Overview of neutrino electromagnetic properties
(theory, laboratory experiments, and astrophysical probes)

The 22nd International Workshop on Neutrinos from Accelerators
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Outline

1. (short) reminder of $\nu$ electromagnetic properties
   constraints on $\mu_\nu$, $d_\nu$, $q_\nu$ and $<r_\nu^2>$

2. effects of electromagnetic $\nu$ interactions in astrophysics

3. astrophysical probes of electromagnetic $\nu$

4. new effects in $\nu$oscillations related to electromagnetic $\nu$ interactions

5. ... two interesting new phenomena in $\nu$ spin (flavor) oscillations in moving and polarized matter and magnetic field
Neutrino electromagnetic interactions: A window to new physics

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INFN, Torino Section, Via P. Giuria 1, I-10125 Torino, Italy

Chemistry

Electromagnetic properties of neutrinos: New constraints and new effects in oscillations, arXiv: 2102.05468

Electromagnetic interactions: A window to new physics – II, PoS EPS-HEP2017 (2017) 137

Detailed review and discussion of electromagnetic properties

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.

CONTENTS

I. Introduction 531

II. Neutrino Masses and Mixing 532

A. Dirac neutrinos 533

B. Majorana neutrinos 533

C. Three-neutrino mixing 534

D. Neutrino oscillations 535

E. Status of three-neutrino mixing 538

F. Sterile neutrinos 540

III. Electromagnetic Form Factors 540

A. Dirac neutrinos 541

B. Majorana neutrinos 545

C. Massless Weyl neutrinos 546

IV. Magnetic and Electric Dipole Moments 547

A. Theoretical predictions for Dirac neutrinos 547

B. Theoretical predictions for Majorana neutrinos 549

C. Neutrino-electron elastic scattering 550

D. Effective magnetic moment 551

E. Experimental limits 553

F. Theoretical considerations 554

V. Radiative Decay and Related Processes 556

A. Radiative decay 556

B. Radiative decay in matter 559

C. Cherenkov radiation 560

D. Plasmon decay into a neutrino-antineutrino pair 561

E. Spin light 562

VI. Interactions with Electromagnetic Fields 563

A. Effective potential 564

B. Spin-flavor precession 565

C. Magnetic moment in a strong magnetic field 571

D. Beta decay of the neutron in a magnetic field 573

E. Neutrino pair production by an electron 574

F. Neutrino pair production by a strong magnetic field 575

G. Energy quantization in rotating media 576

VII. Charge and Anapole Form Factors 578

A. Neutrino electric charge 578

B. Neutrino charge radius 580

C. Neutrino anapole moment 583

VIII. Summary and Perspectives 585

Acknowledgments 585

References 585
Constraints on Neutrino Electric Millicharge from Experiments of Elastic Neutrino-Electron Interaction and Future Experimental Proposals Involving Coherent Elastic Neutrino-Nucleus Scattering

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In several extensions of the Standard Model of Particle Physics (SMPP), the neutrinos acquire electromagnetic properties such as the electric millicharge. Theoretical and experimental bounds have been reported in the literature for this parameter. In our work, we first carried out a statistical analysis by using data from reactor neutrino experiments, which include elastic neutrino-electron scattering (ENES) processes, in order to obtain both individual and combined limits on the neutrino electric millicharge (NEM). Then, we performed a similar calculation to show an estimate of the sensitivity of future experiments of reactor neutrinos to the NEM, by involving coherent elastic neutrino-nucleus scattering (CENNS). In the first case, the constraints achieved from the combination of several experiments are $-1.1 \times 10^{-13} < q_e \times 1.8 \times 10^{-13}$ (90% CL), and in the second scenario, we obtained the bounds $-1.8 \times 10^{-12} < q_e < 1.8 \times 10^{-14}$ (90% CL). As we will show here, these combined analyses of different experimental data can lead to stronger constraints than those based on individual analysis, where CENNS interactions would stand as an important alternative to improve the current limits on NEM.

1. Introduction

In the SMPP, the neutrinos are massless, electrically neutral, and only interact weakly with leptons and quarks. Nevertheless, the neutrino oscillation experiments show that neutrinos have mass and are also mixed [1–4]. Hence, the idea of extending the SMPP so as to explain the origin of neutrino mass. Different extensions of SMPP allow the neutrino to have properties such as magnetic and electric dipole moments as well as anapole moment and electric millicharge [5–7]. Even in the Standard Model, it is well-known that the neutrinos also can have nonzero charge radius, as shown in reference [8, 9]. Among these properties, the neutrino magnetic moment (NMM) has been quite studied in several research works, where different experimental constraints to this parameter were obtained, for instance, from reactor neutrino experiments [10–14], solar neutrinos [15, 16], and astrophysical measurements [17, 18]. The limits achieved for the NMM are around $10^{-15} \mu_B$, while the prediction of the simplest extension of the Standard Model, by including right-handed neutrinos, is $3.2 \times 10^{-14} \mu_B$ [19]. Furthermore, considering the representation of three active neutrinos, the magnetic moment is described by a $3 \times 3$ matrix whose components are the diagonal and transition magnetic moments. A complete analysis by considering the NMM matrix and using data from solar, reactor, and accelerator experiments was presented in reference [20, 21]. In addition to NMM, the study of the remainder form factors is also important as they are a tool to probe new physics. Among them, the NEM has also been under consideration in the literature, and several constraints have been found mainly from reactor experiments and astrophysical measurements. The most restrictive bound on NEM so far, $q_e \leq 3.0 \times 10^{-15}$, was obtained in [18] based on the neutrality of matter. A limit
9 presentations at TAUP 2021 dedicated to electromagnetic properties and related issues

1) A. Studenikin, Electromagnetic neutrino: The theory, laboratory experiments and astrophysical probes, oral presentation # 230

2) A. Popov, A. Studenikin, Effects of nonzero Majorana CP phases on oscillations of supernova neutrinos, poster # 231

3) K. Stankevich, V. Shakhov, A. Studenikin, Spin and spin-flavor oscillations due to neutrino charge radii interaction with an external environment, poster # 241

4) A. Lichkunov, R. Stankevich, A. Studenikin, M. Vialkov, Neutrino quantum decoherence engendered by neutrino decay to photons, familons and gravitons, poster # 242

5) V. Shakhov, U. Abdullaeva, A. Studenikin, A. Tsvirov, Dirac and Majorana neutrino oscillations in magnetized moving and polarized matter, poster # 245

6) Y. F. Li, Z. Chen, A. Kouzakov, V. Shakhov, K. Stankevich, A. Studenikin, Collective neutrino oscillations in moving and polarized matter, poster # 249

7) A. Kouzakov, D. Abeyadira, A. Studenikin, Dirac and Majorana neutrino oscillations in magnetized moving and polarized matter, poster # 266

8) G. Donchenko, K. Kouzakov, A. Studenikin, Neutrino magnetic moments in low-energy neutrino scattering on condensed matter systems, poster # 268

9) F. Lazarev, K. Kouzakov, A. Studenikin, Electromagnetic effects in elastic neutrino scattering on nucleons and nuclei, poster # 289
m_\nu \neq 0

electromagnetic properties

(flash on theory)
The electromagnetic vertex function

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

The 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

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

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

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

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: \( \text{Im} f_Q = \text{Im} f_M = \text{Im} f_A = 0 \)

\( \text{EM properties \quad \Rightarrow \quad a way to distinguish Dirac and Majorana} \)

...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

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

and

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

form factors are matrices in mass eigenstates space.

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

2) CP invariance + Hermiticity

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

1) CP invariance + hermiticity

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

or

Majorana

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

are relatively real (no relative phases).

