Electromagnetic properties of neutrinos

(new constraints and new effects in oscillations)

European Physical Society
Conference on
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Alexander Studenikin
Moscow State University
&
JINR –Dubna
(GEMMA coll.)

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

REVIEWS OF MODERN PHYSICS, VOLUME 87, APRIL–JUNE 2015

Neutrino electromagnetic interactions: A window to new physics

+ upgrade: Studenikin, "ν electromagnetic interactions: A window to new physics – II", arXiv: 1801.18887

Carlo Giunti*

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

Alexander Studenikin†

Department of Theoretical Physics, Faculty of Physics, Moscow State University and Joint Institute for Nuclear Research, Dubna, Russia

(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

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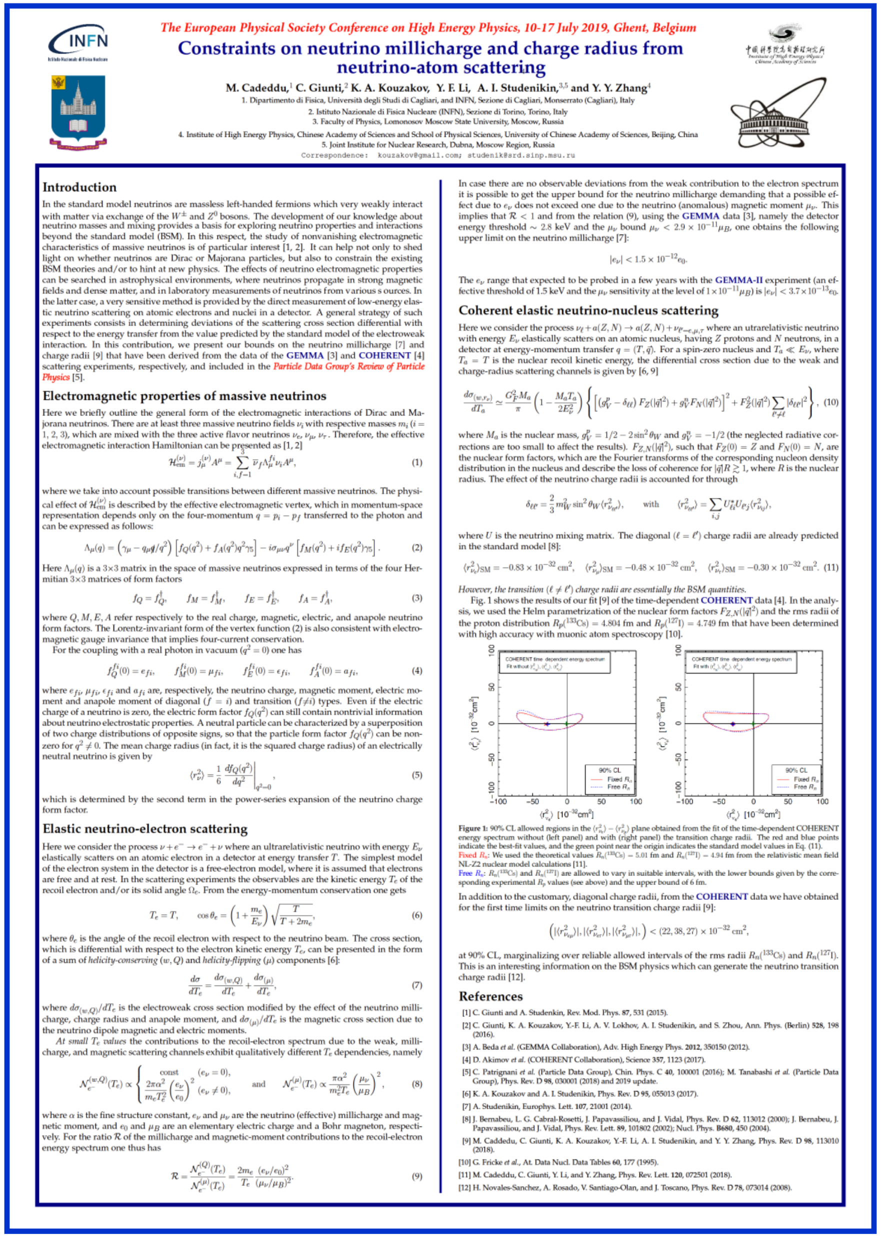
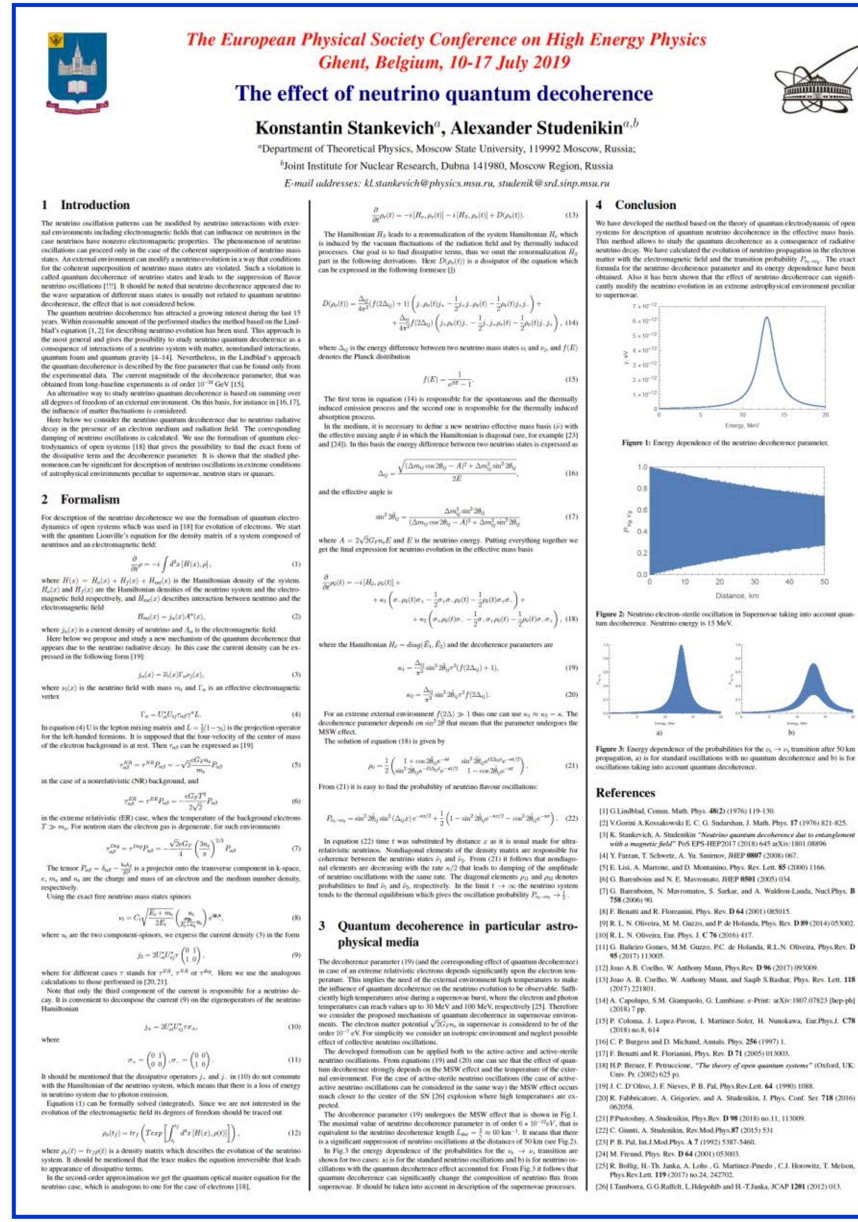




M. Cadeddu, C. Giunti, K. Kouzakov, Y.F. Li, A. Studenikin, Y. Zhang

poster # 34

"Constraints on neutrino millicharge and charge radius from neutrino-atom scattering"

poster # 29

K. Stankevich, A. Studenikin

"The effect of neutrino quantum decoherence"

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)

