Electromagnetic properties of neutrinos

(new constraints and new effects in oscillations)

13-е Черенковские чтения,
Москва, 14 апреля 2020 года

Alexander Studenikin

supported by RFBR grant
20-52-53022

Moscow State University
JINR –Dubna

Outline (1)

1. (short) review of ν electromagnetic properties

2. experimental constraints

on μ_ν , q_ν and $<r^2_\nu>$

magnetic moment — millicharge — charge radius

Particle Data Group
Review of Particle Properties (2014-2018)
update of 2019

Neutrino electromagnetic interactions: A window to new physics

+ upgrade:

Studenikin,

"ν electromagnetic interactions: A window to new physics – II,

arXiv: 1801.18887

Electromagnetic properties of neutrinos,

arXiv: 1912.12497

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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.

DOI: 10.1103/RevModPhys.87.531 PACS numbers: 14.60.St, 13.15.+g, 13.35.Hb, 14.60.Lm

CONTENTS

Outline (2)

③ ν electromagnetic interactions (new effects)

– two interesting new phenomena in

ν spin (flavour) oscillations

in moving matter and B

50 years of ν oscillation formulae
Gribov & Pontecorvo (1969)

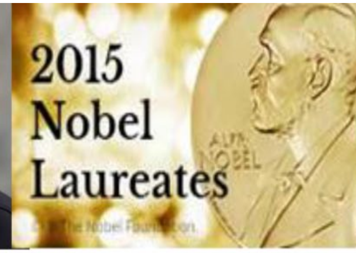
new developments in ν spin and flavour oscillations

① generation of ν spin (flavour) oscillations by interaction with transversal matter current $j_{\perp}$

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

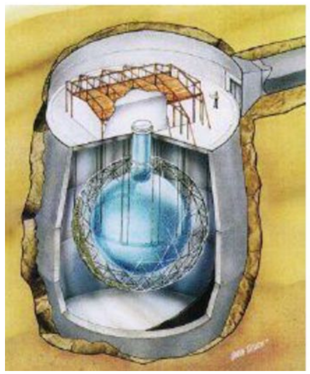
A. Popov, A. Studenikin,
"Neutrino eigenstates and flavour, spin and spin-flavor oscillations in a constant magnetic field"
- Eur. Phys .J. C 79 (2019) no.2, 144, arXiv: 1902.08195



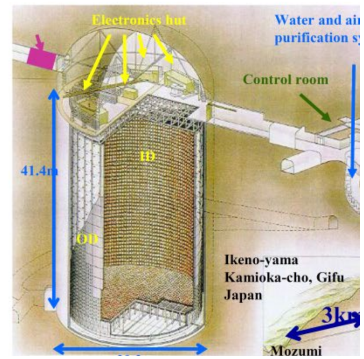
Arthur McDonald

The Nobel Prize in Physics 2015

Takaaki Kajita



«for the discovery of neutrino oscillations, which shows that neutrinos have mass»



$$m_\nu \neq 0$$

✓ electromagnetic properties (flash on theory)

Astrophysical bounds

$$\mu_\nu \lesssim 3 \cdot 10^{-12} \mu_B$$

G. Raffelt (1990)

Theory (Standard Model with ν_R)

$m_\nu \neq 0$

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

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

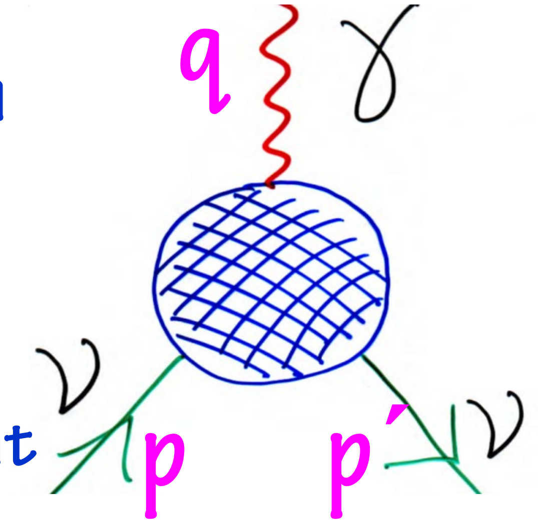
Lee, Shrock, 1977; Fujikawa, Shrok, 1980

Limits from reactor ν-e scattering experiments

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

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

ν electromagnetic vertex function



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

Matrix element of electromagnetic current is a Lorentz vector

$\Lambda_\mu(q,l)$ should be constructed using

- matrices $\hat{1}, \quad \gamma_5, \quad \gamma_\mu, \quad \gamma_5\gamma_\mu, \quad \sigma_{\mu\nu},$
- tensors $g_{\mu\nu}, \quad \epsilon_{\mu\nu\sigma\gamma}$
- vectors q_μ and l_μ

$$q_\mu = p'_\mu - p_\mu, \; l_\mu = p'_\mu + p_\mu$$

- Lorentz covariance (1) and electromagnetic gauge invariance (2) $\Longrightarrow$

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

$$\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2)i\sigma_{\mu\nu}q^\nu - f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

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

- Hermiticity and discrete symmetries of EM current J_μ^{EM} put constraints on form factors

Dirac ν

1) CP invariance + Hermiticity ⟹ $f_E = 0$,

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 ⟹ three form factors are real: $Im f_Q = Im f_M = Im f_A = 0$

Majorana ν

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 ν

In general case matrix element of $J_\mu^{\rm EM}$ can be considered between different initial $\psi_i(p)$ and final $\psi_j(p')$ states of different masses

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

$p^2 = m_i^2, \ p'^2 = m_j^2$:

... beyond SM... ν

and

$$\Lambda_\mu(q) = \Big(f_Q(q^2)_{ij} + f_A(q^2)_{ij}\gamma_5\Big)(q^2\gamma_\mu - q_\mu \not{q}) + f_M(q^2)_{ij} i\sigma_{\mu\nu}q^\nu + f_E(q^2)_{ij}\sigma_{\mu\nu}q^\nu\gamma_5$$

form factors are matrices in ν mass eigenstates space.

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

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).

... quite different EM properties ...

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 have nonvanishing values

$$\mu_\nu = f_M(0)$$ ⟸ ν magnetic moment

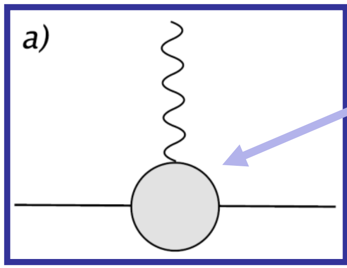
$$\epsilon_\nu = f_E(0)$$ ⟸ ν electric moment ???

3.3 Naïve relationship between m_ν and μ_ν

... problem to get large μ_ν and still acceptable m_ν

If μ_ν is generated by physics beyond the SM at energy scale Λ,

P. Vogel e.a., 2006

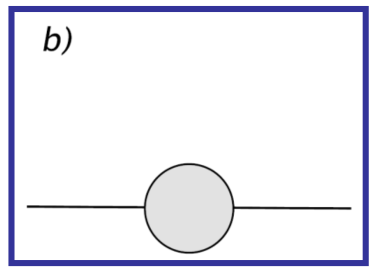


then

$$\mu_\nu \sim \frac{eG}{\Lambda},$$

...combination of constants and loop factors...

contribution to m_ν given by



, then

$$m_\nu \sim G\Lambda$$

$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \frac{\mu_\nu}{10^{-18}\mu_B}[\Lambda(\mathrm{TeV})]^2 \ \mathrm{eV}$$

Voloshin, 1988;
Barr, Freire,
Zee, 1990

ν magnetic moment in experiments

… most easily accepted are dipole magnetic and electric moments

however most accessible for experimental studies are charge radii $<r_{\nu}^{2}>$

Studies of ν-e scattering - most sensitive method for experimental investigation of μ_ν

Cross-section:

