough account of electromagnetic interactions of massive neutrinos in the theoretical formulation of low-energy elastic neutrino-electron scattering is given. The formalism of neutrino charge, magnetic, electric, and anapole form factors defined as matrices in the mass basis is employed under the assumption of three-neutrino mixing. The flavor change of neutrinos traveling from the source to the detector is taken into account and the role of the source-detector distance is inspected. The effects of neutrino flavor-transition millicharges and charge radii in the scattering experiments are pointed out.

DOI: 10.1103/PhysRevD.95.055013

... all experimental constraints on charge radius should be redone
Magnetic moment contribution dominates at low electron recoil energies when

\[
\left( \frac{d\sigma}{dT} \right)_{\mu_\nu} > \left( \frac{d\sigma}{dT} \right)_{SM}
\]

and

\[
\frac{T}{m_e} < \frac{\pi^2 \alpha_{em}}{G_F m_e^4 \mu_\nu^2}
\]

... the lower the smallest measurable electron recoil energy is, smaller values of \( \mu_\nu^2 \) can be probed in scattering experiments ...

3, 4, 5 mean NMM values in units \( 10^{-11} \) Bohr magneton

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

... courtesy of A. Starostin...
GEMMA (2005-2012)
Germanium Experiment for Measurement of Magnetic Moment of Antineutrino

JINR (Dubna) + ITEP (Moscow) at Kalinin Nuclear Power Plant

World best experimental limit

\[ \mu_\nu < 2.9 \times 10^{-11} \mu_B \]

June 2012

editors: J. Bernabeu, G. Fogli, A. McDonald, K. Nishikawa

... quite realistic prospects of the near future ... 2018-2019 ?

\[ \mu_\nu^a \sim 0.7 \times 10^{-12} \mu_B \]  
unprecedentedly low threshold  

\[ T \sim 200 \text{ eV} \]
# Experimental limits for different effective $\mu_v$

<table>
<thead>
<tr>
<th>Method</th>
<th>Experiment</th>
<th>Limit</th>
<th>CL</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor $\bar{\nu}_e$-$e^-$</td>
<td>Krasnoyarsk</td>
<td>$\mu_{\nu_e} &lt; 2.4 \times 10^{-10}$ $\mu_B$</td>
<td>90%</td>
<td>Vidyakin et al. (1992)</td>
</tr>
<tr>
<td></td>
<td>Rovno</td>
<td>$\mu_{\nu_e} &lt; 1.9 \times 10^{-10}$ $\mu_B$</td>
<td>95%</td>
<td>Derbin et al. (1993)</td>
</tr>
<tr>
<td></td>
<td>MUNU</td>
<td>$\mu_{\nu_e} &lt; 0.9 \times 10^{-10}$ $\mu_B$</td>
<td>90%</td>
<td>Daraktchieva et al. (2005)</td>
</tr>
<tr>
<td></td>
<td>TEXONO</td>
<td>$\mu_{\nu_e} &lt; 7.4 \times 10^{-11}$ $\mu_B$</td>
<td>90%</td>
<td>Wong et al. (2007)</td>
</tr>
<tr>
<td></td>
<td>GEMMA</td>
<td>$\mu_{\nu_e} &lt; 2.9 \times 10^{-11}$ $\mu_B$</td>
<td>90%</td>
<td>Beda et al. (2012)</td>
</tr>
<tr>
<td>Accelerator $\nu_e$-$e^-$</td>
<td>LAMPF</td>
<td>$\mu_{\nu_e} &lt; 10.8 \times 10^{-10}$ $\mu_B$</td>
<td>90%</td>
<td>Allen et al. (1993)</td>
</tr>
<tr>
<td>Accelerator $(\nu_\mu, \bar{\nu}_\mu)$-$e^-$</td>
<td>BNL-E734</td>
<td>$\mu_{\nu_\mu} &lt; 8.5 \times 10^{-10}$ $\mu_B$</td>
<td>90%</td>
<td>Ahrens et al. (1990)</td>
</tr>
<tr>
<td></td>
<td>LAMPF</td>
<td>$\mu_{\nu_\mu} &lt; 7.4 \times 10^{-10}$ $\mu_B$</td>
<td>90%</td>
<td>Allen et al. (1993)</td>
</tr>
<tr>
<td></td>
<td>LSND</td>
<td>$\mu_{\nu_\mu} &lt; 6.8 \times 10^{-10}$ $\mu_B$</td>
<td>90%</td>
<td>Auerbach et al. (2001)</td>
</tr>
<tr>
<td>Accelerator $(\nu_\tau, \bar{\nu}_\tau)$-$e^-$</td>
<td>DONUT</td>
<td>$\mu_{\nu_\tau} &lt; 3.9 \times 10^{-7}$ $\mu_B$</td>
<td>90%</td>
<td>Schwienhorst et al. (2001)</td>
</tr>
<tr>
<td>Solar $\nu_e$-$e^-$</td>
<td>Super-Kamiokande</td>
<td>$\mu_S(E_\nu \gtrsim 5$ MeV) $&lt; 1.1 \times 10^{-10}$ $\mu_B$</td>
<td>90%</td>
<td>Liu et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>Borexino</td>
<td>$\mu_S(E_\nu \lesssim 1$ MeV) $&lt; 5.4 \times 10^{-11}$ $\mu_B$</td>
<td>90%</td>
<td>Arpesella et al. (2008)</td>
</tr>
</tbody>
</table>