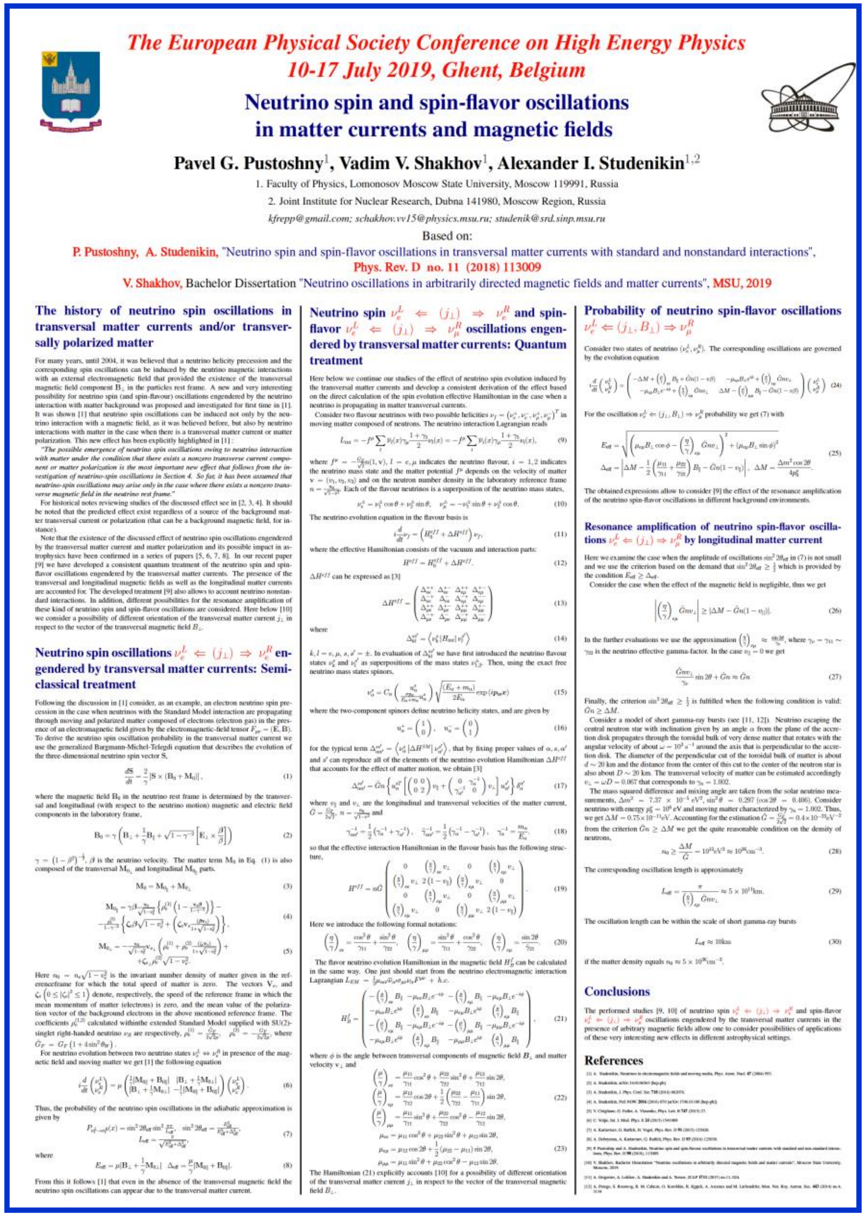
new developments in ν spin and flavour oscillations