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

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

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

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

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

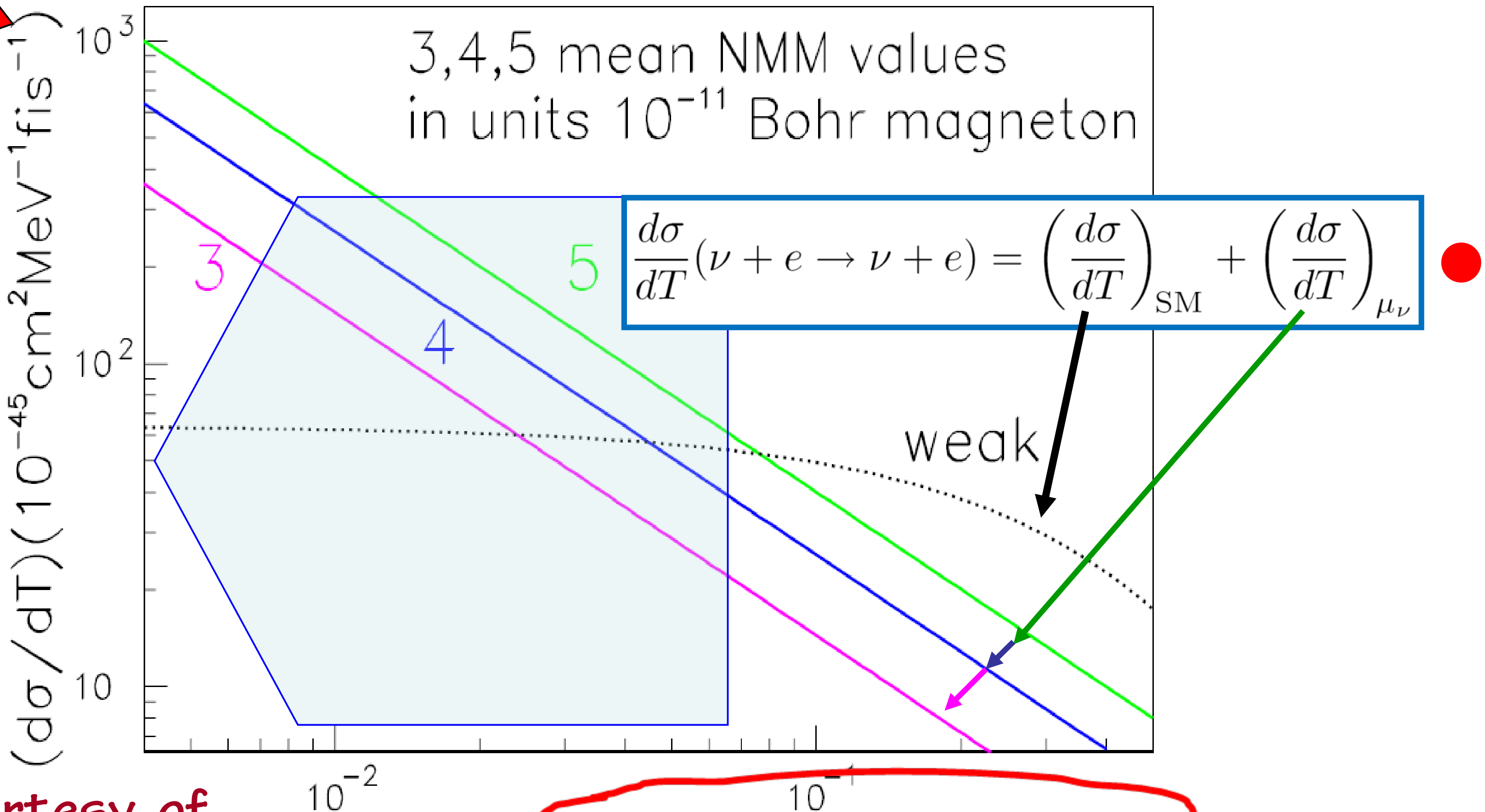
$$g_V = \begin{cases} 2\sin^2\theta_W + \frac{1}{2} & \text{for } \nu_e\,, \\ 2\sin^2\theta_W - \frac{1}{2} & \text{for } \nu_\mu, \nu_\tau\,, \end{cases} \qquad g_A = \begin{cases} \frac{1}{2} & \text{for } \nu_e\,, \\ -\frac{1}{2} & \text{for } \nu_\mu, \nu_\tau \end{cases}$$

for anti-neutrinos $g_A \to -g_A$

- to incorporate charge radius: $g_V \to g_V + \frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2\theta_W$???

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

… the lower the smallest measurable electron recoil energy is, smaller values of μ_ν^2 can be probed in scattering experiments …



… courtesy of A.Starostin…

GEMMA (2005 – 2012 - running)
Germanium Experiment for Measurement of Magnetic Moment of Antineutrino

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

World best experimental (reactor) limit

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

• June 2012

A. Beda et al, in:

Special Issue on "Neutrino Physics",

Advances in High Energy Physics (2012) 2012,

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

… quite realistic prospects of the near future … 2020 ?

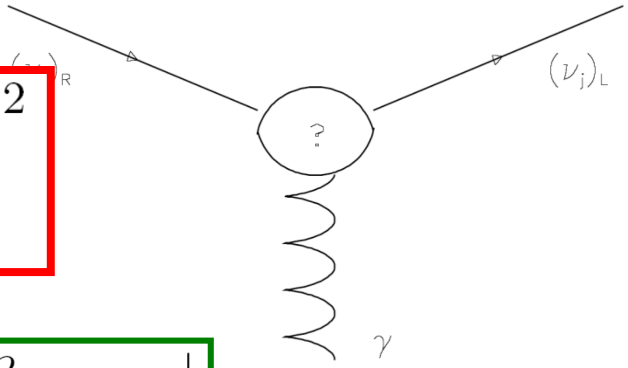
• $$\mu_\nu^a \sim 0.7 \times 10^{-12} \mu_B$$

unprecedentedly low threshold

$T \sim 200 \;\; eV$

Effective ν magnetic moment in experiments

(for neutrino produced as ν_l with energy E_ν and after traveling a distance L)



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

where neutrino mixing matrix

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

magnetic and electric moments

- Observable μ_ν is an effective parameter that depends on neutrino flavour composition at the detector.

- Implications of μ_ν limits from different experiments (reactor, solar $^8\mathrm{B}$ and $^7\mathrm{Be}$) are different.

Mitglied der Helmholtz-Gemeinschaft

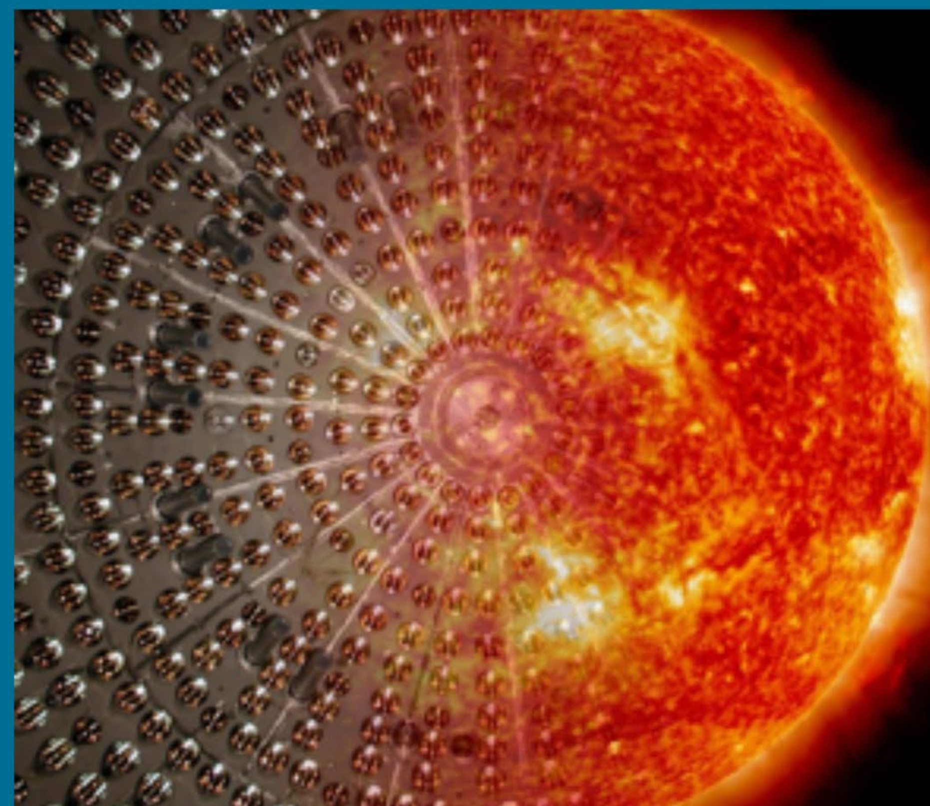
TAUP 2017 Topics in Astroparticle and Underground Physics

JÜLICH FORSCHUNGSZENTRUM

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 μ_ν with Borexino Phase-II solar neutrino data