**new 2017 PRD:** $\mu_{\nu_{eff}} < 2.8 \times 10^{-11}$ $\mu_B$ at 90% c.l.

Effective magnetic moment in experiments
(for neutrino produced as $\nu_l$ with energy $E_{\nu}$ and after traveling a distance $L$)

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

where

neutrino mixing matrix

$$\mu_{i,j} = |\beta_{i,j} - \epsilon_{i,j}|$$

magnetic and electric moments

Observable $\mu_{\nu}$ is an effective parameter that depends on neutrino flavour composition at the detector.

Implications of $\mu_{\nu}$ limits from different experiments (reactor, solar $^8$B and $^7$Be) are different.
Bounds on millicharge $q_\nu$ from $\mu_\nu$

$\nu - e$ cross-section

$$\left( \frac{d\sigma}{dT} \right)_{\nu-e} = \left( \frac{d\sigma}{dT} \right)_{SM} + \left( \frac{d\sigma}{dT} \right)_{\mu_\nu} + \left( \frac{d\sigma}{dT} \right)_{q_\nu}$$

Bounds on $q_\nu$ from $\mu_\nu$

$$R = \frac{\left( \frac{d\sigma}{dT} \right)_{q_\nu}}{\left( \frac{d\sigma}{dT} \right)_{\mu_\nu}} = \frac{2m_e}{T} \left( \frac{q_\nu}{e_0} \right)^2 \left( \frac{\mu_\nu}{\mu_B} \right)^2 < 1$$

Expected new constraints from GEMMA:

now $\mu_\nu^a < 2.9 \times 10^{-11} \mu_B$ ( $T \sim 2.8$ keV )

$2018/19$ (expected) $\mu_\nu^a \sim 0.7 \times 10^{-12} \mu_B$ ( $T \sim 200$ eV )

...unprecedentedly low threshold...

| $q_\nu$ | $< 1.5 \times 10^{-12} e_0$ | Constraints on $q_\nu$

two not seen contributions:

$$\left( \frac{d\sigma}{dT} \right)_{q_\nu} \approx \frac{\pi \alpha^2}{m_e^2 T} \left( \frac{\mu_\nu^a}{\mu_B} \right)^2$$

$$\left( \frac{d\sigma}{dT} \right)_{q_\nu} \approx 2\pi \alpha \frac{1}{m_e T^2 q_\nu^2}$$

Studenikin, Eurphys. Lett. 107 (2014) 21001

• Particle Data Group, 2016 •
Experimental limits for different effective $q_{\nu}$


<table>
<thead>
<tr>
<th>Limit</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>q_{\nu_e}</td>
<td>\lesssim 3 \times 10^{-21} e$</td>
</tr>
<tr>
<td>$</td>
<td>q_{\nu_e}</td>
<td>\lesssim 3.7 \times 10^{-12} e$</td>
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<tr>
<td>$</td>
<td>q_{\nu_e}</td>
<td>\lesssim 1.5 \times 10^{-12} e$</td>
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<tr>
<td>$</td>
<td>q_{\nu}\tau</td>
<td>\lesssim 4 \times 10^{-4} e$</td>
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<tr>
<td>$</td>
<td>q_{\nu}\tau</td>
<td>\lesssim 3 \times 10^{-4} e$</td>
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<tr>
<td>$</td>
<td>q_{\nu}</td>
<td>\lesssim 6 \times 10^{-14} e$</td>
</tr>
<tr>
<td>$</td>
<td>q_{\nu}</td>
<td>\lesssim 2 \times 10^{-14} e$</td>
</tr>
</tbody>
</table>


electromagnetic interactions

\( \nu \) decay, Cherenkov radiation

\( \nu \) decay in plasma

\( e / N \) Scattering

\( \nu_L \) Spin precession

\( \nu_R \) external source
Astrophysical bound on $\mu_{\nu}$ comes from cooling of red giant stars by plasmon decay $\gamma^* \rightarrow \nu \nu$

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

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

$$\Gamma_{\gamma \rightarrow \nu \bar{\nu}} = \frac{\mu^2}{24\pi} \frac{(\omega^2 - k^2)^2}{\omega} = O \text{ in vacuum} \quad \omega = k$$

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

Energy-loss rate per unit volume

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

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

distribution function of plasmons
Astrophysical bound on $\mathcal{M}_\nu$

Magnetic moment plasmon decay enhances the Standard Model photo-neutrino cooling by photon polarization tensor

more fast star cooling

In order not to delay helium ignition (≤5% in $Q$)

... best astrophysical limit on magnetic moment...