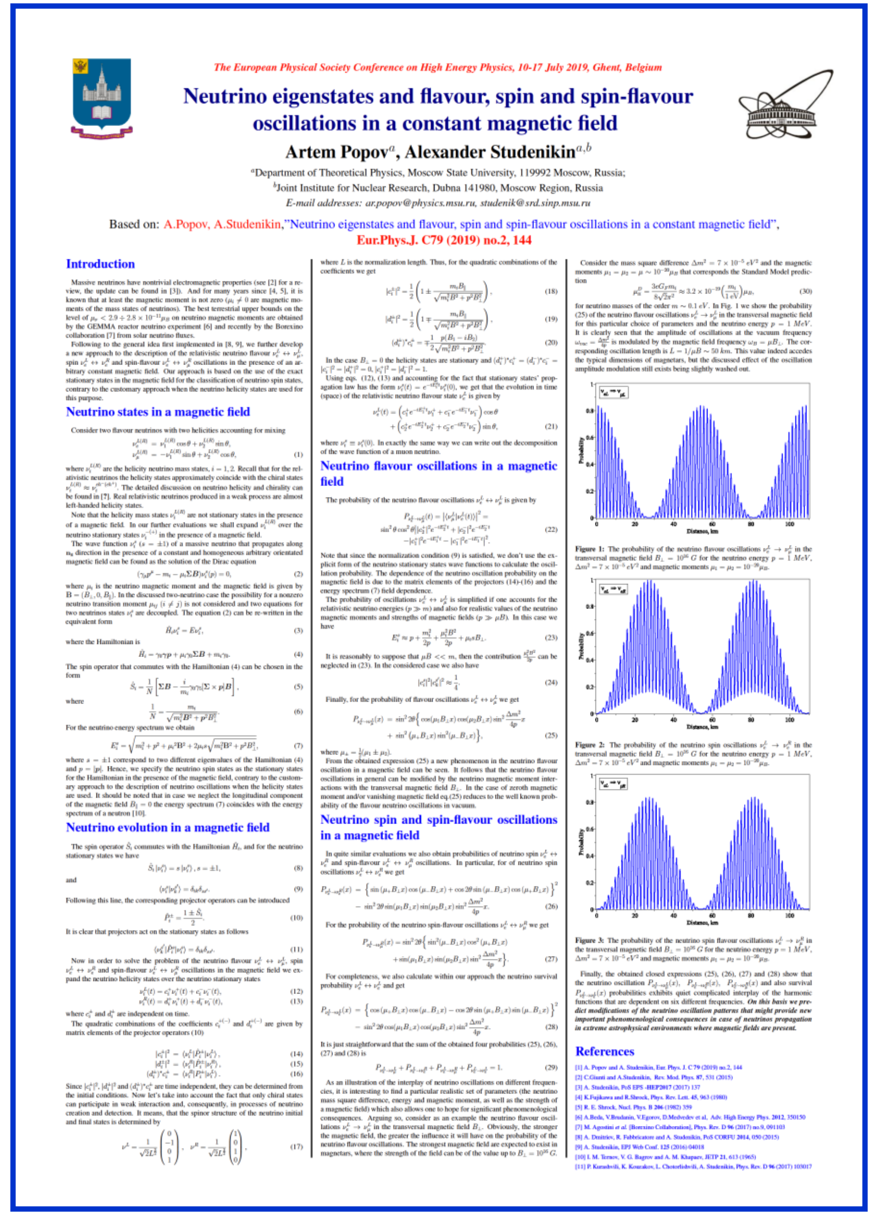
generation of ν spin (flavour) oscillations by interaction with transversal matter current $j_{\perp}$

1. 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

inherent interplay of ν spin and flavour oscillations in B

2. 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





A. Pustoshny, V. Shakhov, A. Studenikin
"Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions" poster # 25

poster # 34 A. Popov, A. Studenikin
"Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field"

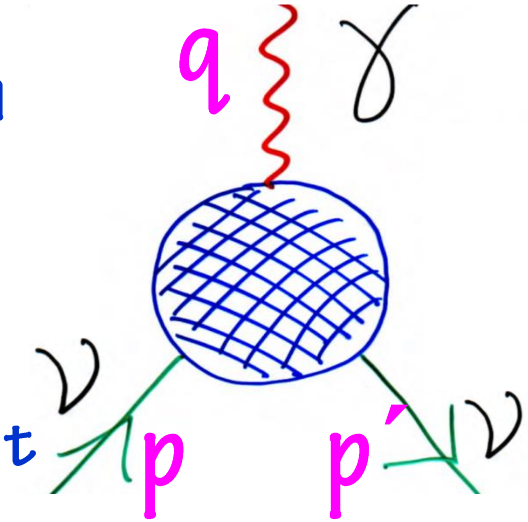
①

ν electromagnetic properties

(flash on theory)

$m_\nu \neq 0$

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) $\Rightarrow$

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…

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 ???