... quite different EM properties ...

... beyond SM...
Dipole magnetic and electric form factors are most well studied and theoretically understood among form factors because in the limit they have nonvanishing values.

\[ \mu_\nu = f_M(0) \]

\[ \epsilon_\nu = f_E(0) \]
... Why ✓ electromagnetic properties are important?

... Why ✓ em properties to new physics?

... How does it all relate to ✓ oscillations?

$\Rightarrow \quad m_\nu \neq 0$

$\Rightarrow \quad \mu_\nu \neq 0$

magnetic moment

The Nobel Prize in Physics 2015

Arthur McDonald

Takaaki Kajita

«for the discovery of neutrino oscillations, which shows that neutrinos have mass»
In the easiest generalization of SM

\[ \mu_{\mu} \approx \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19} \left( \frac{m_i}{1\text{ eV}} \right) \mu_B \]

if \( m_i \sim 1\text{ eV} \)  \( \Rightarrow \)  KATRIN limit

then \( \mu_{\mu} \approx 3.2 \times 10^{-19} \mu_B \)

many orders of magnitude smaller than present experimental limits:
- \( \mu_{\nu} \sim 10^{-11} \mu_B \) reactor \( \checkmark \) limits GEMMA 2012
- \( \mu_{\nu} \sim 10^{-11} \div 10^{-12} \mu_B \) astrophysical (\( \checkmark \) \( \nu \) \( \text{solar} \) and \( \checkmark \) \( \nu \) \( \text{SN} \)) limits Borexino 2017

\( \mu_{\nu} \) is no less extravagant than possibility of \( q_{\nu} \neq 0 \)

- limitations imposed by general principles of any theory are very strict
  \( q_{\nu} \leq 3 \times 10^{-21}e \) from neutrality of hydrogen atom
- much weaker constraints are imposed by astrophysics

K. Fujikawa, R. Shrock, Phys. Rev. Lett. 45 (1980) 963
Laboratory experimental constraints on $\mu$, $q$, and $\langle r^2 \rangle$

- magnetic moment
- millicharge
- charge radius

Particle Data Group
Review of Particle Properties (2014-2020)
update of 2021

... so far there is no any evidence in favour of non-zero $\nu$ electromagnetic properties

- either from laboratory experiments
- or from astrophysical observations
... most easily accepted are dipole magnetic and electric moments

however most accessible for experimental studies are charge radii $\langle r^2 \rangle$
Studies of $\nu$-$e$ scattering - most sensitive method for experimental investigation of $\mu$.

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

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

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

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

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

for anti-neutrinos

$g_A \rightarrow -g_A$

to incorporate charge radius:

$$g_V \rightarrow g_V + \frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2 \theta_W$$
Magnetic moment contribution dominates at low electron recoil energies when

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

and

\[
\frac{T}{m_e} \lesssim \frac{\pi^2 \alpha_{em}}{G^2_F m_e^4} \mu^2_{\nu}
\]

... the lower the smallest measurable electron recoil energy is, smaller values of \( \mu^2_{\nu} \) 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 - running)
Germanium Experiment for Measurement of Magnetic Moment of Antineutrino
JINR (Dubna) + ITEP (Kurchatov Inst., Moscow)
at Kalinin Nuclear Power Plant

World best experimental (reactor) limit

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

June 2012

... quite realistic prospects for future ...

- GEMMA-2 / νGeN experiment
  - searching for \( \mu_\nu \) and CEνNS
  - unprecedentedly low threshold \( T \sim 200 \) eV

\[ \mu_\nu \sim (5 - 9) \times 10^{-12} \mu_B \]

2021 + few years of data taking ?

... courtesy of Alexey Lobashevsky, first results of νGeN are reported at TAUP 2021...
Effective magnetic moment in experiments
(for neutrino produced as $\nu_l$ with energy $E$ and after traveling a distance $L$)

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

where

- $\mu_{ij} \equiv |\beta_{ij} - \epsilon_{ij}|$

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.
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
Limiting the effective magnetic moment of solar neutrinos with the Borexino detector

Livia Ludhova on behalf of the Borexino collaboration

IKP-2 FZ Jülich, RWTH Aachen, and JARA Institute, Germany

Phys. Rev. D 96 (2017) 091103

Limiting $\mu$ with Borexino Phase-II solar neutrino data
**NMM results from Phase 2**

**Data selection:**
- **Fiducial volume:** $R < 3.021 \text{ m}$, $|z| < 1.67 \text{ m}$
- Muon, $^{214}\text{Bi}$-$^{214}\text{Po}$, and noise suppression

**Free fit parameters:** solar-$\nu$ (pp, $^{7}\text{Be}$) and backgrounds ($^{85}\text{Kr}$, $^{210}\text{Po}$, $^{210}\text{Bi}$, $^{11}\text{C}$, external bgr.), **response parameters** (light yield, $^{210}\text{Po}$ position and width, $^{11}\text{C}$ edge (2 x 511 keV), 2 energy resolution parameters)

**Constrained parameters:** $^{14}\text{C}$, pile up

**Fixed parameters:** pep-, CNO-, $^{8}\text{B}$-$\nu$ rates

**Systematics:** treatment of pile-up, energy estimators, pep and CNO constraints with LZ and HZ SSM

---

**Without radiochemical constraint**

$\mu_{\text{eff}} < 4.0 \times 10^{-11} \mu_B$ (90% C.L.)

**With radiochemical constraint**

$\mu_{\text{eff}} < 2.6 \times 10^{-11} \mu_B$ (90% C.L.)

Adding systematics

$\mu_{\text{eff}} < 2.8 \times 10^{-11} \mu_B$ (90% C.L.)

---

Livia Ludhova: Limiting the effective magnetic moment of solar neutrinos with the Borexino detector

TAUP 2017, Sudbury

---

Profiling $\mu_{\text{eff}}$ with $\sigma_{\text{EM}}$ for pp & $^{7}\text{Be}$

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

12/2011 - 05/2016

1291 days

90% C.L.
## Experimental limits for different effective $\mu$,

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

C. Giunti, A. Studenikin, “Electromagnetic interactions of neutrinos: A window to new physics”, Rev. Mod. Phys. 87 (2015) 531

- **new 2017 Borexino PRD**: $\mu_{\nu}^{eff} < 2.8 \times 10^{-11} \mu_B$ at 90% c.l.
- Particle Data Group, 2014-2020 and update of 2021
A remark on electric charge of neutrality $Q=0$ is attributed to gauge invariance + anomaly cancellation constraints imposed in SM of electroweak interactions.

General proof:

In SM:

\begin{align*}
Q &= I_3 + \frac{Y}{2} \\
S(U(2)_L \times U(1)_Y)
\end{align*}

In SM (without $\nu_R$) triangle anomalies cancellation constraints $\Longrightarrow$ certain relations among particle hypercharges 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.

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.

Beyond Standard Model...

Foot, Joshi, Lew, Volkas, 1990; Foot, Lew, Volkas, 1993; Babu, Mohapatra, 1989, 1990; Foot, He (1991).

Foot, He (1991).