NEW

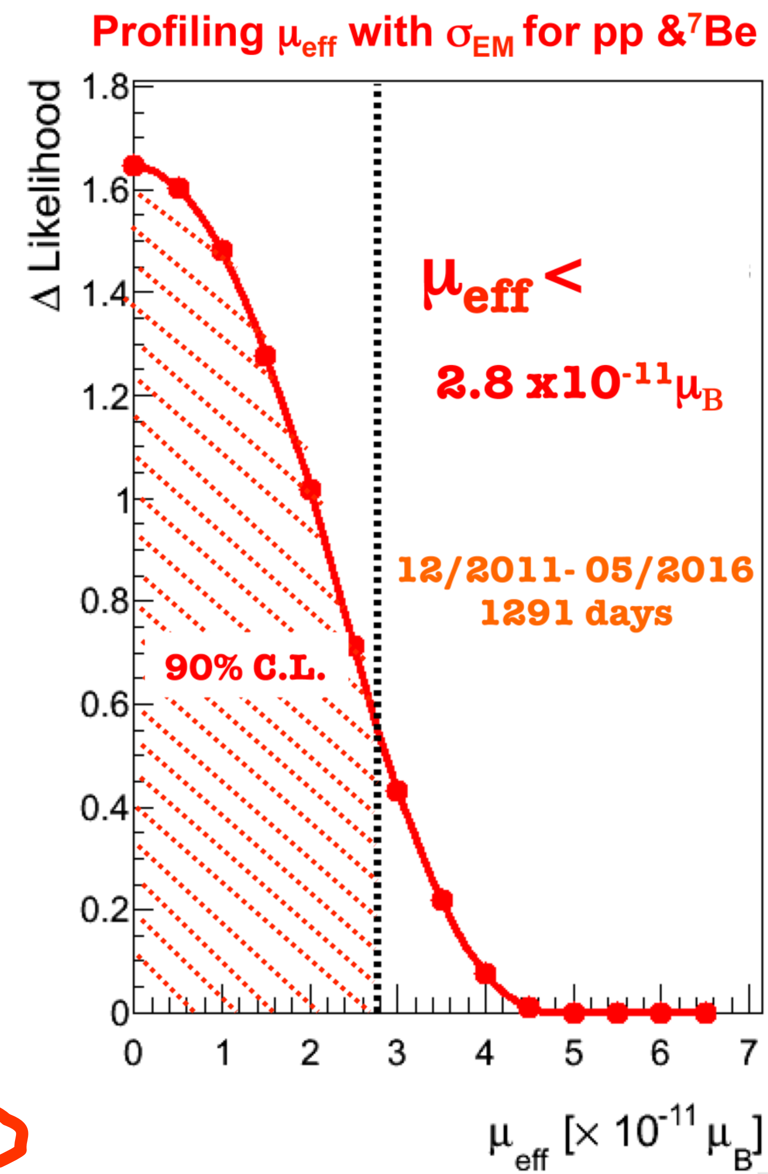
NMM results from Phase 2

JÜLICH FORSCHUNGSZENTRUM

Data selection:
Fiducial volume: R < 3.021 m, |z| < 1.67 m
Muon, ^{214}Bi-^{214}Po, and noise suppression
Free fit parameters: **solar-ν** (pp, ^{7}Be) and **backgrounds** (^{85}Kr, ^{210}Po, ^{210}Bi, ^{11}C, external bgr.), **response parameters** (light yield, ^{210}Po position and width, ^{11}C edge (2 x 511 keV), 2 energy resolution parameters)
Constrained parameters: ^{14}C, pile up
Fixed parameters: pep-, CNO-, ^{8}B-ν rates
Systematics: treatment of pile-up, energy estimators, pep and CNO constraints with LZ and HZ SSM

Without radiochemical constraint
$\mu_{eff} < 4.0 \times 10^{-11} \mu_B$ (90% C.L.)

With radiochemical constraint
$\mu_{eff} < 2.6 \times 10^{-11} \mu_B$ (90% C.L.)
adding systematics
$\mu_{eff} < 2.8 \times 10^{-11} \mu_B$ (90% C.L.)



Experimental limits for different effective μ_ν

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 ν_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 ν_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: $\mu_\nu^{eff} < 2.8 \cdot 10^{-11}\ \mu_B$ at 90% c.l.

- Particle Data Group, 2014-2018 and update of 2019

... comprehensive analysis of ν-e scattering ...

PHYSICAL REVIEW D **95**, 055013 (2017)

Electromagnetic properties of massive neutrinos in low-energy elastic neutrino-electron scattering

Konstantin A. Kouzakov*

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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

ν charge radii

… most accessible for experimental studies are charge radii $<r_\nu^2>$

ν charge radius and anapole moment

$$\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2) i\sigma_{\mu\nu}q^\nu - f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

1. electric
2. magnetic
3. electric

dipole

4. anapole

Although it is usually assumed that ν are electrically neutral (charge quantization implies $Q \sim \frac{1}{3}e$),

ν can dissociates into charged particles so that $f_Q(q^2) \neq 0 \; for \; q^2 \neq 0$

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

where the massive ν charge radius

$$\langle r_\nu^2 \rangle = -6 \frac{df_Q}{dq^2}(0)$$

For massless ν

anapole moment

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

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

??? For massive ν ???

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

Concluding remarks

Kouzakov, Studenikin
Phys. Rev. D 95 (2017) 055013

- cross section of ν-e is determined in terms of 3x3 matrices of ν electromagnetic form factors
- in short-baseline experiments one studies form factors in flavour basis
- long-baseline experiments more convenient to interpret in terms of fundamental form factors in mass basis
- ν millicharge when it is constrained in reactor short-baseline experiments (GEMMA, for instance) should be interpreted as

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

- ν charge radius in ν-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

!

PHYSICAL REVIEW D **98**, 113010 (2018)

Editors' Suggestion

Ch – It – Ru collaboration

Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering

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(Received 15 October 2018; published 26 December 2018)

Coherent elastic neutrino-nucleus scattering is a powerful probe of neutrino properties, in particular of the neutrino charge radii. We present the bounds on the neutrino charge radii obtained from the analysis of the data of the COHERENT experiment. We show that the time information of the COHERENT data allows us to restrict the allowed ranges of the neutrino charge radii, especially that of ν_μ. We also obtained for the first time bounds on the neutrino transition charge radii, which are quantities beyond the standard model.

DOI: 10.1103/PhysRevD.98.1130…

Physical Review D – Highlights 2018 – Editors' Suggestion

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

$$(|\langle r^2_{\nu_{e\mu}}\rangle|, |\langle r^2_{\nu_{e\tau}}\rangle|, |\langle r^2_{\nu_{\mu\tau}}\rangle|) < (22, 38, 27) \times 10^{-32}\ \mathrm{cm}^2$$

K. Kouzakov, A. Studenikin, "Electromagnetic properties of massive neutrinos in low-energy elastic neutrino-electron scattering" Phys. Rev. D 95 (2017) 055013

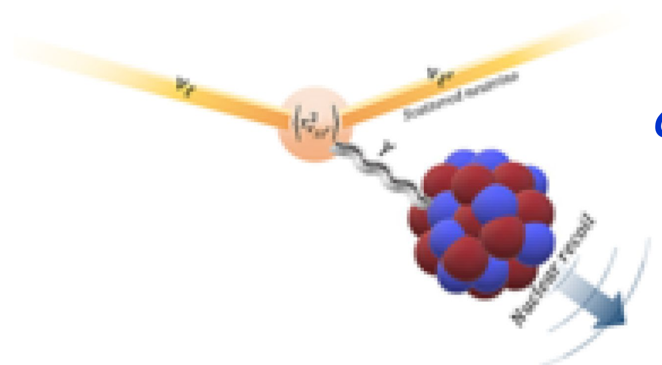
Physical Review D – Highlights 2018 – Editors' Suggestion

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



coherent ν scattering due to charge radius

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.

Show Abstract + ()

Particle Data Group,
Review of Particle Properties (2018),
update of 2019

Experimental limits on ν charge radius $\langle r_\nu^2 \rangle$

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	$\lvert\langle r_{\nu_e}^2\rangle\rvert < 7.3\times10^{-32}$	90%	Vidyakin *et al.* (1992)
	TEXONO	$-4.2\times10^{-32} < \langle r_{\nu_e}^2\rangle < 6.6\times10^{-32}$	90%	Deniz *et al.* (2010)[a]
Accelerator ν_e-e^-	LAMPF	$-7.12\times10^{-32} < \langle r_{\nu_e}^2\rangle < 10.88\times10^{-32}$	90%	Allen *et al.* (1993)[a]
	LSND	$-5.94\times10^{-32} < \langle r_{\nu_e}^2\rangle < 8.28\times10^{-32}$	90%	Auerbach *et al.* (2001)[a]
Accelerator ν_μ-e^-	BNL-E734	$-4.22\times10^{-32} < \langle r_{\nu_\mu}^2\rangle < 0.48\times10^{-32}$	90%	Ahrens *et al.* (1990)[a]
	CHARM-II	$\lvert\langle r_{\nu_\mu}^2\rangle\rvert < 1.2\times10^{-32}$	90%	Vilain *et al.* (1995)[a]

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

$$(\lvert\langle r_{\nu_{e\mu}}^2\rangle\rvert, \lvert\langle r_{\nu_{e\tau}}^2\rangle\rvert, \lvert\langle r_{\nu_{\mu\tau}}^2\rangle\rvert) < (22, 38, 27)\times10^{-32}\ \mathrm{cm}^2,$$

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

JHEP

Published for SISSA by Springer

Received: May 14, 2019
Revised: June 21, 2019
Accepted: July 9, 2019
Published: July 17, 2019

Probing neutrino transition magnetic moments with coherent elastic neutrino-nucleus scattering

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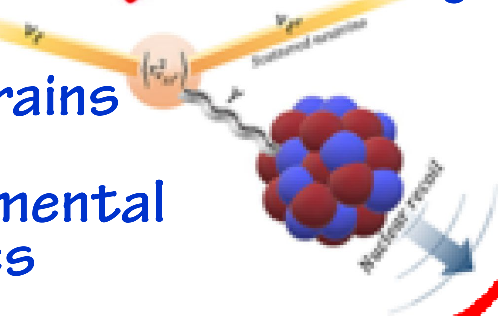
Abstract: We explore the potential of current and next generation of coherent elastic neutrino-nucleus scattering (CEνNS) experiments in probing neutrino electromagnetic interactions. On the basis of a thorough statistical analysis, we determine the sensitivities on each component of the Majorana neutrino transition magnetic moment (TMM), $|\Lambda_i|$, 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.