② ✓

magnetic moment in experiments

(most easily understood
and accessible for experimental
studies are dipole moments)

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

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

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

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

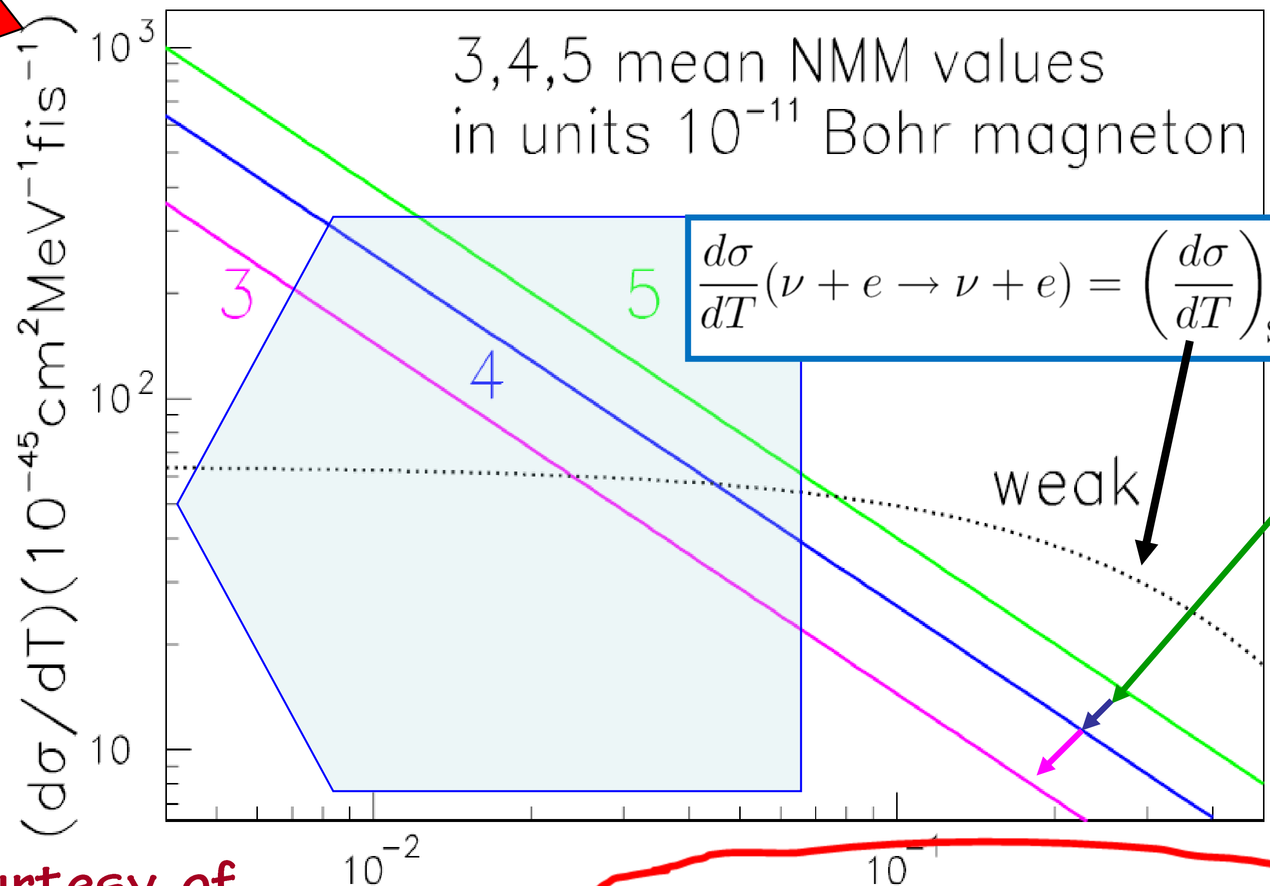
$$g_V = \begin{cases} 2\sin^2\theta_W + \frac{1}{2} & \text{for } \nu_e, \\ 2\sin^2\theta_W - \frac{1}{2} & \text{for } \nu_\mu, \nu_\tau, \end{cases} \qquad g_A = \begin{cases} \frac{1}{2} & \text{for } \nu_e, \\ -\frac{1}{2} & \text{for } \nu_\mu, \nu_\tau \end{cases}$$

for antineutrinos $g_A \to -g_A$

- 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 …



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

… courtesy of A.Starostin…

GEMMA (2005-2012)

Germanium Experiment for Measurement of Magnetic Moment of Antineutrino

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

!