In SM:

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

Bardeen, Gastmans, Lautrup, 1972; Cabral-Rosetti, Bernabeu, Vidal, Zepeda, 2000; Beg, Marciano, Ruderman, 1978; Marciano, Sirlin, 1980; Sakakibara, 1981; Dvornikov, Studenikin, 2004 (for SM in one-loop calculations).
Bounds on millicharge $q_\nu$ from (GEMMA Coll. data)

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

$v$-e cross-section

Bounds on $q_\nu$ from $\mu_\nu$ effects of New Physics

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

Expected new constraints from GEMMA:

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

2021 + few years data taking

$\nu$-Gen experiment

Constraints on $q_\nu$ in Table of Particle Data Group since 2016

Particle Data Group, 2016-2020

Studenikin, Europhys. Lett. 107 (2014) 210011

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

$|q_\nu| < 1.1 \times 10^{-13} e_0$

... low threshold ...
Studenikin, New bounds on neutrino electric millicharge from limits on neutrino magnetic moment, *Europhysics Letters* 107 (2014) 21001
**Experimental limits for different effective $q_e$**

C. Giunti, A. Studenikin, “Electromagnetic interactions of neutrinos: a window to new physics”, Rev. Mod. Phys. 87 (2015) 531

| Limit        | Method                                      | Reference                        |
|--------------|---------------------------------------------|----------------------------------|
| $|q_{\nu_\tau}| \lesssim 3 \times 10^{-4} e$ | SLAC $e^-$ beam dump             | Davidson et al. (1991)           |
| $|q_{\nu_\tau}| \lesssim 4 \times 10^{-4} e$ | BEBC beam dump                   | Babu et al. (1994)               |
| $|q_{\nu}| \lesssim 6 \times 10^{-14} e$ | Solar cooling (plasmon decay)     | Raffelt (1999a)                  |
| $|q_{\nu}| \lesssim 2 \times 10^{-14} e$ | Red giant cooling (plasmon decay) | Raffelt (1999a)                  |
| $|q_{\nu_e}| \lesssim 3 \times 10^{-21} e$ | Neutrality of matter              | Raffelt (1999a)                  |
| $|q_{\nu_e}| \lesssim 3.7 \times 10^{-12} e$ | Nuclear reactor                   | Gninenko et al. (2007)           |
| $|q_{\nu_e}| \lesssim 1.5 \times 10^{-12} e$ | Nuclear reactor                   | Studenikin (2013)                |

A. Studenikin: “New bounds on neutrino electric millicharge from limits on neutrino magnetic moment”, Eur.Phys.Lett. 107 (2014) 2100

… since that C. Patrignani et al (Particle Data Group), “The Review of Particle Physics 2016”, Chinese Physics C 40 (2016) 100001
... most accessible for experimental studies are charge radii $<r^2_\nu>$

Bernabeu, Papavassiliou, Vidal, 2004

... astrophysical bounds ???
Charge radius and anapole moment

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

Although it is usually assumed that \( \nu \) are electrically neutral
(\( \text{charge quantization implies } Q \sim \frac{1}{3} e \)),
\( \nu \) can dissociate 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 \( \nu \) charge radius

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 \( \nu \) and charged particles, which receives radiative corrections from several diagrams (including \( g \) exchange) to be considered simultaneously \( \Rightarrow \) calculated CR is infinite and gauge dependent quantity.
For massless \( \nu \), \( a_\nu \) and \( \langle r_\nu^2 \rangle \) can be defined (finite and gauge independent) from scattering cross section.

Bernabeu, Papavassiliou, Vidal,
Nucl. Phys. B 680 (2004) 450
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.

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Concluding remarks

- **$\nu$-e** cross section is determined in terms of 3x3 matrices of electromagnetic form factors.
- In short-baseline experiments, one studies form factors in flavour basis.
- Long-baseline experiments are more convenient to interpret in terms of fundamental form factors in mass basis.
- **$\nu$** millicomponent when it is constrained in reactor short-baseline experiments (GEMMA, for instance) should be interpreted as

$$|e_{\nu e}| = \sqrt{|(e_{\nu}e)e|^2 + |(e_{\nu}e)\mu|^2 + |(e_{\nu}e)\tau|^2}$$

- **$\nu$** charge radius in $\nu$-e elastic scattering can’t be considered as a shift

$$g_V \rightarrow g_V + \frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2 \theta_W$$

, there are also contributions from flavor-transition charge radii.
Using data from the COHERENT experiment, the authors put bounds on electromagnetic charge radii, including the first bounds on transition charge radii. These results show promising prospects for current and upcoming ν-nucleus experiments.

\[
\left( \left| \langle r_{\nu_{e\mu}}^2 \rangle \right|, \left| \langle r_{\nu_{e\tau}}^2 \rangle \right|, \left| \langle r_{\nu_{\mu\tau}}^2 \rangle \right| \right) < (22, 38, 27) \times 10^{-32} \text{ cm}^2
\]
Editors' Suggestion

**Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering**

/prd/abstract/10.1103/PhysRevD.98.113010

M. Cadeddu, C. Giunti, K. A. Kouzakov, Y. F. Li, A. I. Studenikin, and Y. Y. Zhang

Phys. Rev. D 98, 113010 (2018) – Published 26 December 2018

Using data from the COHERENT experiment, the authors put bounds on neutrino electromagnetic charge radii, including the first bounds on the transition charge radii. These results show promising prospects for current and upcoming neutrino-nucleus scattering experiments.
Probing neutrino transition magnetic moments with coherent elastic neutrino-nucleus scattering

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ABSTRACT: We explore the potential of current and next generation of coherent elastic neutrino-nucleus scattering (CEνNS) experiments in probing neutrino electromagnetic interactions. On the basis of a thorough statistical analysis, we determine the sensitivities on each component of the Majorana neutrino transition magnetic moment (TMM), $|\Delta|$, that follow from low-energy neutrino-nucleus experiments. We derive the sensitivity to neutrino TMM from the first CEνNS measurement by the COHERENT experiment, at the Spallation Neutron Source. We also present results for the next phases of COHERENT using HPGe, LAr and NaI[Tl] detectors and for reactor neutrino experiments such as CONUS, CONNIE, MINER, TEXONO and RED100. The role of the CP violating phases in each case is also briefly discussed. We conclude that future CEνNS experiments with low-threshold capabilities can improve current TMM limits obtained from Borexino data.

- Neutrino, electroweak, and nuclear physics from COHERENT … with refined quenching factor, Cadeddu, Dordei, Giunti, Li, Zhang, PRD 2020
- nuclear neutron distributions
  Cadeddu, Giunti, Li, Zhang, PRL 2018
- weak mixing angle
  Cadeddu & Dordei, PRD 2019
  Huang & Chen 2019
- electromagnetic properties
  Papoulia & Kosmas PRD 2018
- non-standard interactions
  Coloma, Gonzalez-Garcia, Maltoni, Schwetz PRD 2017
  Liao & Marfatia PLB 2017
Experimental limits on $\nu$ charge radius $<r^2_{\nu}>$

C. Giunti, A. Studenikin, “Electromagnetic interactions of neutrinos: a window to new physics”, Rev. Mod. Phys. 87 (2015) 531

| Method          | Experiment | Limit (cm$^2$)                             | C.L. | Reference                      |
|-----------------|------------|-------------------------------------------|------|--------------------------------|
| Reactor $\bar{\nu}_e$-e$^-$ | Krasnoyarsk | $|\langle r^2_{\bar{\nu}_e} \rangle| < 7.3 \times 10^{-32}$ | 90%  | Vidyakin et al. (1992)         |
|                 | TEXONO     | $-4.2 \times 10^{-32} < \langle r^2_{\bar{\nu}_e} \rangle < 6.6 \times 10^{-32}$ | 90%  | Deniz et al. (2010)$^a$        |
| Accelerator $\nu_e$-e$^-$ | LAMPF      | $-7.12 \times 10^{-32} < \langle r^2_{\nu_e} \rangle < 10.88 \times 10^{-32}$ | 90%  | Allen et al. (1993)$^a$        |
|                 | LSND       | $-5.94 \times 10^{-32} < \langle r^2_{\nu_e} \rangle < 8.28 \times 10^{-32}$ | 90%  | Auerbach et al. (2001)$^a$     |
| Accelerator $\nu_\mu$-e$^-$ | BNL-E734  | $-4.22 \times 10^{-32} < \langle r^2_{\nu_\mu} \rangle < 0.48 \times 10^{-32}$ | 90%  | Ahrens et al. (1990)$^a$       |
|                 | CHARM-II   | $|\langle r^2_{\nu_\mu} \rangle| < 1.2 \times 10^{-32}$ | 90%  | Vilain et al. (1995)$^a$       |