JHEP07(2019)103

Kate Scholberg,
plenary talk at TAUP 2019

coherent ν scattering

constrains on fundamental physics



COHERENT data have been used for different purposes:

- nuclear neutron distributions
  Cadeddu, Giunti, Li, Zhang PRL 2018
- weak mixing angle
  Cadeddu & Dordei, PRD 2019
  Huang & Chen 2019
- ν electromagnetic properties
  Papoulias & Kosmas PRD 2018
- ν non-standard interactions
  Coloma, Gonzalez-Garcia, Maltoni, Schwetz PRD 2017
  Liao & Marfatia PLB 2017

… A remark on electric charge of ν … Beyond Standard Model…

ν neutrality $Q=0$ is attributed to

gauge invariance + anomaly cancellation constraints

imposed in SM of electroweak interactions

- …General proof:

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

- In SM: $SU(2)_L \times U(1)_Y$

$$Q = I_3 + \frac{Y}{2}$$

- In SM (without ν_R triangle anomalies cancellation constraints → certain relations among particle hypercharges Y that is enough to fix all Y so that they, and consequently Q, are quantized

$Q=0$

- $Q=0$ 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;
M.Dvornikov, A.S., 2004 (for extended SM in one-loop calculations)

- … However, strict requirements for Q quantization may disappear in extensions of standard $SU(2)_L \times U(1)_Y$ EW model if ν_R with $Y \neq 0$ are included : in the absence of Y quantization electric charges Q gets dequantized → **millicharged ν**

Experimental limits for different effective q_ν

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

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

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

C.Patrignani et al (Particle Data Group), "The Review of Particle Physics 2016" Chinese Physics C 40 (2016) 100001

Particle Data Group
Review of Particle Properties
(2016-2018)
update of 2019

Bounds on millicharge q_ν from μ_ν (GEMMA Coll. data)

②

two not seen contributions:

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

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

ν-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_ν from … unobserved effects of New Physics

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

!

Studenikin, Europhys. Lett. 107 (2014) 210011

Particle Data Group, 2016-2018 and update of 2019

Expected new constraints from GEMMA:

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

2020 (expected)

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

Constraints on q_ν

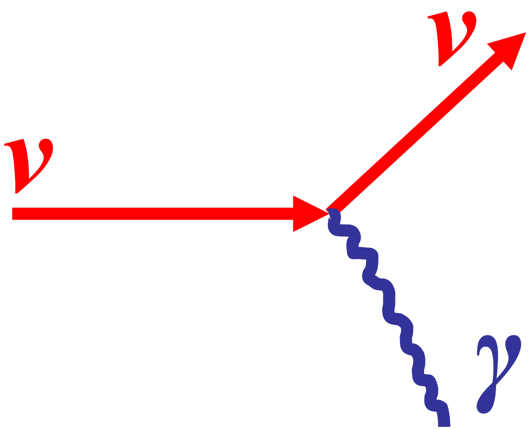
$| q_\nu | < 1.5 \times 10^{-12} e_0$ ●

… unprecedentedly low threshold …

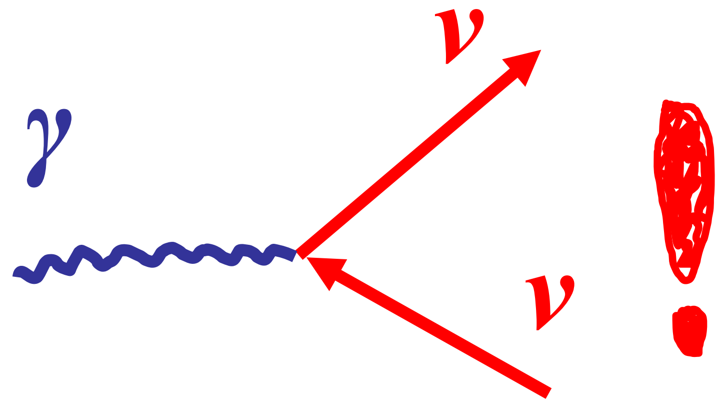
$|q_\nu| < 1.1 \times 10^{-13} e_0$

!
!

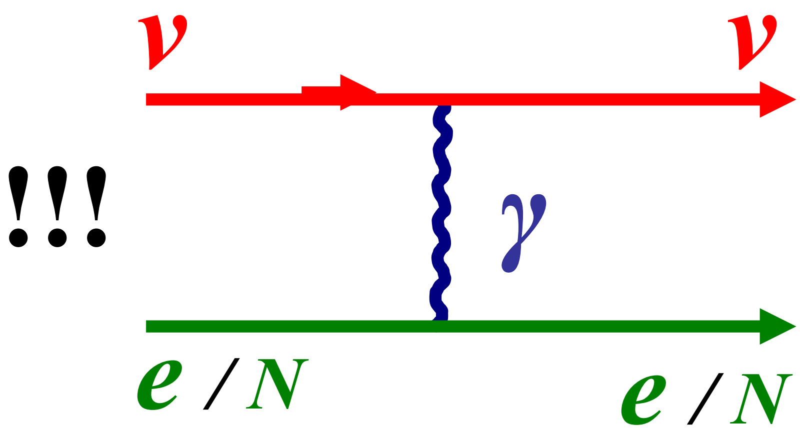
ν electromagnetic interactions



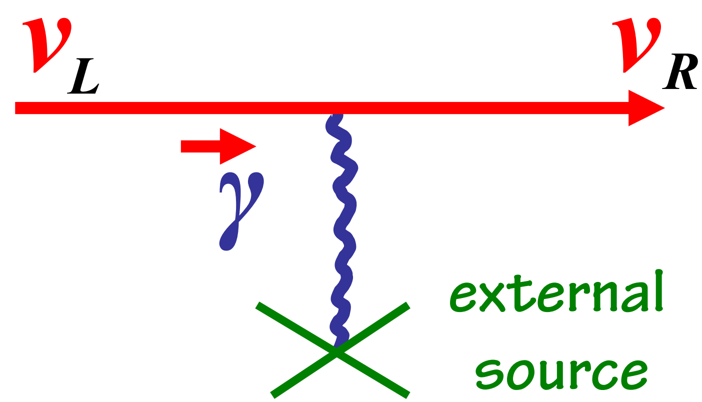
ν decay, Cherenkov radiation



γ decay in plasma



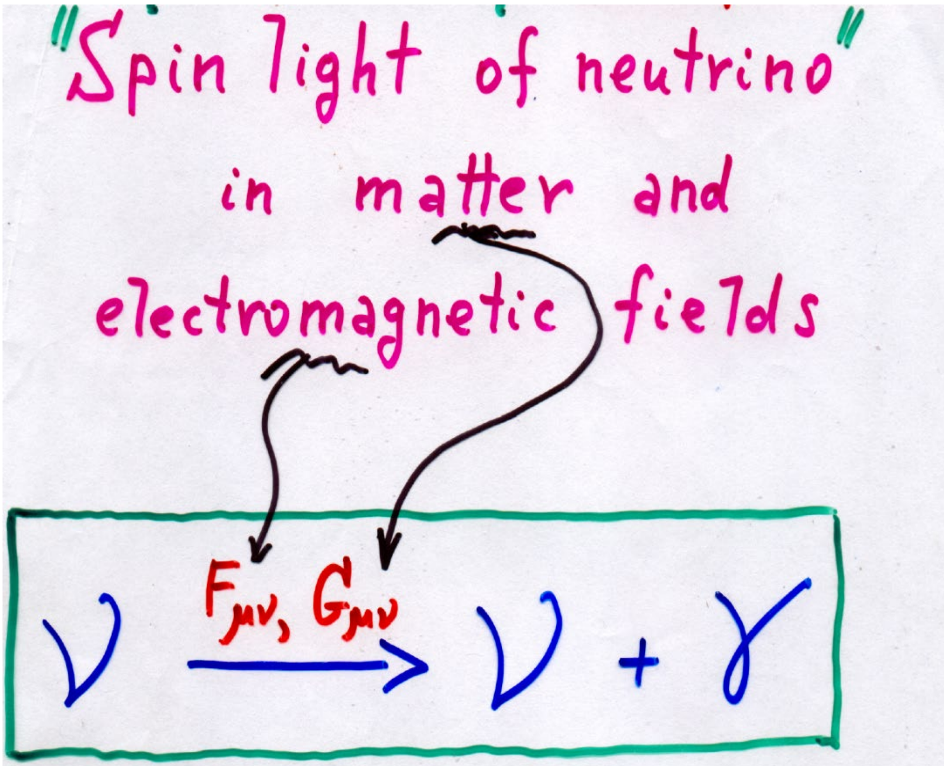
Scattering



Spin precession

• New mechanism of electromagnetic radiation

$SL\nu$



A.Lobanov, A.Studenikin,
Phys.Lett. B 564 (2003) 27
Phys.Lett. B 601 (2004) 171
Studenikin, A.Ternov,
Phys.Lett. B 608 (2005) 107