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

G. Raffelt, PRL 1990

$\mu^2 \rightarrow \sum_{a,b} \left( |\mu_{a,b}|^2 + |\epsilon_{a,b}|^2 \right)$
New mechanism of electromagnetic radiation

A. Egorov, A. Lobanov, A. Studenikin,

Lobanov, Studenikin,

Studenikin, A. Ternov,

A. Grigoriev, Studenikin, Ternov,

Studenikin,

Grigoriev, A. Lokhov, Studenikin, Ternov,
Nuovo Cim. 35 C (2012) 57
Spin light of neutrino in astrophysical environments

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Published November 16, 2017
**SLν in neutron matter of real astrophysical objects [4]**

- **Plasma effects [5]**
  - Photon dispersion with plasmon mass in the degenerate electron gas:
    \[ \omega = \sqrt{k^2 + m_p^2} \]
    
    \[ m_p = \left( \frac{2\alpha}{\pi} \right)^{1/2} \mu_e \approx 8.87 \times \left( \frac{n_e}{10^{24} \text{ cm}^{-3}} \right)^{1/3} \text{ MeV} \]
  
  - Threshold condition for the SLν [10]
    \[ (I_f - n_0 n_\nu) \]
  
  - Neutron matter:
    (antineutrons act)
    \[ \frac{\tilde{n}_e}{E_e} \approx 5 \times 10^{23} \text{ eV} \]
    \[ n_\nu = 10^{24} \text{ cm}^{-3}, \quad Y_e = 0.1 \]
  
  - Mean photon energy near the threshold:
    \[ \langle \omega \rangle = T \approx p \approx E_0 \]

For most favorable conditions as low density of the charged matter component is needed as possible.

**W-boson production**
\[ \nu_e + e^- \to W^- \]

W-boson threshold energy
\[ E_W = \frac{m_W^2}{4E_e} \approx 5.77 \times \left( \frac{10^{-8} \text{ cm}^{-3}}{Y_e n_\nu} \right)^{1/2} \text{ TeV} \]

- Electron antineutrinos: t-channel interaction with matter through W-boson, importance of the propagator effects
- \( \mu \) and \( \tau \) antineutrinos: only t-channel interaction with matter through Z-boson, no propagator effects

The SLν is allowed if neutrino energy is greater than the W-boson threshold \( E_W \).

Neutrino lifetime with respect to the SLν for most optimistic set of parameters:
\[ \tau_{SL\nu} = 10^{-5} - 10^{-7} \text{ s}, \quad \text{for} \quad n_\nu = 10^{21} - 10^{22} \text{ cm}^{-2} \]

---

**The SLν in short Gamma-Ray Bursts (SGRBs)**

**Factors for best SLν generation efficiency**
- High neutrino energy and density
- High background neutral matter density
- Low density of the charged matter component
- Low temperature of the charged component
- Considerable extension of the medium

**SLν radiation by ultra high-energy neutrino in the diffuse neutrino wind blown during neutron stars merger**

---

**Matter characteristics [6]:**
- Neutrinos
  \[ n_\nu \sim 10^{32} \text{ cm}^{-3} \]
  \[ n_e \sim 3 \times 10^{25} \text{ cm}^{-3} \]
- Electrons
  \[ Y_e = 0.01 \]
  \[ T = 0.1 \text{ MeV} \]
  \[ \rho = 5 \times 10^3 \text{ g/cm}^3 \]

**Radiation time**
\[ \tau_{SL\nu} \approx 5.4 \times 10^5 \left( \frac{10^{-11} \mu_B}{\mu} \right)^2 \left( \frac{10^{23} \text{ cm}^{-3}}{n_\nu} \right)^{1/2} \left( \frac{1 \text{ PeV}}{E} \right) \text{s} \]

**Neutrino parameters:**
- \( \mu \) and \( \tau \) antineutrinos: only t-channel interaction with matter through Z-boson, no propagator effects
- Neutrino energy
  \[ E_\nu \sim 10^{12} - 10^{18} \text{ eV} \]

**Radiation time**
\[ \tau_{SL\nu} \approx 6.4 \times 10^{11} - 10^{17} \text{ s} = 2 \times 10^4 - 10^{10} \text{ years} \]
... astrophysical bound on millicharge $q_\nu$ from energy quantization in rotating magnetized media