... updated by the recent constraints (effects of physics Beyond Standard Model)

\[
\left( |\langle r^2_{\nu_{e\mu}} \rangle|, |\langle r^2_{\nu_{e\tau}} \rangle|, |\langle r^2_{\nu_{\mu\tau}} \rangle| \right) < (22, 38, 27) \times 10^{-32} \text{ cm}^2
\]

M.Cadeddu, C. Giunti, K.Kouzakov, Yu-Feng Li, A. Studenikin, Y.Y.Zhang, Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering, Phys.Rev.D 98 (2018) 113010
Electromagnetic $\nu$ in astrophysics and bounds on $m_\nu$ and $q_\nu$. 
Electromagnetic interactions

- Neutrino decay, Cherenkov radiation, spin-light (SL $\nu$)

- Scattering

- Spin precession

- External source
New mechanism of electromagnetic radiation

A. Egorov, A. Lobanov, A. Studenikin, Phys.Lett. B 491 (2000) 137
Lobanov, Studenikin, Phys.Lett. B 515 (2001) 94
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Studenikin, A. Ternov, Phys.Lett. B 608 (2005) 107
A. Grigoriev, Studenikin, Ternov, Phys.Lett. B 622 (2005) 199
Studenikin,
J.Phys.A: Math.Gen. 39 (2006) 6769
J.Phys.A: Math.Theor. 41 (2008) 16402
Grigoriev, A. Lokhov, Studenikin, Ternov, Nuovo Cim. 35 C (2012) 57
Phys.Lett.B 718 (2012) 512
Spin light of neutrino in astrophysical environments

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Astrophysical bounds on $\mu$. 
... important for astrophysics consequence of $\mu_\nu$ is appearance $\nu_R$ ... examples 1-3 ...

a) helicity change in $\nu$ magnetic moment scattering on $e (p, n)$ (active) (sterile) $\nu_L \Rightarrow \nu_R$

b) spin (spin-flavor) precession in $B_\perp$

c) spin (spin-flavor) precession in transversal matter currents or polarization

... important for astrophysics consequence of $q_\nu \neq 0$ is $\nu$ deviation from a rectilinear trajectory
Astrophysics bounds on $\mu \nu$

... example 4 ...

1) SN 1987A provides energy-loss limit on related to observed duration of $\nu$ signal

... in magnetic moment scattering $\nu_e + e \rightarrow \nu_e^R + e$

due to change of helicity $\nu_L \Rightarrow \nu_R$

proto-neutron star formed in core-collapse SN can cool faster since $\nu_R$ are sterile and not trapped in a core like $\nu_L$ for a few sec

- escaping $\nu_R$ will cool the core very efficient and fast ( $\sim 1$ s)

the observed 5-10 s pulse duration in Kamioka II and IMB is in agreement with the standard model $\nu_L$ trapping ...

... inconsistent with SN1987A observed cooling time

$\mu^D_\nu \sim 10^{-12} \mu_B$

Barbieri, Mahapatra, Lattimer, Cooperstein, 1988
Raffelt, 1996
Astrophysics bounds on $\mu$$_{\nu}$

... example 5...

2) SN 1987A provides energy-loss limit on $\mathcal{M}_{\nu}$ related to observed $\nu$ energies

... helicity change in $\nu$ magnetic moment scattering $\nu_e^L + e \rightarrow \nu_e^R + e$ on $e (p, n)$

from inner SN core have larger energy than emitted $\nu_l$ from neutrino sphere

then $\nu_R \leftrightarrow \nu_L$ in galactic $B$ and higher-energy $\nu_l$ would arrive to detector as a signal of SN 1987A

from absence of anomalous high-energy $\nu$ Nötzold 1988

$$\mu_{\nu}^D \sim 10^{-12} \mu_B$$
Astrophysical bound on $\mu_\nu$ comes from cooling of red giant stars by plasmon decay $\gamma^* \rightarrow \nu\nu$. G. Raffelt, PRL 1990

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

Matrix element

$$|M|^2 = M_{\alpha\beta} p^\alpha p^\beta, \quad M_{\alpha\beta} = 4\mu^2 (2k_\alpha k_\beta - 2k^2 \epsilon^*_\alpha \epsilon_\beta - k^2 g_{\alpha\beta}), \quad \epsilon_\alpha k^\alpha = 0$$

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 $\omega^2 - k^2 = \omega_{\text{pl}}^2$

Energy-loss rate per unit volume

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

distribution function of plasmons
Astrophysical bound on $\mu_
u$

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

more fast star cooling

slightly reducing the core temperature

delay of helium ignition in low-mass red giants (due to nonstandard $\nu$ losses)

astronomical observable

can be related to luminosity of stars before and after helium flash

... in order not to delay helium ignition in an unacceptable way (a significant brightness increase is constraint by observations …)

... best astrophysical limit on magnetic moment…

$\mu^2 \leq 3 \times 10^{-12} \mu_B$

G. Raffelt, PRL 1990

D+M

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

Energy-loss rate per unit volume

$\ast$
Neutrino radiative decay

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

\[ m_i > m_j \]

\[ L_{int} = \frac{1}{2} \Bar{\psi}_i \sigma_{\alpha\beta} (\sigma_{ij} + \epsilon_{ij} \gamma_5) \psi_j F^{\alpha\beta} + h.c. \]

Radiative decay rate

\[ \Gamma_{\nu_i \rightarrow \nu_j + \gamma} = \frac{\mu_{\text{eff}}^2}{8\pi} \left( \frac{m_i^2 - m_j^2}{m_i^2} \right)^3 \approx 5 \left( \frac{\mu_{\text{eff}}}{\mu_B} \right)^2 \left( \frac{m_i^2 - m_j^2}{m_i^2} \right)^3 \left( \frac{m_i}{1 \text{ eV}} \right)^3 \text{s}^{-1} \]

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

- 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
Neutrino quantum decoherence engendered by neutrino radiative decay

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A new theoretical framework, based on the quantum field theory of open systems applied to neutrinos, has been developed to describe the neutrino evolution in external environments accounting for the effect of the neutrino quantum decoherence. The developed new approach enables one to obtain the explicit expressions of the decoherence and relaxation parameters that account for a particular process, in which the neutrino participates, and also for the characteristics of an external environment and of the neutrino itself, including the neutrino energy. We have used this approach to consider a new mechanism of the neutrino quantum decoherence engendered by the neutrino radiative decay to photons and dark photons in an astrophysical environment. The importance of the performed studies is highlighted by the prospects of the forthcoming new large volume neutrino detectors that will provide new frontier in high-statistics measurements of neutrino fluxes from supernovae.

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1. INTRODUCTION

Half a century ago Gribov and Pontecorvo derived [1] the first analytical expression for the neutrino oscillation probability that has opened a new era in the theoretical and experimental studies of the neutrino oscillation phenomenon. The neutrino oscillation patterns can be modified by neutrino interactions with external environments including electromagnetic fields that can influence neutrinos in the case neutrinos have nonzero electromagnetic properties [2].