A.Grigoriev, A.S., Ternov,
Phys.Lett. B 622 (2005) 199
Studenikin,
J.Phys.A: Math.Gen. 39 (2006) 6769
J.Phys.A: Math.Theor. 41 (2008) 16402

A.Grigoriev, A.Lokhov,
A.Studenikin, A.Ternov,
Nuovo Cim. 35 C (2012) 57
Phys.Lett.B 718 (2012) 512

A.Grigoriev, A.Lokhov,
A.Ternov, A.Studenikin

The effect of plasmon mass on Spin Light of Neutrino in dense matter

Phys.Lett. B 718 (2012) 512

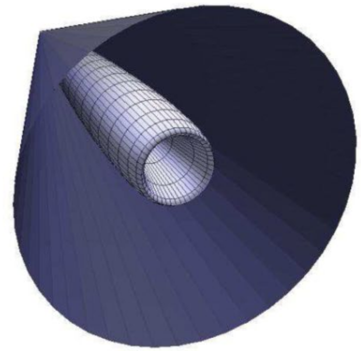


Figure 1: 3D representation of the radiation power distribution.

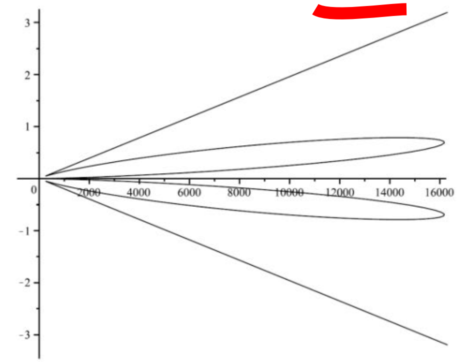


Figure 2: The two-dimensional cut along the symmetry axis. Relative units are used.

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 $a = m_\gamma^2/4\tilde{n}p$ 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 $n = 10^{41} cm^{-3}$) for ultra-high energy neutrinos for a wide range of energies starting from $E = 1$ 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].

Astrophysics bounds on μ_ν

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

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

Red Giant lumin.
! $\mu_\nu \lesssim 3 \cdot 10^{-12} \mu_B$
G. Raffelt, D. Dearborn, J. Silk, 1989.

Bounds depend on

- modeling of astrophysical system,
- on assumption on he neutrino properties .

Generic assumption:

- absence of other nonstandard interactions accept for μ_ν

A global treatment would be desirable, incorporating oscillations and matter effects, as well as the complications due to interference and competitions among various channels

Astrophysics bounds on μ_ν —

... examples...

1) SN 1987A provides energy-loss limit on μ_ν (also d and transition moments)

...in magnetic moment scattering (change of helicity) $\nu_L \Rightarrow \nu_R$

proto-neutron star formed in core-collapse SN can cool faster

$$\Updownarrow \quad \mu_\nu^D \sim 10^{-12} \mu_B \quad \Updownarrow$$

... inconsistent with SN1987A observed cooling time

Barbieri, Mahapatra
Lattimer, Cooperstein
1988

2) ν_R from inner SN core have larger energy than ν_L emitted from neutrino sphere
then $\nu_R \overset{B}{\longleftrightarrow} \nu_L$ in galactic B
(sterile) (active)

⇨ from absence of anomalous high-energy ν

Nötzold
1988

- … astrophysical bound on millicharge q_ν from

ν 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

In quasi-classical approach

✓ quantum states in rotating matter

✓ motion in circular orbits

$$R = \int_0^\infty \Psi_L^\dagger \, \mathrm{r} \, \Psi_L \, d\mathbf{r} = \sqrt{\frac{2N}{|2Gn_n\omega - \epsilon q_0 B|}}$$

due to effective Lorentz force

$$\mathbf{F}_{eff} = q_{eff}\mathbf{E}_{eff} + q_{eff}\left[\boldsymbol{\beta} \times \mathbf{B}_{eff}\right]$$

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

$$q_{eff}\mathbf{E}_{eff} = q_m\mathbf{E}_m + q_0\mathbf{E} \qquad q_{eff}\mathbf{B}_{eff} = |q_m B_m + q_0 B|\mathbf{e}_z$$

where $q_m = -G, \quad \mathbf{E}_m = -\boldsymbol{\nabla} n_n, \quad \mathbf{B}_m = 2n_n\boldsymbol{\omega}$

matter induced "charge", "electric" and "magnetic" fields

- ν Star Turning mechanism (ν ST)

Studenikin, Tokarev, Nucl. Phys. B 884 (2014) 396

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

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

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

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

.. best astrophysical bound ...

50 years of ν oscillation formulae
Gribov & Pontecorvo (1969)

new developments in ν spin and flavour oscillations

(1) generation of ν spin (flavour) oscillations by interaction with transversal matter current $j_{\perp}$

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

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

Artem Popov, A. S..
"Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field",
Eur. Phys .J. C79 (2019) no.2, 144

Main steps in ν oscillations

63 years !
early history of ν oscillations

1. $\nu_e \overset{vac}{\longleftrightarrow} \bar{\nu}_e$, B. Pontecorvo, 1957
2. $\nu_e \overset{vac}{\longleftrightarrow} \nu_\mu$, Z. Maki, M. Nakagava, S. Sakata, 1962
3. $\nu_e \overset{matter,\ \rho=const}{\longleftrightarrow} \nu_\mu$, L. Wolfenstein, 1978
4. $\nu_e \overset{matter,\ \rho\neq const}{\longleftrightarrow} \nu_\mu$, S. Mikheev, A. Smirnov, 1985
   - resonances in ν flavour oscillations ⇒ MSW-effect, solution for $\nu_\odot$-problem
5. $\nu_{e_L} \overset{B_\perp}{\longleftrightarrow} \nu_{e_R}$, A. Cisneros, 1971; M. Voloshin, M. Vysotsky, L. Okun, 1986, $\nu_\odot$
6. $\nu_{e_L} \overset{B_\perp}{\longleftrightarrow} \nu_{e_R}, \nu_{\mu_R}$, E. Akhmedov, 1988; C.-S. Lim & W. Marciano, 1988
   - resonances in ν spin (spin-flavour) oscillations in matter

> 30 years !

only in $B_\perp$ and matter at rest

Bruno Pontecorvo
1913–1993

ν spin and spin-flavour oscillations in $B_\perp$

$$\nu_{e_L} \Leftrightarrow \nu_{\mu_R}$$

$$B = |\mathbf{B}_\perp| e^{i\phi(t)}$$

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

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

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

- Resonance amplification of oscillations in matter:

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

Akhmedov, 1988
Lim, Marciano

... similar to MSW effect

1

ν

Neutrino spin $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$ and

spin-flavour $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R$

oscillations engendered

by transversal matter currents $j_\perp$

~~($\mu_\nu B$)~~

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

Physics of Atomic Nuclei, Vol. 67, No. 5, 2004, pp. 993–1002. Translated from Yadernaya Fizika, Vol. 67, No. 5, 2004, pp. 1014–1024.

ELEMENTARY PARTICLES AND FIELDS
Theory

Phys.Atom.Nucl. 67 (2004) 993-1002

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.