Millicharged $\nu$ in rotating magnetized matter


Modified Dirac equation for $\nu$ wave function

$$
\left( \gamma_\mu (p^\mu + q_0 A^\mu) - \frac{1}{2} \gamma_\mu (c_l + \gamma_5) f^\mu - \frac{i}{2} \mu \sigma_{\mu\nu} F^{\mu\nu} - m \right) \Psi (x) = 0
$$

external magnetic field

$$
V_m = \frac{1}{2} \gamma_\mu (c_l + \gamma_5) f^\mu
$$

$c_l = 1$

matter potential

$$
f^\mu = -G n_m (1, -\epsilon y \omega, \epsilon x \omega, 0)
$$

rotating matter

rotation angular frequency
Energy is quantized in rotating matter

\[ p_0 = \sqrt{p_3^2 + 2N \left| 2Gn_n \omega - \epsilon q_u B \right| + m^2 - Gn_n - q\phi} \]

\( N = 0, 1, 2, \ldots \)

- Matter rotation frequency
- Scalar potential of electric field

Energy is quantized in rotating matter like electron energy in magnetic field (Landau energy levels):

\[ p_0^{(e)} = \sqrt{m_c^2 + p_3^2 + 2\gamma N}, \quad \gamma = eB, \quad N = 0, 1, 2, \ldots \]
Star Turning mechanism (νST)


Escaping millicharged νs move on curved orbits inside magnetized rotating star and feedback of effective Lorentz force should effect initial star rotation

New astrophysical constraint on ν millicharge

\[
\left| \frac{\Delta \omega}{\omega_0} \right| = 7.6 \varepsilon \times 10^{18} \left( \frac{P_0}{10 \text{ s}} \right) \left( \frac{N_\nu}{10^{58}} \right) \left( \frac{1.4 M_\odot}{M_\odot} \right) \left( \frac{B}{10^{14} \text{ G}} \right)
\]

\[
|\Delta \omega| < \omega_0
\]

...to avoid contradiction of νST impact with observational data on pulsars...

\[
q_0 < 1.3 \times 10^{-19} e_0
\]

...best astrophysical bound...
\( m_v \neq 0 \)

electromagnetic properties

magnetic moment
Main steps in $\nu$ oscillations

1. $\nu_e \leftrightarrow \bar{\nu}_e$, B. Pontecorvo, 1957
2. $\nu_e \leftrightarrow \nu_\mu$, S. Maki, M. Nakagawa, S. Sakata, 1962
3. $\nu_e \leftrightarrow \nu_\mu$, L. Wolfenstein, 1978
4. $\nu_e \leftrightarrow \nu_\mu$, S. Mikheev, A. Smirnov, 1985

- resonances in $\nu$ flavour oscillations $\Rightarrow$ MSW-effect, solution for $\nu_0$-problem

5. $\nu_{eL} \leftrightarrow \nu_{eR}$, A. Cisneros, 1979
6. $\nu_{eL} \leftrightarrow \nu_{eR}$, E. Akhmedov, 1988

- resonances in $\nu$ spin (spin-flavour) oscillations in matter

61 years! early history of $\nu$ oscillations

30 years!

Bruno Pontecorvo 1913-1993

only in and matter at rest
spin and spin-flavour oscillations in $\mathbf{B}$

Consider two different neutrinos: $\nu_{eL}$, $\nu_{\mu R}$, $m_L \neq m_R$

with magnetic moment interaction

$$L \sim \bar{\nu}_\sigma \chi_{\nu} F^{\lambda\rho} \nu' = \bar{\nu}_L \sigma_{\lambda\rho} F^{\lambda\rho} \nu_R' + \bar{\nu}_R \sigma_{\lambda\rho} F^{\lambda\rho} \nu_L'. $$

Twisting magnetic field $B = |\mathbf{B}_\perp|e^{i\phi(t)}$ or solar $\nu$ etc...

evolution equation

$$i \frac{d}{dt} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} = H \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

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

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

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

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

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

- Resonance amplification of oscillations in matter:
  - $\Delta_{LR} \rightarrow 0$ $\Rightarrow$ $\sin^2 \beta \rightarrow 1$

