Neutrino magnetic moment
and millicharge: new limits
and phenomenology

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Neutrino
Oscillation Workshop,
Conca Specchilla,
Otranto, Italy
13/09/2014

Moscow State
University
&
JINR - Dubna
The past two years since Neutrino Oscillation Workshop 2012 … has been celebrated by spectacular step further in High Energy Physics …
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

(as it has been fixed by ICHEP in Valencia, July 2014)
What is next?
unique particle that is precursor of BSM physics

BEH physics $\Rightarrow$ BSM physics
electromagnetic properties

(\text{short review})

m_{\nu} \neq 0


electromagnetic properties
(new limits and
astrophysical consequences)


electromagnetic properties
(up to now nothing has been seen)

is a tool for studying

Beyond
Extended
Standard
Model physics…

BEH physics \Rightarrow BSM physics \Rightarrow BESM physics
... a tool for studying physics Beyond Standard Model...

\[ m_\nu \neq 0 \]

**Theory (Standard Model with \( \nu_R \))**

\[ \mu_\nu = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \sim 3 \times 10^{-19} \mu_B \left( \frac{m_\nu}{1\text{eV}} \right), \quad \mu_B = \frac{e}{2m_e} \]

magnetic moment

... much greater values are desired for astrophysical or cosmology visualization of \( \mu_\nu \)

... hopes for physics BESM ...
Astrophysical bounds

\[ \mu_\nu < 3 \times 10^{-12} \mu_B \]

G. Raffelt (1990)

Theory (Standard Model with \( \nu_R \))

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

Lee Shrock, 1977; Fujikawa Shrock, 1980

Limits from reactor \( \nu-e \) scattering experiments

A. Beda et al. (GEMMA Coll.) (2012):

\[ \mu_\nu < 2.9 \times 10^{-11} \mu_B \]
... a bit of electromagnetic properties theory ...
The electromagnetic vertex function is defined by:

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

Matrix element of the 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 \( l_{\mu} \).

Lorentz covariance (1) and electromagnetic gauge invariance (2):

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

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

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

1) \[ CP \text{ invariance} + \text{hermiticity} \implies f_E = 0 \]
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 \[ \text{three form factors are real:} \quad Im f_Q = Im f_M = Im f_A = 0 \]

EM properties a way to distinguish Dirac and Majorana

1) from CPT invariance (regardless \( CP \text{ or } \bar{CP} \)).

\[ f_Q = f_M = f_E = 0 \]

...as early as 1939, W.Pauli...
In general case matrix element of $J_{EM}^\mu$ can be considered between different initial $\psi_i(p)$ and final $\psi_j(p')$ states of different masses $p^2 = m_i^2$, $p'^2 = m_j^2$:

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

and

$$\Lambda_{\mu}(q) = \left( f_Q(q^2)_{ij} + f_A(q^2)_{ij}\gamma_5 \right) (q^2 \gamma_\mu - q_\mu \gamma_1) +$$

$$f_M(q^2)_{ij} i\sigma_{\mu\nu} q^\nu + f_E(q^2)_{ij} \sigma_{\mu\nu} q^\nu \gamma_5$$

Form factors are matrices in $\nu$ mass eigenstates space.

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).

---

... beyond SM...

---

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

1) CP invariance + hermiticity

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

or

$$\mu_{ij}^M = 0$$ and $$\epsilon_{ij}^M = 2\epsilon_{ij}^D$$
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 $q^2 \to 0$ they can have nonvanishing values.

$\mu_\nu = f_M(0) \quad \text{\nu magnetic moment}$

$\epsilon_\nu = f_E(0) \quad \text{\nu electric moment}$
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 $\mu_\nu$

Cross-section:

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

where the Standard Model contribution

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

$T$ is the electron recoil energy and

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

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

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

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}

g_A \rightarrow -g_A

to incorporate charge radius: $g_V \rightarrow g_V + \frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2 \theta_W$
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...
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)
\[ \mu_\nu \leq 5.4 \times 10^{-11} \mu_B \]

…was considered as the world best constraint…

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

based on first release of BOREXINO data

Montanino, Picariello, Pulido, PRD 2008

…attempts to improve bounds
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


… quite realistic prospects of the near future

$$\mu_\nu \sim 1 \times 10^{-11} \mu_B$$

(V. Brudanin, A. Starostin, priv. comm.)
... quite recent claim that $\nu$-e cross section should be increased by Atomic Ionization Effect:

$$\nu + (A, Z) \rightarrow \nu' + (A, Z)^+ + e^-$$

↓ recombination

$$(A, Z) + \gamma$$

H. Wong et al. (TEXONO Coll.), PRL 105 (2010) 061801

(\(\nu\) scattering on bound \(e\))

... an interesting hypothetical possibility to improve bounds...