Consider spin, spin-flavour

$$\nu_{e_L} \to \nu_{e_R}, \quad \nu_{e_L} \to \nu_{\mu_R}$$

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

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

$$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}, \quad \Delta_{\text{eff}}^2 = \frac{\mu}{\gamma_\nu}\left|\mathbf{M}_{0\parallel} + \mathbf{B}_{0\parallel}\right|. \quad E_{\text{eff}} = \mu\left|\mathbf{B}_\perp + \frac{1}{\gamma_\nu}\mathbf{M}_{0\perp}\right|,$$

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

- transversal current $j_\perp$

$$\vec{M}_0 = \gamma_\nu \rho n_e \left(\vec{\beta}_\nu (1 - \vec{\beta}_\nu \vec{v}_e) - \frac{1}{\gamma_\nu} \vec{v}_{e_\perp}\right),$$

matter density

$\parallel$ $\perp$

$$\gamma_\nu = \frac{E_\nu}{m_\nu},$$

where

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

Physics of Atomic Nuclei, Vol. 67, No. 5, 2004, pp. 993–1002. Translated from Yadernaya Fizika, Vol. 67, No. 5, 2004, pp. 1014–1024.

ELEMENTARY PARTICLES AND FIELDS
Theory

Neutrino in Electromagnetic Fields and Moving Media

A. I. Studenikin*
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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, $\mathbf{M}_{0\perp} \neq 0$) 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.

… the effect of ν helicity conversions and oscillations induced by transversal matter currents has been recently confirmed:

$$\nu_{e_L} \to \nu_{e_R}, \quad \nu_{e_L} \to \nu_{\mu_R}$$

- J. Serreau and C. Volpe, "Neutrino-antineutrino correlations in dense anisotropic media", Phys .Rev. D90 (2014) 125040

- V. Cirigliano, 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 …

- ν spin evolution effective Hamiltonian in moving matter ? transversal and longitudinal currents $\vec{j}_\perp + \vec{j}_\parallel$
- two flavor ν with two helicities: $\nu_f = (\nu_e^+, \nu_e^-, \nu_\mu^+, \nu_\mu^-)^T$

ν interaction with matter composed of neutrons: $n = \frac{n_0}{\sqrt{1-v^2}}$ neutron number density in laboratory reference frame

$\mathbf{v} = (v_1, v_2, v_3)$ velocity of matter

- $$L_{int} = -f^\mu \sum_l \bar{\nu}_l(x)\gamma_\mu \frac{1+\gamma_5}{2}\nu_l(x) = -f^\mu \sum_i \bar{\nu}_i(x)\gamma_\mu \frac{1+\gamma_5}{2}\nu_i(x)$$ $l = e,\ or\ \mu$, $i = 1,\ 2$

$$f^\mu = -\frac{G_F}{2\sqrt{2}} j_n^\mu$$

- $$j_n^\mu = n(1, \mathbf{v})$$

$$\nu_e^\pm = \nu_1^\pm \cos\theta + \nu_2^\pm \sin\theta,$$
$$\nu_\mu^\pm = -\nu_1^\pm \sin\theta + \nu_2^\pm \cos\theta$$

ν flavour and mass states

P. Pustoshny, A. Studenikin,
Phys. Rev. D98 (2018) no. 11, 113009

ν (2 flavours x 2 helicities) evolution equation

$$i\frac{d}{dt}\nu_f^s = \left(H_0 + \Delta H_0^{SM} + \Delta H_{j_{||}+j_\perp}^{SM} + \Delta H_{B_{||}+B_\perp}^{SM} + \Delta H_0^{NSI} + \Delta H_{j_{||}+j_\perp}^{NSI}\right)\nu_f^s$$

- H_0: vacuum
- ΔH_0^{SM}: matter at rest (Standard Model)
- $\Delta H_{j_{||}+j_\perp}^{SM}$: moving matter (Standard Model)
- $\Delta H_{B_{||}+B_\perp}^{SM}$: B
- ΔH_0^{NSI}: matter at rest (Non-Standard Interactions)
- $\Delta H_{j_{||}+j_\perp}^{NSI}$: moving matter (Non-Standard Interactions)

Resonant amplification of ν oscillations:

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

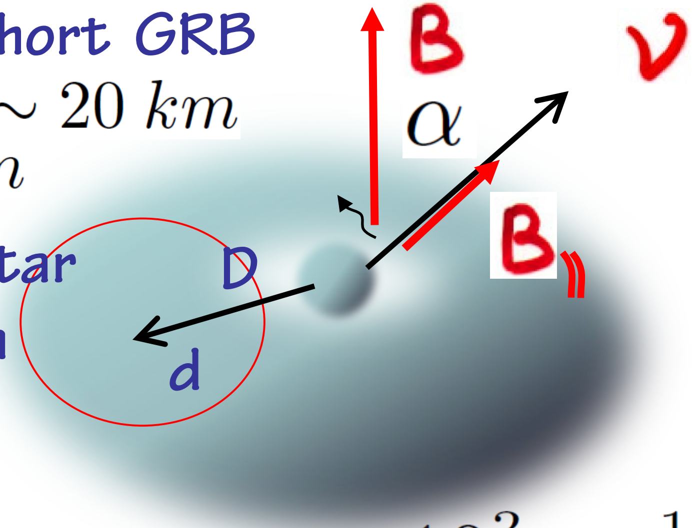
P. Pustoshny, A. Studenikin, Phys. Rev. D98 (2018) no. 11, 113009

$$\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$$

a model of short GRB

$D \sim 20\ km$

$d \sim 20\ km$



- Consider ν escaping central neutron star with inclination angle α from accretion disk: $B_{\parallel} = B \sin\alpha \sim \frac{1}{2} B$

- Toroidal bulk of rotating dense matter with $\omega = 10^3\ s^{-1}$

- transversal velocity of matter

$v_\perp = \omega D = 0.067$ and $\gamma_n = 1.002$

- Perego et al, Mon.Not.Roy.Astron.Soc. 443 (2014) 3134
- Grigoriev, Lokhov, Studenikin, Ternov, JCAP 1711 (2017) 024

$$E_{eff} = \left(\frac{\eta}{\gamma}\right)_{ee} \widetilde{G} n v_\perp = \frac{\cos^2\theta}{\gamma_{11}} \widetilde{G} n v_\perp \approx \widetilde{G} n_0 \frac{\gamma_n}{\gamma_\nu} v_\perp$$

$$\Delta_{eff} = \left| \left(\frac{\mu}{\gamma}\right)_{ee} \boldsymbol{B}_{||} + \eta_{ee} \widetilde{G} n \boldsymbol{\beta} \right| \approx \left| \frac{\mu_{11}}{\gamma_\nu} B_{||} - \widetilde{G} n_0 \gamma_n \right|$$

$$\boldsymbol{B}_{||} \boldsymbol{\beta} = -1$$

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

resonance condition

$$\left| \frac{\mu_{11} B_{||}}{\widetilde{G} n_0 \gamma_n} - \gamma_\nu \right| \leq 1$$

Resonance amplification of spin-flavor oscillations (in the absence of $j_{\parallel}$)

$$\nu_e^L \Leftarrow (j_\perp, B_\perp) \Rightarrow \nu_\mu^R$$

$\vec{B} = \vec{B}_\perp + \vec{B}_\parallel \rightarrow 0$

Criterion – oscillations are important:

$$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2} \geq \frac{1}{2}$$

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

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

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

$$\left| \left(\frac{\eta}{\gamma}\right)_{e\mu} \tilde{G} n v_\perp \right| \geq \left| \Delta M - \tilde{G} n (1 - \boldsymbol{v\beta}) \right| \Longrightarrow \tilde{G} n \sim \Delta M$$

$$\Delta m^2 = 7.37 \times 10^{-5}\ eV^2$$
$$\sin^2 \theta = 0.297$$
$$p_0^\nu = 10^6\ eV$$

$$\Longrightarrow \Delta M = 0.75 \times 10^{-11} eV$$

$$\tilde{G} = \frac{G_F}{2\sqrt{2}} = 0.4 \times 10^{-23}\ \ eV^{-2}$$

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

$$L_{eff} = \frac{\pi}{(\frac{\eta}{\gamma})_{e\mu} \tilde{G} n v_\perp} \approx 5 \times 10^{11}\ km$$

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

② ν

"Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field"

$$\nu_e^L \leftrightarrow \nu_\mu^L \qquad \nu_e^L \leftrightarrow \nu_e^R \qquad \nu_e^L \leftrightarrow \nu_\mu^R$$

A.Popov, A.Studenikin,

Eur. Phys .J. C79 (2019) 144

arXiv: 1902.08195

Consider two flavour ν with two helicities as superposition of **helicity mass states** $\nu_i^{L(R)}$

$$\nu_e^{L(R)} = \nu_1^{L(R)} \cos\theta + \nu_2^{L(R)} \sin\theta,$$
$$\nu_\mu^{L(R)} = -\nu_1^{L(R)} \sin\theta + \nu_2^{L(R)} \cos\theta$$

however, $\nu_i^{L(R)}$ are not stationary states in magnetic field $\mathbf{B} = (B_\perp, 0, B_\parallel)$

$$\nu_i^L(t) = c_i^+ \nu_i^+(t) + c_i^- \nu_i^-(t),$$
$$\nu_i^R(t) = d_i^+ \nu_i^+(t) + d_i^- \nu_i^-(t)$$