In magnetic field

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

\[
\begin{align*}
  i \frac{d}{dz} \nu_{eL} &= -\frac{\Delta_{LR}}{4E} \nu_{eL} + \mu_{e\mu} B \nu_{\mu R} \\
  i \frac{d}{dz} \nu_{\mu L} &= \frac{\Delta_{LR}}{4E} \nu_{\mu L} + \mu_{e\mu} B \nu_{eR}
\end{align*}
\]
new phenomena in $\nu$ oscillations

spin and spin-flavour oscillations in transversal matter currents

Studenikin (2004)
Neutrino in Electromagnetic Fields and Moving Media

A. I. Studenikin

Moscow State University, Vorob'evy gory, Moscow, 119899 Russia

Received March 26, 2003; in final form, August 12, 2003

Abstract—The history of the development of the theory of neutrino-flavor and neutrino-spin oscillations in electromagnetic fields and in a medium is briefly surveyed. A new Lorentz-invariant approach to describing neutrino oscillations in a medium is formulated in such a way that it makes it possible to consider the motion of a medium at an arbitrary velocity, including relativistic ones. This approach permits studying neutrino-spin oscillations under the effect of an arbitrary external electromagnetic field. In particular, it is predicted that, in the field of an electromagnetic wave, new resonances may exist in neutrino oscillations. In the case of spin oscillations in various electromagnetic fields, the concept of a critical magnetic-field component strength is introduced above which the oscillations become sizable. The use of the Lorentz-invariant formalism in considering neutrino oscillations in moving matter leads to the conclusion that the relativistic motion of matter significantly affects the character of neutrino oscillations and can radically change the conditions under which the oscillations are resonantly enhanced. Possible new effects in neutrino oscillations are discussed for the case of neutrino propagation in relativistic fluxes of matter.

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From neutrino electromagnetic interactions to spin oscillations in transversal matter currents, PoS NOW2016 (2017) 070

General types non-derivative interaction with external fields

$$-\mathcal{L} = g_s s(x) \bar{\nu} \nu + g_p \pi(x) \bar{\nu} \gamma^5 \nu + g_V V^\mu(x) \bar{\nu} \gamma_\mu \nu + g_A A^\mu(x) \bar{\nu} \gamma_\mu \gamma^5 \nu +$$
$$+ \frac{g_t}{2} T^{\mu\nu} \bar{\nu} \sigma_{\mu\nu} \nu + \frac{g_t'}{2} \Pi^{\mu\nu} \bar{\nu} \sigma_{\mu\nu} \gamma^5 \nu,$$

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:

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

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

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

$$\vec{M} = \gamma (A^0 \vec{\beta} - \vec{A})$$

$$\vec{P} = -\gamma [\vec{\beta} \times \vec{A}],$$
Neutrino in Electromagnetic Fields and Moving Media

A. I. Studenikin*

Moscow State University, Vorob’evy gory, Moscow, 119899 Russia

Received March 26, 2003; in final form, August 12, 2003

Abstract—The history of the development of the theory of neutrino-flavor and neutrino-spin oscillations in electromagnetic fields and in a medium is briefly surveyed. A new Lorentz-invariant approach to describing neutrino oscillations in a medium is formulated in such a way that it makes it possible to consider the motion of a medium at an arbitrary velocity, including relativistic ones. This approach permits studying neutrino-spin oscillations under the effect of an arbitrary external electromagnetic field. In particular, it is predicted that, in the field of an electromagnetic wave, new resonances may exist in neutrino oscillations. In the case of spin oscillations in various electromagnetic fields, the concept of a critical magnetic-field-component strength is introduced above which the oscillations become sizable. The use of the Lorentz-invariant formalism in considering neutrino oscillations in moving matter leads to the conclusion that the relativistic motion of matter significantly affects the character of neutrino oscillations and can radically change the conditions under which the oscillations are resonantly enhanced. Possible new effects in neutrino oscillations are discussed for the case of neutrino propagation in relativistic fluxes of matter.

© 2004 MAIK “Nauka/Interperiodica”.
Consider

\[ \nu_{eL} \rightarrow \nu_{eR}, \quad \nu_{eL} \rightarrow \nu_{\mu R} \]

\[ P(\nu_i \rightarrow \nu_j) = \sin^2(2\theta_{\text{eff}}) \frac{\sin^2 \frac{\pi x}{L_{\text{eff}}}}{L_{\text{eff}}}, \quad i \neq j \]

\[ L_{\text{eff}} = \frac{2\pi}{\sqrt{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}} \]

\[ \sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}, \quad \Delta_{\text{eff}}^2 = \frac{\mu}{\gamma_{\nu}} \left| M_{0||} + B_{0||} \right|. \]

\[ E_{\text{eff}} = \mu \left| B_{\perp} + \frac{1}{\gamma_{\nu}} M_{0\perp} \right|. \]