... new bounds...
K.Kouzakov, A.Studenikin,
- “Magnetic neutrino scattering on atomic electrons revisited”
  Phys.Lett. B 105 (2011) 061801,
- “Electromagnetic neutrino-atom collisions: The role of electron binding”

K.Kouzakov, A.Studenikin, M.Voloshin,
- “Neutrino electromagnetic properties and new bounds on neutrino magnetic moments”
- “Neutrino-impact ionization of atoms in search for neutrino magnetic moment”
  Phys.Rev.D 83 (2011) 113001
- “On neutrino-atom scattering in searches for neutrino magnetic moments”
- “Testing neutrino magnetic moment in ionization of atoms by neutrino impact”
  JETP Lett. 93 (2011) 699

M.Voloshin,
- “Neutrino scattering on atomic electrons in search for neutrino magnetic moment”
No important effect of Atomic Ionization on cross section in $\mu$ experiments once all possible final electronic states accounted for …free electron approximation …

### Experimental limits for different effective $\mu_e$

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

C. Giunti, A. Studenikin, arXiv: 1403.6344
... if one trusts a precursor for BESM physics ...
A remark on electric charge of a neutrino... Beyond Standard Model...

- Neutrality $Q=0$ is attributed to gauge invariance and anomaly cancellation constraints.

...General proof:

- In SM:
  
  $Q = I_3 + \frac{Y}{2}$

- In SM (without $\nu_R$) triangle anomalies cancelation constraints lead to certain relations among particle hypercharges $Y$, that is enough to fix all $Y$ so that they, and consequently $Q$, are quantized.

$Q=0$ is proven also by direct calculation in SM within different gauges and methods.

...However, strict requirements for $Q$ quantization may disappear in extensions of standard $SU(2)_L \times U(1)_Y$ EW model if $\nu_R$ with $Y \neq 0$ are included: in the absence of $Y$ quantization electric charges $Q$ gets dequantized.
## Experimental limits for different effective $q_v$

<table>
<thead>
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<tr>
<td>$</td>
<td>q_{\nu_\tau}</td>
<td>\lesssim 3 \times 10^{-4} e$</td>
</tr>
<tr>
<td>$</td>
<td>q_{\nu_\tau}</td>
<td>\lesssim 4 \times 10^{-4} e$</td>
</tr>
<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>
<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>
</tr>
<tr>
<td>$</td>
<td>q_{\nu_e}</td>
<td>\lesssim 1.5 \times 10^{-12} e$</td>
</tr>
</tbody>
</table>
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 $\mu_\nu$

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

Constraints on $\mu_\nu$ from GEMMA: Constraints on $q_\nu$

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

2015 (expected) $\mu_\nu^a \sim 1.5 \times 10^{-11} \mu_B \ (T = 1.5 \text{ keV})$

2018 (expected) $\mu_\nu^a \sim 0.9 \times 10^{-12} \mu_B \ (T = 350 \text{ eV})$

... no observable effects of New Physics

$\left| q_\nu \right| < 1.5 \times 10^{-12} e_0$

$\left| q_\nu \right| < 3.7 \times 10^{-13} e_0$

$\left| q_\nu \right| < 1.8 \times 10^{-13} e_0$
... 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 $\mathcal{M}_\nu$ 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

- limit evaluated using statistical procedures

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

is of the same order as previously discussed

**Electromagnetic Interactions**

**ν decay, Cherenkov radiation**

**γ decay in plasma**

**e/N Scattering**

**Spin precession**

**νL** → **γ** → **νR**

**external source**
New mechanism of electromagnetic radiation

"Spin light of neutrino in matter and electromagnetic fields"

\[ F_{\mu \nu}, G_{\mu \nu} \rightarrow \nu + \gamma \]

A. Lobanov, A. Studenikin,

Studenikin, A. Ternov,

A. Grigoriev, A. S., Ternov,

Studenikin,

A. Grigoriev, A. Lokhov,
A. Studenikin, A. Ternov,
Nuovo Cim. 35 C (2012) 57,
Neutrino – photon coupling

“Spin light of neutrino in matter”

... within the quantum treatment based on method of exact solutions ...

broad neutrino lines account for interaction with environment
4. Conclusions

We developed a detailed evaluation of the spin light of neutrino in matter accounting for effects of the emitted plasmon mass. On the base of the exact solution of the modified Dirac equation for the neutrino wave function in the presence of the background matter the appearance of the threshold for the considered process is confirmed. The obtained exact and explicit threshold condition relation exhibit a rather complicated dependance on the matter density and neutrino mass. The dependance of the rate and power on the neutrino energy, matter density and the angular distribution of the $SL\nu$ is investigated in details. It is shown how the rate and power wash out when the threshold parameter $a = m^2/4\bar{n}p$ approaching unity. From the performed detailed analysis it is shown that the $SL\nu$ mechanism is practically insensitive to the emitted plasmon mass for very high densities of matter (even up to $n = 10^{41} \text{cm}^{-3}$) for ultra-high energy neutrinos for a wide range of energies starting from $E = 1 \text{ TeV}$. This conclusion is of interest for astrophysical applications of $SL\nu$ radiation mechanism in light of the recently reported hints of $1 \div 10$ PeV neutrinos observed by IceCube [17].
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

\[ \Gamma_{\gamma \rightarrow \nu\bar{\nu}} = \frac{\mu^2}{24\pi} \frac{(\omega^2 - k^2)^2}{\omega} = 0 \text{ in vacuum} \quad \omega = k \]