$\Leftarrow$ $\nu_i^{-(+)}$ stationary states in B

- Dirac equation $(\gamma_\mu p^\mu - m_i - \mu_i \boldsymbol{\Sigma} \boldsymbol{B}) \nu_i^s(p) = 0$ in a constant B

$$\hat{H}_i \nu_i^s = E \nu_i^s \qquad \hat{H}_i = \gamma_0 \boldsymbol{\gamma} \boldsymbol{p} + \mu_i \gamma_0 \boldsymbol{\Sigma} \boldsymbol{B} + m_i \gamma_0 \quad (s = \pm 1)$$

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

ν spin operator that commutes with $\hat{H}_i$:

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

$$\hat{S}_i \left| \nu_i^s \right\rangle = s \left| \nu_i^s \right\rangle, \; s = \pm 1$$

"bra-ket" products

- $$\langle \nu_i^s | \nu_k^{s'} \rangle = \delta_{ik} \delta_{ss'}$$

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

- ν energy spectrum

$$E_i^s = \sqrt{m_i^2 + p^2 + \mu_i{}^2 \mathbf{B}^2 + 2\mu_i s \sqrt{m_i^2 \mathbf{B}^2 + p^2 B_\perp^2}}$$

Probabilities of ν oscillations (flavour, spin and spin-flavour)

$\nu_e^L \leftrightarrow \nu_\mu^L$ $\quad P_{\nu_e^L \to \nu_\mu^L}(t) = \left|\langle \nu_\mu^L | \nu_e^L(t)\rangle\right|^2$ $\qquad \mu_\pm = \frac{1}{2}(\mu_1 \pm \mu_2)$ magnetic moments of ν mass states

flavour

$$P_{\nu_e^L \to \nu_\mu^L}(t) = \sin^2 2\theta \Big\{ \cos(\mu_1 B_\perp t) \cos(\mu_2 B_\perp t) \sin^2 \frac{\Delta m^2}{4p} t + \sin^2 (\mu_+ B_\perp t) \sin^2 (\mu_- B_\perp t) \Big\}$$

spin

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

spin-flavour

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

… interplay of oscillations on vacuum $\omega_{vac} = \frac{\Delta m^2}{4p}$ and on magnetic $\omega_B = \mu B_\perp$ frequencies

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

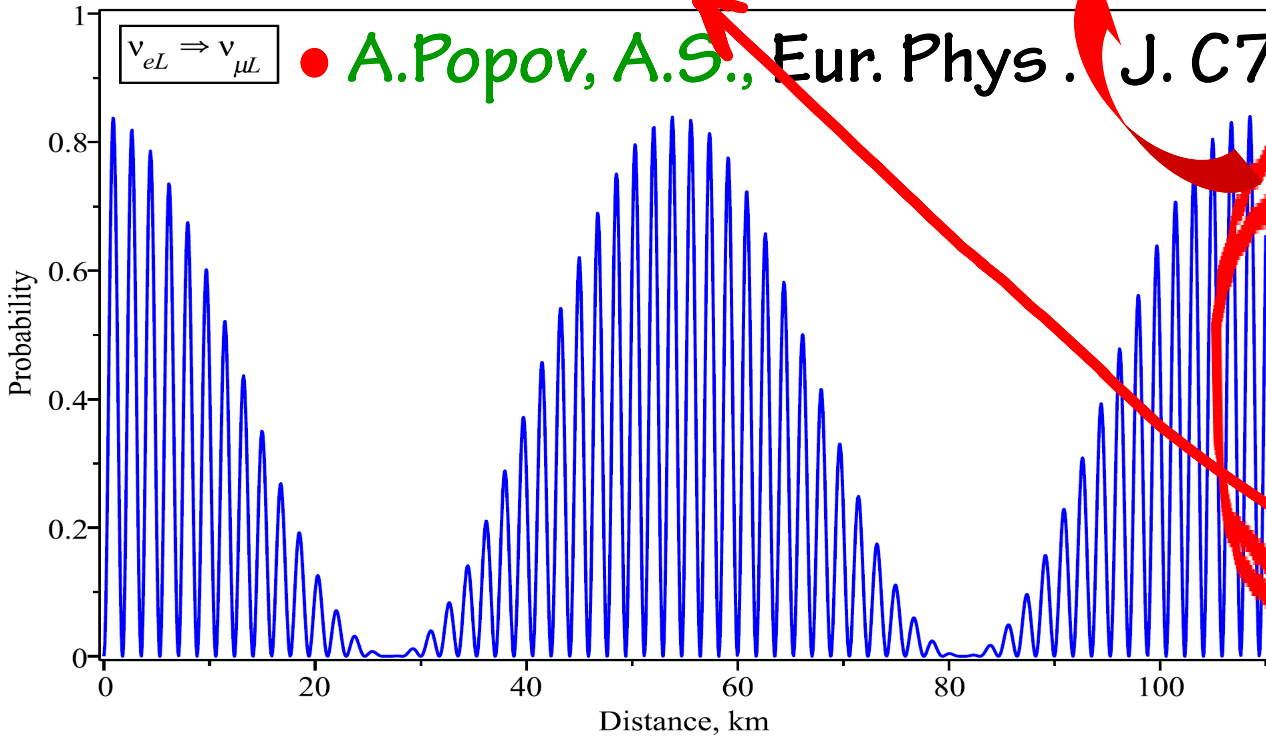
- For the case $\mu_1 = \mu_2$: probability of flavour oscillations

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

flavour

no spin oscillations

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



... amplitude of flavour oscillations on vacuum frequency $\omega_{vac} = \frac{\Delta m^2}{4p}$ is modulated by magnetic frequency $\omega_B = \mu B_\perp$

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 $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

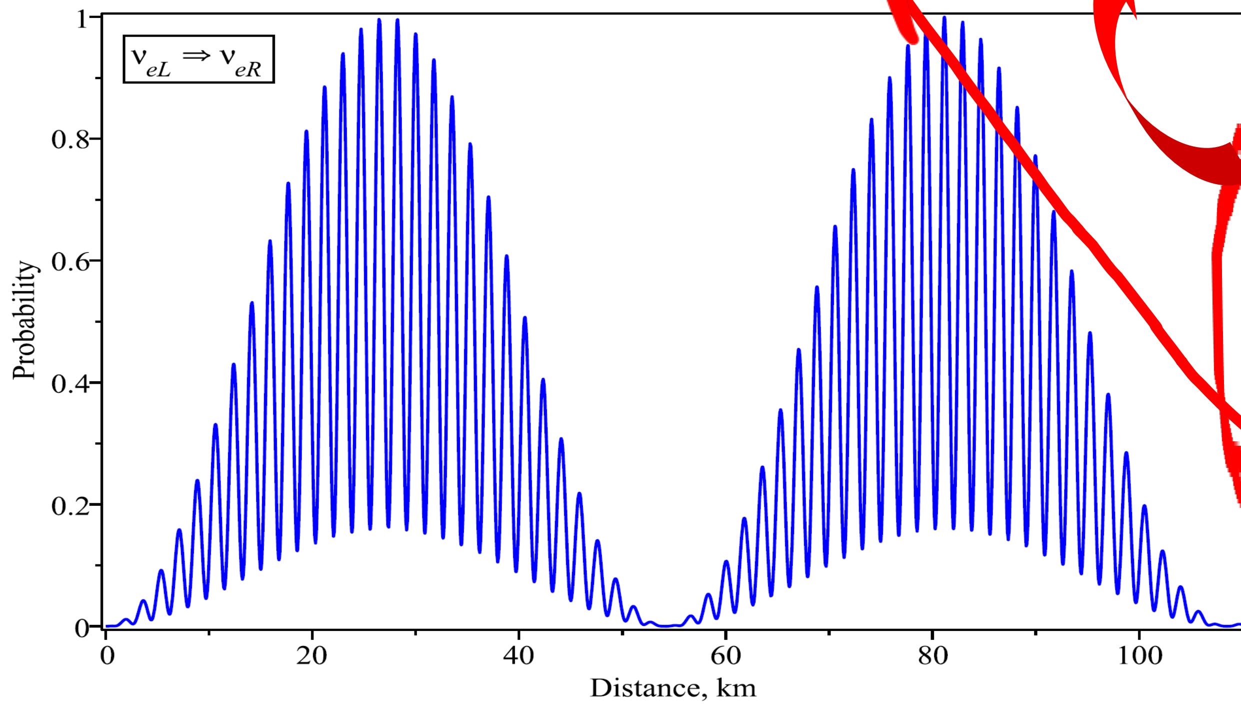
Chotorlishvili, Kouzakov, Kurashvili, Studenikin,
Spin-flavor oscillations of ultrahigh-energy cosmic neutrinos in interstellar space: The role of neutrino magnetic moments,
Phys. Rev. D96 (2017) 103017

For the case $\mu_1 = \mu_2$: probability of spin oscillations

no flavour oscillations

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

spin



... amplitude of spin oscillations on magnetic frequency $\omega_B = \mu B_\perp$ is modulated by vacuum frequency $\omega_{vac} = \frac{\Delta m^2}{4p}$

Fig. 2 The probability of the neutrino spin oscillations $\nu_e^L \to \nu_e^R$ 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 $\mu_1 = \mu_2 = 10^{-20}\mu_B$.