---

A. Studenikin, "Status and perspectives of neutrino magnetic moments”

interaction of neutrino with matter

transversal matter current

\[ \hat{\mathbf{M}}_0 = \gamma_{\nu} g_n n_e \left( \beta_{\nu} (1 - \beta_{\nu} \bar{\mathbf{v}}_e) - \frac{1}{\gamma_{\nu}} \bar{\mathbf{v}}_e \right), \]

\[ \gamma_{\nu} = \frac{E_{\nu}}{m_{\nu}}. \]

\[ \rho = \frac{G_F}{2\mu_{\nu}\sqrt{2}} (1 + 4\sin^2 \theta_W) \]

where
ELEMENTARY PARTICLES AND FIELDS

Theory


Neutrino in Electromagnetic Fields and Moving Media

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Received March 26, 2003; in final form, August 12, 2003

The possible emergence of neutrino-spin oscillations (for example, $\nu_{eL} \leftrightarrow \nu_{eR}$) owing to neutrino interaction with matter under the condition that there exists a nonzero transverse current component or matter polarization (that is, $M_{0\perp} \neq 0$) is the most important new effect that follows from the investigation of neutrino-spin oscillations in Section 4. So far, it has been assumed that neutrino-spin oscillations may arise only in the case where there exists a nonzero transverse magnetic field in the neutrino rest frame.
... quantum treatment new phenomena in $\nu$ oscillations

$\nu$ spin and spin-flavour oscillations in transversal matter currents

Studenikin (2004)
... the effect of helicity conversions and oscillations induced by transversal matter currents has been recently confirmed:

- J. Serreau and C. Volpe,

- V. Ciriglianoa, G. M. Fuller, and A. Vlasenko,

- A. Kartavtsev, G. Raffelt, and H. Vogel,

- A. Dobrynina, A. Kartavtsev, and G. Raffelt,
Conclusions
Electromagnetic Properties of $\nu$
(effects of magnetic moments)

C. Giunti, A. Studenikin,
"$\nu$ electromagnetic interactions: A window to new physics", Rev. Mod. Phys., 2015

Alexander Studenikin

1 $\nu$EP theory - $\nu$ vertex function

$$\Lambda_{\mu}(q) = f_Q(q^2)\gamma_{\mu} + f_M(q^2)i\sigma_{\mu\nu}q^\nu + f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A(q^2)(q^2\gamma_{\mu} - q_{\mu}q^5)\gamma_5,$$

form factors $f_X(q^2)$ at $q^2 = 0$
static EP of $\nu$

electric charge moment
magnetic moment

electric moment
anapole moment

Hermiticity and discrete symmetries of EM current put constraints on form factors

$$\langle \nu(p')|j_{\mu}^{EM}|\nu(p)\rangle = \bar{u}(p')\Lambda_{\mu}(q)u(p)$$

Dirac $\nu$ Majorana

$$q_{\text{if}}$$
$$\mu_{\text{if}}$$
$$\varepsilon_{\text{if}}$$
$$a_{\text{if}}$$

$CPT +$ charge conservation

Fujikawa & Shrock, 1980

2 $\mu_D^{ij} = \frac{3e_0G_Fm_j}{8\sqrt2\pi^2} \approx 3.2 \times 10^{-19} \mu_B$$

much greater values are Beyond Minimally Extended SM

transition moments $\mu_{i\neq f}$ are GIM suppressed

3 experimental bounds

$\mu_{\nu}^{\text{eff}} < 2.8 \times 10^{-11} \mu_B$

GEMMA Coll. 2012

Borexino Coll. 2017

Astrophysics, Raffelt ea 1988

Arcoa Dias ea 2015

$\nu$ scattering

AS '14, Chen ea '14

reactor $\nu$ scattering

AS '14 (astrophysics)

neutrality of matter
Effects of $\nu$ magnetic moment: spin precession and oscillations in $B_\perp$


New effects reported at ICHEP 2018

1. Electromagnetic interactions and oscillations of ultrahigh-energy cosmic $\nu$ in interstellar space

$$P_{\nu_e^L \rightarrow \nu_e^L}(x) = [1 - P_{\nu_e^L \rightarrow \nu_e^R}(x)] \sin^2 2\theta \sin^2 \left(\frac{\pi x}{L_{\text{vac}}}\right)$$

2. $\nu$ flavour, spin and spin-flavour oscillations and consistent account for a constant magnetic field

$$P_{\nu_e^L \rightarrow \nu_e^R} = \left\{ \sin (\mu_+ B_\perp t) \cos (\mu_- B_\perp t) + \cos 2\theta \sin (\mu_- B_\perp t) \cos (\mu_+ B_\perp t) \right\}^2 - \sin^2 2\theta \sin(\mu_1 B_\perp t) \sin(\mu_2 B_\perp t) \sin^2 \frac{\Delta m^2}{4p} t$$

3. $\nu$ spin and spin-flavour oscillations engendered by transversal matter current