The phenomenon of neutrino oscillations can proceed only in the case of the coherent superposition of neutrino mass states. An external environment can modify a neutrino evolution in a way that conditions for the coherent superposition of neutrino mass states are violated. Such a violation is called quantum decoherence of neutrino states and leads to the suppression of flavor neutrino oscillations. It should be noted that the quantum neutrino decoherence differs from the standard neutrino decoherence that appears due to separation of neutrino wave packets, the effect that is not considered below.

The quantum neutrino decoherence has attracted a growing interest during the last 15 years. Within reasonable amount of the performed studies, the method based on the Lindblad master equation [3,4] for describing neutrino evolution has been used. This approach is usually considered as the most general one that gives a possibility to study neutrino quantum decoherence as a consequence of standard and nonstandard interactions of a neutrino system with an external environment [5–15].

The Lindblad master equation can be written in the following form (see, for instance, [13]):

$$\frac{\partial \rho_{\nu}(t)}{\partial t} = -i[H_{\nu}, \rho_{\nu}(t)] + D[\rho_{\nu}], \quad (1)$$

where $\rho_{\nu}$ is the density matrix that describes the neutrino evolution, $H_{\nu}$ is the Hamiltonian, and the dissipation term (or dissipator) is given by

$$D[\rho_{\nu}(t)] = \frac{1}{2} \sum_{i=1}^{N_{\nu}-1} [V_{i} \rho_{\nu}(t) V_{i}^\dagger + \text{c.c.}], \quad (2)$$

where $V_{i}$ are dissipative operators that arise from interaction between the neutrino system and the external...
Astrophysical bounds on $q_\nu$
Constraints on neutrino millicharge from red giants cooling

Plasma process (photon decay)

Interaction Lagrangian

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

Decay rate

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

Delay of helium ignition in low-mass red giants due to nonstandard neutrino losses

... to avoid delay of helium ignition in low-mass red giants

... absence of anomalous energy-dependent dispersion of SN1987A neutrino signal, most model independent

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

Halt, Raffelt, Weiss, PRL 1994

Dobroliubov, Ignatiev 1990; Babu, Volkas 1992; Mohapatra, Nussinov 1992...
... astrophysical bound on millicharge $q_\nu$ from energy quantization in rotating magnetized star

Grigoriev, Savochkin, Studenikin, Russ. Phys. J. 50 (2007) 845
Studenikin, J. Phys. A: Math. Theor. 41 (2008) 164047
Balantsev, Popov, Studenikin, J. Phys. A: Math. Theor. 44 (2011) 255301
Balantsev, Studenikin, Tokarev, Phys. Part. Nucl. 43 (2012) 727
Phys. Atom. Nucl. 76 (2013) 489
Studenikin, Tokarev, Nucl. Phys. B 884 (2014) 396
Millicharged $\nu$ in rotating magnetized star

Balatsev, Tokarev, Studenikin, Phys.Part.Nucl., 2012, Phys.Atom.Nucl., Nucl.Phys. B, 2013, Studenikin, Tokarev, Nucl.Phys.B (2014)

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

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

matter potential

\[ c_l = 1 \]

rotating matter

rotation angular frequency

\[ f^\mu = -Gn_m(1, -e_y \omega, e_x \omega, 0) \]
Energy is quantized in rotating and magnetized star

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

\[ N = 0, 1, 2, \ldots \]

Integer number

Matter rotation frequency

Millicharge

Scalar potential of electric field

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

\[ p_0^{(e)} = \sqrt{m_e^2 + p_3^2 + 2\gamma N}, \quad \gamma = eB, \quad N = 0, 1, 2, \ldots \]

A. Studenikin, I. Tokarev, Nucl. Phys. B (2014)
In quasi-classical approach quantum states in rotating matter motion in circular orbits due to effective Lorentz force

\[ R = \int_0^\infty \Psi_L^\dagger r \Psi_L \, dr = \sqrt{\frac{2N}{|2Gn_n \omega - \epsilon q_0 B|}} \]

\[ \mathbf{F}_{\text{eff}} = q_{\text{eff}} \mathbf{E}_{\text{eff}} + q_{\text{eff}} [\mathbf{\beta} \times \mathbf{B}_{\text{eff}}] \]

\[ q_{\text{eff}} \mathbf{E}_{\text{eff}} = q_m \mathbf{E}_m + q_0 \mathbf{E} \quad q_{\text{eff}} \mathbf{B}_{\text{eff}} = |q_m \mathbf{B}_m + q_0 \mathbf{B}| \mathbf{e}_z \]

where

\[ q_m = -G, \quad \mathbf{E}_m = -\nabla n_n, \quad \mathbf{B}_m = 2n_n \omega \]

A. Studenikin, J.Phys.A: Math.Theor. 41(2008) 164047

matter induced “charge”, “electric” and “magnetic” fields
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

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

|Δω| < ω₀ ! …to avoid contradiction of νST impact with observational data on pulsars…

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

..best astrophysical bound…
New developments in ν spin and flavour oscillation... new astrophysical probes of ν

1. Generation of ν spin (flavour) oscillations by interaction with transversal matter current \( j_T \)

   P. Pustoshny, A. Studenikin,
   "Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions"
   • Phys. Rev. D98 (2018) no. 11, 113009

2. Inherent interplay of ν spin and flavour oscillations in B

   A. Popov, A. Studenikin,
   "Neutrino eigenstates and flavour, spin and spin-flavor oscillations in a constant magnetic field"
   • Eur. Phys. J. C 79 (2019) no. 2, 144, arXiv: 1902.08195
Neutrino spin and spin-flavour oscillations engendered by transversal matter currents

P. Pustoshny, A. Studenikin, "Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions" Phys. Rev. D98 (2018) no. 11, 113009
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.
Consider spin-flavour

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

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

\[ \sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}, \quad \Delta_{\text{eff}}^2 = \frac{\mu}{\gamma_\nu} \left| M_0 || + B_0 || \right|, \quad E_{\text{eff}} = \mu \left| B_\perp + \frac{1}{\gamma_\nu} M_0 \perp \right| \]

A. Studenikin, “Neutrinos in electromagnetic fields and moving media”, Phys. Atom. Nucl. 67 (2004)

\[ \tilde{\mu}_0 = \gamma_\nu g \sin \theta_e \left( \vec{p}_\nu \left( 1 - \vec{p}_\nu \vec{e}_\nu \right) - \frac{1}{\gamma_\nu} \vec{e}_\nu \right) \]

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

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

\[ \text{transversal current} \]

\[ \text{matter density} \]
The effect of helicity conversions and oscillations induced by transversal matter currents has been recently confirmed in studies of propagation in astrophysical media:

- J. Serreau and C. Volpe, Neutrino-antineutrino correlations in dense anisotropic media, Phys. Rev. D90 (2014) 125040
- V. Ciriglianoa, G. M. Fuller, and A. Vlasenko, A new spin on neutrino quantum kinetics Phys. Lett. B747 (2015) 27
- A. Kartavtsev, G. Raffelt, and H. Vogel, Neutrino propagation in media: flavor-, helicity-, and pair correlations, Phys. Rev. D91 (2015) 125020...
Neutrino spin (spin-flavour) oscillations in transversal matter currents

... quantum treatment ...