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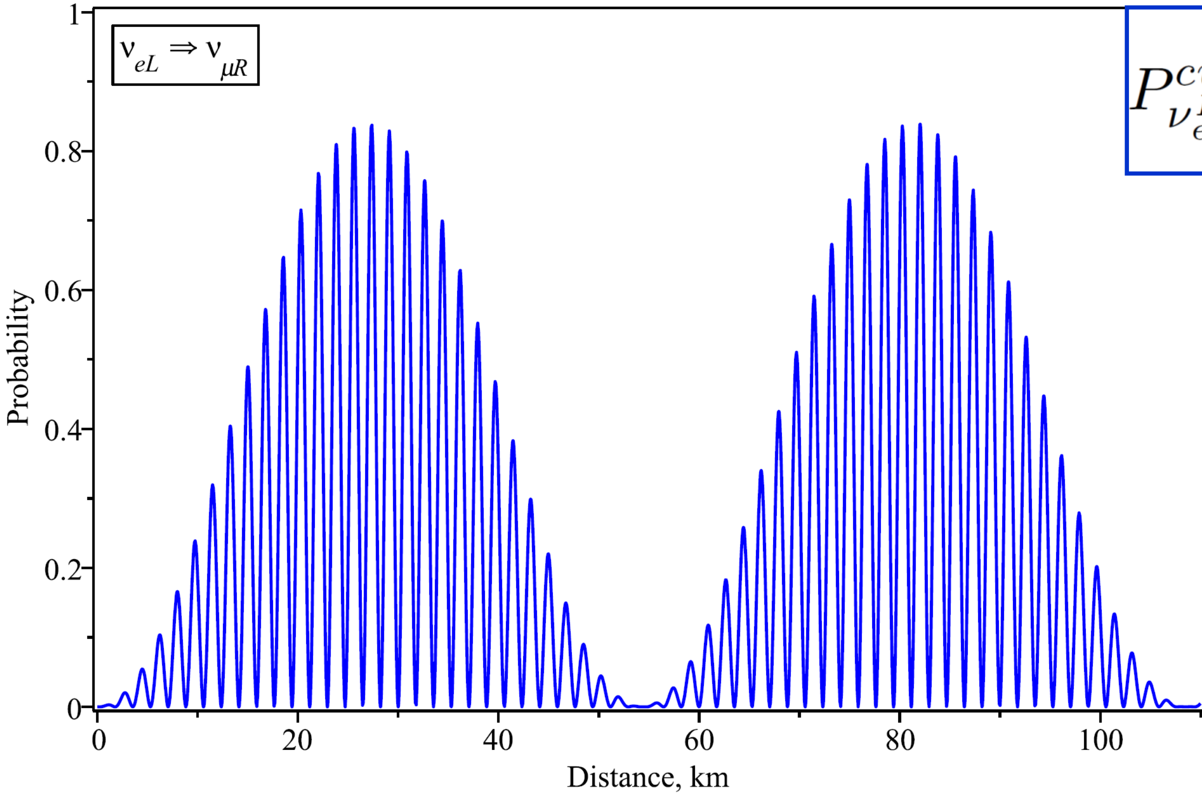
- For the case $\mu_1 = \mu_2$, probability of spin-flavour oscillations

$$P_{\nu_e^L \to \nu_\mu^R} = \sin^2(\mu B_\perp t) \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4p} t = P^{cust}_{\nu_e^L \to \nu_e^R} P^{cust}_{\nu_e^L \to \nu_\mu^L}$$

spin-flavour



$$P^{cust}_{\nu_e^L \to \nu_\mu^L} = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4p} t$$

$$P^{cust}_{\nu_e^L \to \nu_e^R} = \sin^2(\mu B_\perp t)$$

... interplay of oscillations on vacuum $\omega_{vac} = \frac{\Delta m^2}{4p}$ and on magnetic $\omega_B = \mu B_\perp$ frequencies

Fig. 3 The probability of the neutrino spin flavour oscillations $\nu_e^L \to \nu_\mu^R$ 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 $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

... in literature:

- $P_{\nu_e^L \nu_\mu^R} = \sin^2(\mu_{e\mu} B_\perp t) = 0$

$$\mu_{e\mu} = \frac{1}{2}(\mu_2 - \mu_1) \sin 2\theta$$

$$\mu_1 = \mu_2, \quad \mu_{ij} = 0, \quad i \neq j$$

- For completeness: ν survival $\nu_e^L \leftrightarrow \nu_e^L$ probability

… depends on μ_ν and B

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

$\sum$ of all probabilities (as it should be…):

$$P_{\nu_e^L \to \nu_\mu^L} + P_{\nu_e^L \to \nu_e^R} + P_{\nu_e^L \to \nu_\mu^R} + P_{\nu_e^L \to \nu_e^L} = 1$$

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 ν propagation in astrophysical environments

Conclusions

1 2 3

① ν electromagnetic properties: Future prospects

- new constraints on μ_ν (and q_ν) from GEMMA and Borexino (?)

- charge radius in ν - 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

②

μ_ν interactions could have important effects in astrophysical and cosmological environments

A. de Gouvea, S. Shalgar,
Cosmol. Astropart. Phys. 04 (2013) 018

future high-precision observations of supernova ν fluxes (for instance, in JUNO experiment) may reveal effect of collective spin-flavour oscillations due to Majorana

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

3 ν electromagnetic interactions (new effects)

two new aspects of ν spin, spin-flavour and flavour oscillations

1 generation of ν spin and spin-flavour oscillations by ν interaction with transversal matter current $j_{\perp}$

Studenikin, 2014
Pustoshny, Studenikin, Phys.Rev. D98 (2018) 113009

2 consistent treatment of ν spin, flavour and spin-flavour oscillations in B

Popov, Studenikin, Eur. Phys .J. C 79 (2019) 144

new effects in ν oscillations in analysis of supernovae ν fluxes (for JUNO ?)

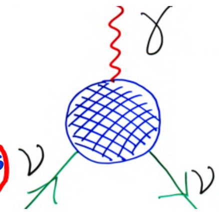
Electromagnetic Properties of ν

MSU Alexander Studenikin JINR

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

Studenikin, "ν electromagnetic interactions: A window to new physics - II", arXiv: 1801.18887

① νEP theory - ν vertex function



matrices in ν mass eigenstates space

$$\Lambda^{if}_\mu(q) = f^{if}_Q(q^2)\gamma_\mu + f^{if}_M(q^2)i\sigma_{\mu\nu}q^\nu + f^{if}_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f^{if}_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5,$$

electric charge
magnetic moment
electric moment
anapole moment

form factors $f^{if}_X(q^2)$ at $q^2 = 0$ $\Rightarrow$ static EP of ν

Dirac	ν Majorana	
q_{if}	$q_{if} = 0$	CPT + charge concervation
μ_{if}	μ_{if} $(i \neq f)$	
ε_{if}	ε_{if} $(i \neq f)$	
a_{if}	a_{if}	

Dirac: $\neq 0$

Hermiticity and discrete symmetries of EM current $\langle \nu(p')|J^{EM}_\mu|\nu(p)\rangle = \bar{u}(p')\Lambda_\mu(q)u(p)$ put constraints on form factors

②

$$\mu^D_{jj} = \frac{3e_0G_Fm_j}{8\sqrt{2}\pi^2} \approx 3.2\times10^{-19}\mu_B\left(\frac{m_j}{1\ \text{eV}}\right)$$

Fujikawa & Shrock, 1980

- much greater values are Beyond Minimally Extended SM
- transition moments $\mu_{i\neq f}$, $\varepsilon_{i\neq f}$ are GIM suppressed

③ ν EMP experimental bounds

$$\mu^{eff}_\nu < \begin{matrix}2.9\\2.8\\\sim 0.1\end{matrix} \times 10^{-11}\mu_B$$

GEMMA Coll. 2012
Borexino Coll. 2017
Astrophysics, Raffelt ea 1988
Arcoa Dias ea 2015

$$q_{\nu_e} < \begin{matrix}\sim 10^{-12}\\ \sim 10^{-19}\\ \sim 10^{-21}\end{matrix} \; e_0$$

reactor ν scattering AS '14, Chen ea '14
AS '14 (astrophysics)
neutrality of matter

Thank you