4. Spin-light of $\nu$ in Gamma-Ray Bursts

Kouzakov & AS, poster # 686
PRD 96 (2017)
$$L_B = \frac{\pi}{\mu_\nu B}$$
$$P_{\nu_e^L \rightarrow \nu_e^R}(x) = \sin^2 \left(\frac{\pi x}{L_B}\right)$$

amplitude of flavour oscillations is modulated by $\mu_\nu B$ frequency

Popov & AS, poster # 754 arXiv: 1803.05766
probability of spin oscillations depends on $\Delta m^2$

Pustoshny & AS, poster # 697 arXiv: 1801.08911
Studenikin 2004, 2017

transversal matter currents $j_\perp$ do change $\nu$ helicity

new mechanism of EM radiation by $\nu$

Grigoriev, Lokhov, Studenikin, Ternov, poster # 775

“SL $\nu$ in astrophysical environments”
$\mu_\nu$, interactions could have important effects in astrophysical and cosmological environments.

Future high-precision observations of supernova $\nu$ fluxes (for instance, in JUNO experiment) may reveal effect of collective spin-flavour oscillations due to Majorana.

$\mu_\nu \sim 10^{-21} \mu_B$

electromagnetic properties: future prospects

- new constraints on $\mu_\nu$ (and $q_\nu$) from GEMMA and Borexino

- charge radius in $\nu$-$e$ elastic scattering can’t be considered as a shift $g_V \to g_V + \frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2 \theta_W$, there are also contributions from flavor-transition charge radii –

- new analysis (re-analysis) of data is needed

- need for inclusion of $\nu_{em}$ interactions in analysis of supernovae $\nu$ fluxes
Thank you
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

Bounds depend on
- modeling of 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.
**Data Set**

- **I phase** – 5184 h ON, 1853 h OFF
  \[ \mu_v < 5.8 \times 10^{-11} \mu_B \]

- **II phase** – 6798 h ON, 1021 h OFF

- **I+II** – 11982 h ON, 2874 h OFF
  \[ \mu_v < 3.2 \times 10^{-11} \mu_B \]

- **III phase** – 6152 h ON, 1613 h OFF

- **I+II+III** – 18134 h ON, 4487 h OFF
  \[ \mu_v < 2.9 \times 10^{-11} \mu_B \]

GEMMA background conditions

- γ-rays were measured with Ge detector. The main sources are: $^{137}\text{Cs}$, $^{60}\text{Co}$, $^{134}\text{Cs}$.
- Neutron background was measured with $^3\text{He}$ counters, i.e., thermal neutrons were counted. Their flux at the facility site turned out to be 30 times lower than in the outside laboratory room.
- Charged component of the cosmic radiation (muons) was measured to be 5 times lower than outside.
Experimental sensitivity

\[ \mu_V \propto \frac{1}{\sqrt{N_V}} \left( \frac{B}{mt} \right)^{\frac{1}{4}} \]

- \( N_V \): number of signal events expected
- \( B \): background level in the ROI
- \( m \): target (detector) mass
- \( t \): measurement time

\[ N_V \sim \varphi_V \left( \sim \text{Power} \div r^2 \right) \]
\[ \sim \left( \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{max}} * T_{\text{min}}} \right)^{1/2} \]

**GEMMA I**

- \( \varphi_V \sim 2.7 \times 10^{13} \text{ } \nu / \text{cm}^2 / \text{s} \)
- \( t \sim 4 \text{ years} \)
- \( B \sim 2.5 \text{ keV}^{-1} \text{ kg}^{-1} \text{ day}^{-1} \)
- \( m \sim 1.5 \text{ kg} \)
- \( T_{\text{th}} \sim 2.8 \text{ keV} \)

\[ \mu_V \leq 2.9 \times 10^{-11} \mu_B \]

... courtesy of D. Medvedev...
Sensitivity of future experiments

$B = 0.2 \text{ 1/keV/kg/day (background level in ROI)}$

<table>
<thead>
<tr>
<th>Mass, kg</th>
<th>Threshold, keV</th>
<th>Sensitivity, $10^{-12}\mu_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>0.4</td>
<td>5.8</td>
</tr>
<tr>
<td>10</td>
<td>0.4</td>
<td>4.7</td>
</tr>
<tr>
<td>20</td>
<td>0.4</td>
<td>4.0</td>
</tr>
<tr>
<td>4.5</td>
<td>0.3</td>
<td>5.6</td>
</tr>
<tr>
<td>10</td>
<td>0.3</td>
<td>4.6</td>
</tr>
<tr>
<td>20</td>
<td>0.3</td>
<td>3.9</td>
</tr>
</tbody>
</table>

...courtesy of D.Medvedev...
... the obtained constraint on neutrino millicharge $q_\nu$

- rough order-of-magnitude estimation,
- exact values should be evaluated using the corresponding statistical procedures

this is because limits on neutrino $\mu_\nu$ are derived from GEMMA experiment data taken over an extended energy range 2.8 keV --- 55 keV, rather than at a single electron energy-bin at threshold

Difference between reactor on and off electron recoil energy spectra (with account for weak interaction contribution) normalized by theoretical electromagnetic spectra.