- Spin evolution effective Hamiltonian in moving matter
- Two flavor with two helicities: \( \nu_f = (\nu_e^+, \nu_e^-, \nu_\mu^+, \nu_\mu^-)^T \)
- Interaction with matter composed of neutrons:
  \[
  L_{\text{int}} = -f_\mu \sum_l \bar{\nu}_l(x) \gamma_\mu \frac{1 + \gamma_5}{2} \nu_l(x) = -f_\mu \sum_i \bar{\nu}_i(x) \gamma_\mu \frac{1 + \gamma_5}{2} \nu_i(x)
  \]
  \( f_\mu = -\frac{G_F}{2\sqrt{2}} j^\mu_n \)
  \( j^\mu_n = n(1, \mathbf{v}) \)
  \( \nu_e^\pm = \nu_1^\pm \cos \theta + \nu_2^\pm \sin \theta, \)
  \( \nu_\mu^\pm = -\nu_1^\pm \sin \theta + \nu_2^\pm \cos \theta \)

P. Pustoshny, A. Studenikin,
Phys. Rev. D98 (2018) 113009
(2 flavours \times 2 helicities) evolution equation

\[ i \frac{d}{dt} \nu_f^s = \left( H_0 + \Delta H_0^{SM} + \Delta H_{j\parallel+j\perp}^{SM} + \Delta H_{B\parallel+B\perp}^{SM} + \Delta H_0^{NSI} + \Delta H_{j\parallel+j\perp}^{NSI} \right) \nu_f^s \]

\[ \text{vacuum} \quad \uparrow \quad \text{matter at rest} \quad \uparrow \quad \text{moving matter} \quad \uparrow \quad B \quad \text{matter at rest} \quad \uparrow \quad \text{moving matter} \]

Standard Model

Non-Standard Interactions

Resonant amplification of neutrino oscillations:

- \( \nu_e^L \leftrightarrow (j_\perp) \Rightarrow \nu_e^R \) by longitudinal matter current \( j_\parallel \)
- \( \nu_e^L \leftrightarrow (j_\perp) \Rightarrow \nu_e^R \) by longitudinal \( B_\parallel \)
- \( \nu_e^L \leftrightarrow (j_\perp) \Rightarrow \nu_\mu^R \) by matter-at-rest effect
- \( \nu_e^L \leftrightarrow (j_\perp^{NSI}) \Rightarrow \nu_\mu^R \) by matter-at-rest effect

P. Pustoshny, A. Studenikin, Phys. Rev. D98 (2018) 113009
“Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field”

\[
\begin{align*}
\nu_e^L &\leftrightarrow \nu_\mu^L \\
\nu_e^L &\leftrightarrow \nu_e^R \\
\nu_e^L &\leftrightarrow \nu_\mu^R
\end{align*}
\]

A. Popov, A. Studenikin, Eur. Phys. J. C79 (2019) 144
Consider two flavour $\nu$ with two helicities as superposition of helicity mass states $\nu^L_i$.

$$
\nu^L_e = \nu_1^L \cos \theta + \nu_2^L \sin \theta,
\nu^L_\mu = -\nu_1^L \sin \theta + \nu_2^L \cos \theta
$$

$\nu^L_i$ are not stationary states in magnetic field $B = (B_\perp, 0, B_\parallel)$.

Dirac equation in a constant $B$

$$
(\gamma^\mu p_\mu - m_i - \mu_i \Sigma B)\nu^s_i(p) = 0
$$

$\hat{H}_i \nu^s_i = E\nu^s_i$

$$
\hat{H}_i = \gamma_0 \gamma^p p + \mu_i \gamma_0 \Sigma B + m_i \gamma_0
$$

$\mu_{ij}(i \neq j) = 0$

Spin operator that commutes with $\hat{H}_i$

$$
\hat{S}_i = \frac{1}{N} \left[ \Sigma B - \frac{i}{m_i} \gamma_0 \gamma_5 [\Sigma \times p] B \right]
$$

$$
\hat{S}_i \ket{\nu^s_i} = s \ket{\nu^s_i}, s = \pm 1
$$

$1/N = \frac{m_i}{\sqrt{m_i^2 B^2 + p^2 B^2_\perp}}$

Energy spectrum

$$
E^s_i = \sqrt{m_i^2 + p^2 + \mu_i^2 B^2 + 2\mu_i s \sqrt{m_i^2 B^2 + p^2 B^2_\perp}}
$$

“bra-ket” products

$$
\langle \nu^s_i | \nu^s_k \rangle = \delta_{ik} \delta_{ss'}
$$
Probabilities of ν oscillations (flavour, spin and spin-flavour)

\[ P_{\nu_e^L \rightarrow \nu_\mu^L}(t) = \left| \langle \nu_\mu^L | \nu_e^L(t) \rangle \right|^2 \]
\[ \mu_{\pm} = \frac{1}{2}(\mu_1 \pm \mu_2) \]

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

Spin

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

Spin-flavour

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

\[ \omega_{vac} = \frac{\Delta m^2}{4p} \]
\[ \omega_B = \mu B_\perp \]

... interplay of oscillations on vacuum and magnetic frequencies

A.Popov, A.S., Eur. Phys. J. C79 (2019) 144
For the case $\mu_1 = \mu_2$, probability of flavour oscillations

$$P_{\nu_e^L \to \nu_\mu^L} = (1 - \sin^2(\mu B_\perp t)) \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4p} t = \left(1 - P_{\nu_e^L \to \nu_e^R}^{\text{cust}}\right) P_{\nu_e^L \to \nu_\mu^L}^{\text{cust}}$$

... amplitude of flavour oscillations on vacuum frequency is modulated by magnetic frequency

$\omega_{\text{vac}} = \frac{\Delta m^2}{4p}$, $\omega_B = \mu B_\perp$

**Fig. 1** The probability of the neutrino flavour oscillations $\nu_e^L \to \nu_\mu^L$ in the transversal magnetic field $B_\perp = 10^{16}$ G for the neutrino energy $p = 1$ MeV, $\Delta m^2 = 7 \times 10^{-5}$ eV$^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

Chotorlishvili, Kouzakov, Kurashvili, Studenikin, Spin-flavor oscillations of ultrahigh-energy cosmic neutrinos in interstellar space: The role of neutrino magnetic moments, Phys. Rev. D96 (2017) 103017
For the case $\mu_1 = \mu_2$, the probability of spin oscillations

$$P_{\nu_e^L \rightarrow \nu_e^R} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2}{4p} t \right) \sin^2 (\mu B \perp t) = \left( 1 - P_{\nu_e^L \rightarrow \nu_\mu}^{\text{cust}} \right) P_{\nu_e^L \rightarrow \nu_e^R}^{\text{cust}}$$

...amplitude of spin oscillations on magnetic frequency is modulated by vacuum frequency $\omega_B = \mu B \perp$.

**Fig. 2** The probability of the neutrino spin oscillations $\nu_e^L \rightarrow \nu_e^R$ in the transversal magnetic field $B \perp = 10^{16} \text{ G}$ for the neutrino energy $p = 1 \text{ MeV}$, $\Delta m^2 = 7 \times 10^{-5} \text{ eV}^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20} \mu_B$. 