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

Energy-loss rate per unit volume

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

distribution function of plasmons

G. Raffelt, PRL 1990
Astrophysical bound on $\mathcal{M}_\nu$.

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

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

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

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

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

G. Raffelt, PRL 1990
Energy quantization in rotating magnetized media

Balantsev, Popov, Studenikin,
Balantsev, Studenikin, Tokarev, Phys.Part.Nucl. 43 (2012), 727

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

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

Rotating matter

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

\[ p_0^{(e)} = \sqrt{m_e^2 + p_3^2 + 2\gamma N}, \quad \gamma = eB, \quad N = 0, 1, 2, \ldots \]
In quasi-classical approach quantum states in rotating matter motion in circular orbits due to effective Lorentz force

\[
R = \int_{0}^{\infty} \Psi^\dagger_L r \Psi_L \, dr = \sqrt{\frac{2N}{|2Gn_n\omega - \epsilon q_0 B|}}
\]

\[
F_{eff} = q_{eff} E_{eff} + q_{eff} [\beta \times B_{eff}]
\]

\[
q_{eff} E_{eff} = q_m E_m + q_0 E \\
q_{eff} B_{eff} = |q_m B_m + q_0 B| e_z
\]

\[
q_m = -G, \quad E_m = -\nabla n_n, \quad B_m = 2n_n\omega
\]


- matter induced “charge”, “electric” and fields “magnetic”
... we predict:

\[ E \sim 1 \text{ eV} \]

1) low-energy particles are trapped in circular orbits inside rotating neutron stars:

\[ R = \sqrt{\frac{2N}{G n \omega}} < R_{NS} = 10 \text{ km} \]

\[ R_{NS} = 10 \text{ km} \]
\[ n = 10^{37} \text{ cm}^{-3} \]
\[ \omega = 2\pi \times 10^3 \text{ s}^{-1} \]

2) rotating neutron stars as filters for low-energy relic:

\[ T_\nu \sim 10^{-4} \text{ eV} \]
... we predict:

3) high-energy \( \nu \) are deflected inside a rotating astrophysical transient sources (GRBs, SNe, AGNs)

absence of light in correlation with signal reported by ANTARES Coll.


Millicharged $\nu$ as star rotation engine

- Single $\nu$ generates feedback force with projection on rotation plane

$$ F = (q_0 B + 2 G n_n \omega) \sin \theta $$

- Single $\nu$ torque

$$ M_0(t) = \sqrt{1 - \frac{r^2(t) \Omega^2 \sin^2 \theta}{4}} Fr(t) \sin \theta $$

- Total $N_\nu$ torque

$$ M(t) = \frac{N_\nu}{4\pi} \int M_0(t) \sin \theta d\theta d\varphi $$

- Shift of star angular velocity

$$ |\Delta \omega| = \frac{5 N_\nu}{6 M_S} (q_0 B + 2 G n_n \omega_0) $$

$$ \Delta \omega = \omega - \omega_0 $$

Escaping $\nu$s move on curved orbits inside magnetized rotating star and feedback of effective Lorentz force should effect initial star rotation.

- **Star Turning mechanism (\nuST)**

- New astrophysical constraint on $\nu$ millicharge

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

- $|\Delta \omega| < \omega_0$ ! … to avoid contradiction of $\nu$ST impact with observational data on pulsars …

\[
q_0 < 1.3 \times 10^{-19} e_0
\] … best astrophysical bound …
Spin light of electron in dense neutrino fluxes

I. Balantsev, A. Studenikin, arXiv: 1405.6598

Dirac eq for $e$ in dense relativistic flux of $\nu$

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

- $c = \delta_e - 12 \sin^2 \theta_W$
- $\delta_e = \frac{n_\mu + n_\tau - n_e}{n}$

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

background matter ($\nu$ flux) potential
Conclusions
e.m. vertex function $\Rightarrow$ 4 form factors

charge dipole magnetic and electric

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

EM properties $\Rightarrow$ a way to distinguish Dirac and Majorana

- Limits from reactor $\nu-e$ scattering experiments (2012): $A.\text{Beda et al. (GEMMA Coll.)}$
- $\mu_\nu < 2.9 \times 10^{-11} \mu_B$
- $|q_\nu| < 1.5 \times 10^{-12} e_0$

- Limits from astrophysics, star cooling (1990): $G.\text{Raffelt}$
- $\mu_\nu < 3 \times 10^{-12} \mu_B$
- $q_0 < 1.3 \times 10^{-19} e_0$

- In extensions of SM: enhancement of magnetic moment, even electrically millicharged

- Standard Model with $\nu_R (m_\nu \neq 0)$: $M_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_e \sim 3 \times 10^{-19} \mu_B \left(\frac{m_{\nu_e}}{10^\text{eV}}\right)$
\[ 10^{-20} \mu_B \leq \mu \nu \leq 10^{-11} \mu_B \]

\( \mu \nu \) provides a tool for exploration possible physics beyond the Standard Model

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

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

any indication for non-trivial electromagnetic properties of \( \nu \) that could be obtained within reasonable time in the future, would give evidence for BESM physics

Beyond Extended Standard Model