- Limit evaluated using statistical procedures is of the same order as previously discussed.

- $|q_{\nu}| < 2.7 \times 10^{-12} e_0$ (90% C.L.)


V. Brudanin, D. Medvedev, A. Starostin, A. Studenikin: “New bounds on neutrino electric millicharge from GEMMA experiment on neutrino magnetic moment”, arXiv: 1411.2279
Radiative decay
3.7 Neutrino radiative decay

\[ \nu_i \rightarrow \nu_j + \gamma \]

\[ m_i > m_j \]

\[ L_{\text{int}} = \frac{1}{2} \bar{\nu}_i \sigma_{\alpha\beta} (\sigma_{ij} + \epsilon_{ij} \gamma_5) \nu_j F^{\alpha\beta} + h.c. \]

Radiative decay rate

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

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

\[ \mu_{\text{eff}}^2 = |\mu_{ij}|^2 + |\epsilon_{ij}|^2 \]

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

**Petkov 1977; Zatsepin, Smirnov 1978; Bilenky, Petkov 1987; Pal, Wolfenstein 1982**

\[ Raffelt 1999 \]

\[ Kolb, Turner 1990; Ressell, Turner 1990 \]
3.8 Neutrino radiative two-photon decay

\[ \nu_i \rightarrow \nu_j + \gamma + \gamma \]

\[ m_i > m_j \]

**fine structure constant**

\[ \Gamma_{\nu_i \rightarrow \nu_j + \gamma + \gamma} \sim \frac{\alpha_{QED}}{4\pi} \Gamma_{\nu_i \rightarrow \nu_j + \gamma} \]

… there is no GIM cancellation…

*Nieves, 1983; Ghosh, 1984*

… can be of interest for certain range of \( \nu \) masses…
quantum states in dense magnetized matter

... new effect of...

Spin Light of
in matter

$SL\nu$

$\Rightarrow$

energy quantization in rotating matter

... phenomenological consequences in astrophysics (pulsars)

in matter treated within «method of exact solutions»

(Dirac equation with matter potential for $\nu$)
2015
the YEAR of LIGHT ...
(United Nations)

I. Balantsev, A. Studenikin


$SL\nu \rightarrow SLe\nu$
Spin light of electron in dense neutrino fluxes $S\nu_e$

I. Balantsev, A. Studenikin, I

Electrons in background matter potential (ultra-relativistic $\nu$ flux)

$$f^\mu = G(n, 0, 0, n)$$

$$n = \frac{n_e + n_\mu + n_\tau}{3}$$

$$\left( \gamma_\mu p^\mu + \gamma_\mu \frac{c + \delta_e \gamma^5}{2} f^\mu - m \right) \Psi(x) = 0$$

$$c = \delta_e - 12 \sin^2 \theta_W$$

$$\delta_e = \frac{n_\mu + n_\tau - n_e}{n}$$
Energy spectrum of electrons in relativistic neutrino flux

Fig. 1. The dependence of the electron energies in two different spin states, $E_+(p)$ and $E_-(p)$, on the momentum component $p_3$.

$$E_s^\varepsilon(p) = \varepsilon \sqrt{m^2 + p_\perp^2 + (p_3 + A)^2} - A$$

$$A = \frac{G_n}{2}(c - s\delta), \quad \delta = |\delta_e|$$

**Wave function of electrons**

$$\psi_i(\mathbf{r}, t) = e^{i(-E_+ t + \mathbf{p}\mathbf{r})} \tilde{\psi}_i,$$

$$\psi_f(\mathbf{r}, t) = e^{i(-E_- t + \mathbf{p}\mathbf{r})} \tilde{\psi}_f$$

$$\tilde{\psi}_i = \frac{1}{L^3 C_+} \begin{pmatrix} 0 \\ m \\ p_\perp e^{-i\phi} \\ E_+ - p_3 \end{pmatrix}, \quad \tilde{\psi}_f = \frac{1}{L^3 C_-} \begin{pmatrix} E_- - p_3 \\ -p_\perp e^{i\phi} \\ m \\ 0 \end{pmatrix}$$

$$C_\pm = \sqrt{m^2 + p_\perp^2 + (E_\pm - p_3)^2}$$
in case of relativistic electrons in dense fluxes at supernovae environment


each second a reasonable part of flux energy can be transformed to gamma-rays


new mechanism of electromagnetic radiation in the Year of Light