A. Popov, A. S., Eur. Phys. J. C 79 (2019) 144
For the case $\mu_1 = \mu_2$, probability of spin-flavour oscillations

$$P_{\nu^L_e \to \nu^R_\mu} = \sin^2(\mu B_\perp t) \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4\rho} t = P_{\nu^L_e \to \nu^L_\mu}^{cust} P_{\nu^L_e \to \nu^R_\mu}^{cust}$$

... interplay of oscillations on vacuum and on magnetic frequencies

\[ \omega_{\text{vac}} = \frac{\Delta m^2}{4\rho} \]
\[ \omega_B = \mu B_\perp \]

**Fig. 3** The probability of the neutrino spin flavour oscillations $\nu^L_e \to \nu^R_\mu$ in the transversal magnetic field $B_\perp = 10^{16} \text{ G}$ for the neutrino energy $p = 1 \text{ MeV}$, $\Delta m^2 = 7 \times 10^{-5} \text{ eV}^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

... in literature:

$$P_{\nu^L_e \nu^L_\mu} = \sin^2(\mu_{e\mu} B_\perp t) = 0$$
\[ \mu_{e\mu} = \frac{1}{2}(\mu_2 - \mu_1) \sin 2\theta \]
\[ \mu_1 = \mu_2, \quad \mu_{ij} = 0, \quad i \neq j \]
For completeness: survival \( \nu_e^L \leftrightarrow \nu_e^L \) probability

\[ P_{\nu_e^L \rightarrow \nu_e^L}(t) = \left\{ \cos(\mu_+ B_\perp t) \cos(\mu_- B_\perp t) - \cos 2\theta \sin(\mu_+ B_\perp t) \sin(\mu_- B_\perp t) \right\}^2 \]

\[ - \sin^2 2\theta \cos(\mu_1 B_\perp t) \cos(\mu_2 B_\perp t) \sin^2 \frac{\Delta m^2}{4p} t \]

\[ \sum \text{of all probabilities (as it should be...)}: \]

\[ P_{\nu_e^L \rightarrow \nu_\mu^L} + P_{\nu_e^L \rightarrow \nu_e^R} + P_{\nu_e^L \rightarrow \nu_\mu^R} + P_{\nu_e^L \rightarrow \nu_e^L} = 1 \]

A. Popov, A.S., Eur. Phys. J. C79 (2019) 144

the discovered correspondence between flavour and spin oscillations in \( B \) can be important in studies of \( \nu \) propagation in astrophysical environments
New effect in flavor oscillation in moving matter

\[ \nu_e^L \leftrightarrow (j_{\|}, j_{\perp}) \Rightarrow \nu_{\mu}^L \quad j_{\perp} = n \nu_{\perp} \]

- Equal role of \( j_{\perp} \) and \( B_{\perp} \) in generation of flavor oscillations
- Invariant number density
- Longitudinal matter currents
- Transversal matter currents

\[ \nu_e^L \leftrightarrow (j_{\perp}, B_{\perp}) \Rightarrow \nu_e^R \quad \text{spin oscillations} \]
\[ \nu_e^L \leftrightarrow (j_{\perp}, B_{\perp}) \Rightarrow \nu_{\mu}^R \quad \text{spin-flavour oscillations} \]

- Probability of flavor oscillations \( \nu_e^L \leftrightarrow (j_{\|}, j_{\perp}) \Rightarrow \nu_{\mu}^L \) in moving matter

\[
P^{(j_{\|}+j_{\perp})}_{\nu_e^L \rightarrow \nu_{\mu}^L}(t) = \left( 1 - P^{(j_{\perp})}_{\nu_e^L \rightarrow \nu_e^R} - P^{(j_{\perp})}_{\nu_e^L \rightarrow \nu_{\mu}^R} \right) P^{(j_{\|})}_{\nu_e^L \rightarrow \nu_{\mu}^L}(t)
\]

Probability of spin survival (not spin flip)

\[
P^{j_{\perp}}_{\nu_e^L \rightarrow \nu_e^R}(t) = \frac{\left( \frac{n}{\gamma} \right)^2 v_\perp^2}{\left( \frac{n}{\gamma} \right)^2 v_\perp^2 + (1 - v\beta)^2} \sin^2 \omega_{ee}^j t
\]

Probability of flavor oscillations in \( j_{\|} \)

\[
P^{j_{\perp}}_{\nu_e^L \rightarrow \nu_{\mu}^L}(t) = \frac{\left( \frac{n}{\gamma} \right)^2 v_\perp^2}{\left( \frac{n}{\gamma} \right)^2 v_\perp^2 + \left( \frac{\Delta M}{G_n} - (1 - v\beta) \right)^2} \sin^2 \omega_{e\mu}^j t
\]

Spin oscillations in \( j_{\perp} \)

\[
\omega_{ee}^j = \tilde{G}_n \sqrt{\left( \frac{n}{\gamma} \right)^2 v_\perp^2 + (1 - v\beta)^2}
\]

\[
\left( \frac{n}{\gamma} \right)^2 = \frac{\cos^2 \theta}{\gamma_{11}} + \frac{\sin^2 \theta}{\gamma_{22}} \quad \gamma_{\alpha'1}^{-1} = \frac{1}{2}(\gamma_{11}^{-1} + \gamma_{22}^{-1}) \quad \gamma_{11}^{-1} = \frac{m_\alpha}{E_\alpha}
\]

Spin-flavor oscillations in \( j_{\perp} \)

\[
\omega_{e\mu}^j = \tilde{G}_n \sqrt{\left( \frac{n}{\gamma} \right)^2 v_\perp^2 + \left( \frac{\Delta M}{G_n} - (1 - v\beta) \right)^2}
\]

\[
\left( \frac{n}{\gamma} \right)^2 = \frac{\sin 2\theta}{\tilde{\gamma}_{21}} \quad \tilde{\gamma}_{\alpha'1}^{-1} = \frac{1}{2}(\gamma_{11}^{-1} - \gamma_{22}^{-1})
\]
Manifestations of nonzero Majorana CP-violating phases in oscillations of supernova neutrinos

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We investigate effects of nonzero Dirac and Majorana CP-violating phases on neutrino-antineutrino oscillations in a magnetic field of astrophysical environments. It is shown that in the presence of strong magnetic fields and dense matter, nonzero CP phases can induce new resonances in the oscillations channels $\nu_e \leftrightarrow \nu_x$, $\nu_x \leftrightarrow \bar{\nu}_e$, and $\nu_x \leftrightarrow \bar{\nu}_x$. We also consider all other possible oscillation channels with $\nu_y$ and $\nu_z$ in the initial state. The resonances can potentially lead to significant phenomena in neutrino oscillations accessible for observation in experiments. In particular, we show that neutrino-antineutrino oscillations combined with Majorana-type CP violation can affect the $\bar{\nu}_e/\nu_e$ ratio for neutrinos coming from the supernovae explosion. This effect is more prominent for the normal neutrino mass ordering. The detection of supernova neutrino fluxes in the future experiments, such as JUNO, DUNE, and Hyper-Kamiokande, can give an insight into the nature of CP violation and, consequently, provides a tool for distinguishing the Dirac or Majorana nature of neutrinos.

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I. INTRODUCTION

CP symmetry implies that the equations of motion of a system remain invariant under the CP transformation, that is a combination of charge conjugation (C) and parity inversion (P). In 1964, with the discovery of the neutral kaon decay [1], it was confirmed that CP is not an underlying symmetry of the electroweak interactions theory, thus opening a vast field of research in CP violation. Currently, CP violation is a topic of intense studies in particle physics that also has important implications in cosmology. In 1967, Sakharov proved that the existence of CP violation is a necessary condition for generation of the baryon asymmetry through baryogenesis in the early Universe [2]. A review of possible baryogenesis scenarios can be found in [3].

Today we have solid understanding of CP violation in the quark sector, that appears due to the complex phase in the Cabibbo-Kobayashi-Maskawa matrix parametrization. Its magnitude is expressed by the Jarlskog invariant $J_{\text{CKM}} = (3.18 \pm 0.15) \times 10^{-5}$ [4], which seems to be excessively small to engender baryogenesis at the electroweak phase transition scale [3]. However, in addition to experimentally confirmed CP violation in the quark sector, CP violation in the lepton (neutrino) sector hypothetically exists (see [5] for a review). Leptonic CP violation is extremely difficult to observe due to weakness of neutrino interactions. In 2019, a first breakthrough happened when NOvA [6] and T2K [7] collaborations reported constraints on the Dirac CP-violating phase in neutrino oscillations. Hopefully, future gigantic neutrino experiments, such as DUNE [8] and Hyper-Kamiokande [9], also JUNO [10] with detection of the atmospheric neutrinos, will have a good chance significantly improve this results. Note that leptonic CP violation plays an important role in baryogenesis through leptogenesis scenarios [11].

The CP-violation pattern in the neutrino sector depends on whether neutrino is a Dirac or Majorana particle. The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix in the most common parametrization has the following form:

$$\nu_e \leftrightarrow \bar{\nu}_e, \mu, \tau$$

in strong B and dense matter of supernovae for two mass hierarchies.

… the role of Majorana CP-violating phases in neutrino oscillations

… Majorana CP phases induce new resonances

… a tool for distinguishing Dirac-Majorana nature of neutrinos.
**Electromagnetic Properties of ν**

**EP theory - ν vertex function**

\[ \Lambda_{\mu}(q) = f_{Q}^{{if}}(q^{2}) \gamma_{\mu} + f_{M}^{{if}}(q^{2}) i \sigma_{\mu\nu} q^{\nu} + f_{E}^{{if}}(q^{2}) \sigma_{\mu\nu} q^{\nu} \gamma_{5} + f_{A}^{{if}}(q^{2})(q^{2} \gamma_{\mu} - q_{\mu} q_{\nu}^{'}) \gamma_{5}, \]

**form factors**

\[ f_{X}^{{if}}(q^{2}) \text{ at } q^{2} = 0 \]

**static EP of ν**

**electric charge**

**magnetic moment**

**electric moment**

**anapole moment**

**Dirac ν**

**Majorana ν**

\[ q_{if}^{{if}} \neq 0, \mu_{if}(i \neq f) \]

\[ \varepsilon_{if}(i \neq f) \]

**CPT + charge conservation**

**Hermiticity and discrete symmetries of EM current**

**put constraints on form factors**

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

**Fujikawa & Shrock, 1980**

**μ_{if}^{D} = \frac{3e_{0}G_{F}m_{j}}{8\sqrt{2}\pi^{2}} \sim 3.2 \times 10^{-19}\mu_{B} \left(\frac{m_{j}}{1\text{eV}}\right)\]

**much greater values**

**are Beyond Minimally Extended SM**

**transition moments**

\[ \mu_{i\neq f} \text{ are GIM suppressed} \]

**ν EMP**

**experimental bounds**

**GEMMA 2012**

**Borexino 2017 ~ XENON1T 2020**

**astrophys., Raffelt ea 1988, 2020**

**Arcoa Dias ea 2015**

**reactor ν scattering**

\[ q_{\nu} < 10^{12} \] AS ‘14, Chen ea ‘14

\[ q_{\nu} < 10^{19} \] AS ‘14 (astrophysics)

\[ e_{0} \] Neutrality of matter

**charge rad. \(< r_{\nu}^{2} >\) is most accessible for exp. observations**

**μ_{\nu}^{eff} < 2.8 \times 10^{-11} μ_{B} \sim 0.1**

**ν eff**

**2.9**
electromagnetic properties: Future prospects

- New constraints on $\mu_\nu$ (and $q_\nu$) from GEMMA-2/\nuGen and Borexino (?)

- XENON1T: an excess in electronic recoil events in <7 keV (2-3 keV) over known backgrounds

- XENONnT: new improved limit from stellar evolution data for global cluster $\omega$-Centauri

- New improved limit comes from improved new calibrations of tip of red-giant branch which allows one to constrain novel energy losses

- New setup to observe coherent elastic neutrino-atom scattering using electron antineutrinos from tritium decay and a liquid helium target

Potentialities of a low-energy detector based on 4 He evaporation to observe atomic effects in coherent neutrino scattering and physics perspectives, Phys. Rev. D100 (2019) no.7, 073014
electromagnetic properties: Future prospects

- liquid xenon (LXe) detectors set limits on electromagnetic properties, including millicharge

XMASS Coll. limits on $q_\nu$:

- in case 3 have common $q_\nu$ $\quad q_\nu < 5.4 \times 10^{-12} e_0$

- for individual $\nu$ flavours $\quad (q_{\nu_e,\mu}; q_{\nu_\tau}) < (1.1; 0.7) \times 10^{-11} e_0$

K. Abe et al, XMASS Coll.,
Search for exotic neutrino-electron Interactions using solar neutrinos in XMASS-I,
Phys. Lett. B 809 (2020) 135741
Thank you

... studies of electromagnetic properties are important

- investigation of properties of an elementary particle
- it provides an important inside to fundamentals of particle physics

Thank you
Backup slides

spin light of \( \nu \)
Consider escaping central neutron star with inclination angle $\alpha$ from accretion disk: $B_\parallel = B \sin \alpha \sim \frac{1}{2} B$

Toroidal bulk of rotating dense matter with transversal velocity of matter $\nu_\perp = \omega D = 0.067$ and $\gamma_n = 1.002$

$$E_{\text{eff}} = \left( \frac{\eta}{\gamma} \right)_{ee} \tilde{G}_n \nu_\perp = \frac{\cos^2 \theta}{\gamma_{11}} \tilde{G}_n \nu_\perp \approx \tilde{G}_n \frac{\gamma_n}{\gamma_\nu} \nu_\perp$$

$$\Delta_{\text{eff}} = \left| \left( \frac{\mu}{\gamma} \right)_{ee} B_\parallel + \eta_{ee} \tilde{G}_n \beta \right| \approx \left| \frac{\mu_{11}}{\gamma_\nu} B_\parallel - \tilde{G}_n \gamma_n \gamma_n \right|$$

$E_{\text{eff}} \geq \Delta_{\text{eff}}$

$B_\parallel \beta = -1$

**resonance condition**

$\left| \frac{\mu_{11} B_\parallel}{\tilde{G}_n \gamma_n} - \gamma_\nu \right| \leq 1$

- Perego et al, Mon.Not.Roy.Astron.Soc. 443 (2014) 3134
- Grigoriev, Lokhov, Studenikin, Ternov, JCAP 1711 (2017) 024
- Pustoshny, Studenikin, Phys. Rev. D98 (2018) 113009
Resonance amplification of spin-flavor oscillations (in the absence of $j_m$)

Criterion – oscillations are important:

$$E_{\text{eff}} = \left| \mu_{e\mu} B_\perp + \left( \frac{\eta}{\gamma} \right)_{e\mu} \tilde{G} n v_\perp \right| \geq \left| \Delta M - \frac{1}{2} \left( \frac{\mu_{11}}{\gamma_{11}} + \frac{\mu_{22}}{\gamma_{22}} \right) B_\parallel - \tilde{G} n (1 - v \beta) \right|$$

neglecting $\hat{B} = \hat{B}_\perp + \hat{B}_\parallel \rightarrow 0$:

$$L_{\text{eff}} = \frac{\pi}{\left( \frac{\eta}{\gamma} \right)_{e\mu} \tilde{G} n v_\perp} \frac{\left( \frac{\eta}{\gamma} \right)_{e\mu} \approx \sin 2\theta}{\gamma_{\nu}}$$

$$\tilde{G} n \sim \Delta M$$

$$\Delta m^2 = 7.37 \times 10^{-5} \text{ eV}^2$$

$$\sin^2 \theta = 0.297$$

$$p_0^\nu = 10^6 \text{ eV}$$

$$n_0 \sim \frac{\Delta M}{\tilde{G}} = 10^{12} \text{ eV}^3 \approx 10^{26} \text{ cm}^{-3}$$

$$L_{\text{eff}} \approx 10 \text{ km} \ (\text{within short GRB}) \text{ if } n_0 \approx 5 \times 10^{36} \text{ cm}^{-3}$$

Pustoshny, Studenikin, Phys. Rev. D98 (2018) 113009