World best experimental limit

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

• June 2012

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 ... 2019 ?

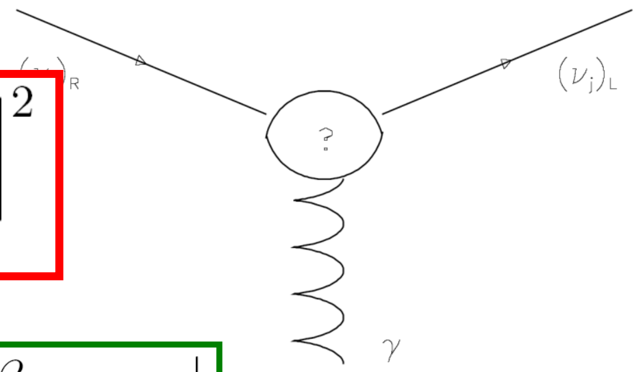
• $$\mu_\nu^a \sim 0.7 \times 10^{-12} \mu_B$$

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)



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

where U_{li} — neutrino mixing matrix

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

β_{ij}, ε_{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.

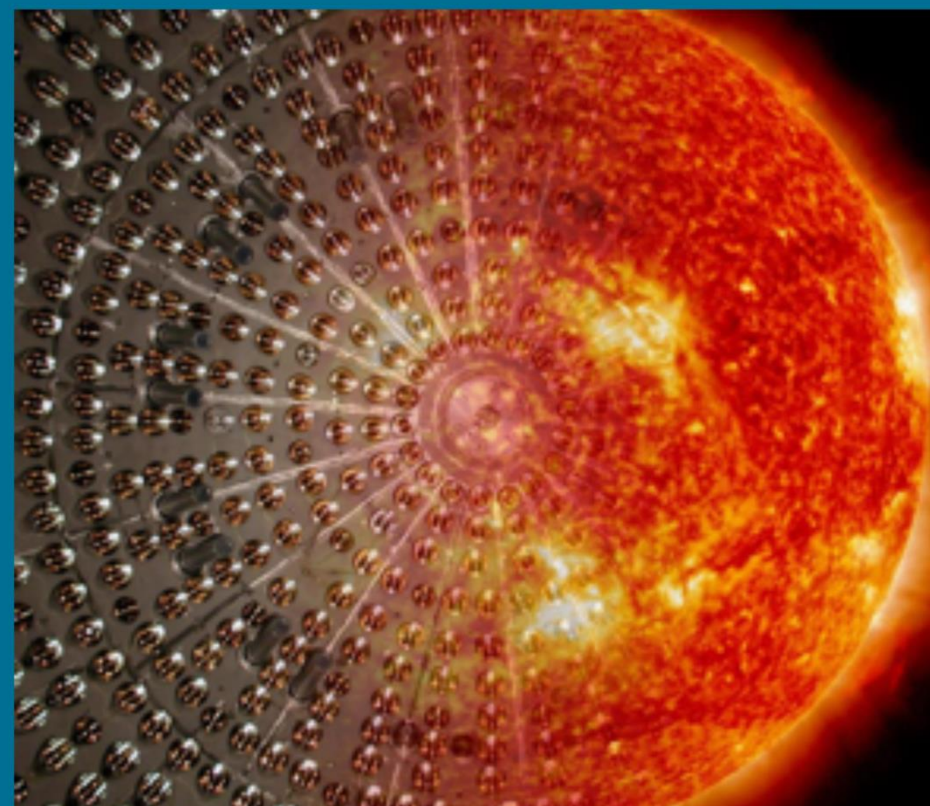
TAUP Topics in Astroparticle and Underground Physics

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

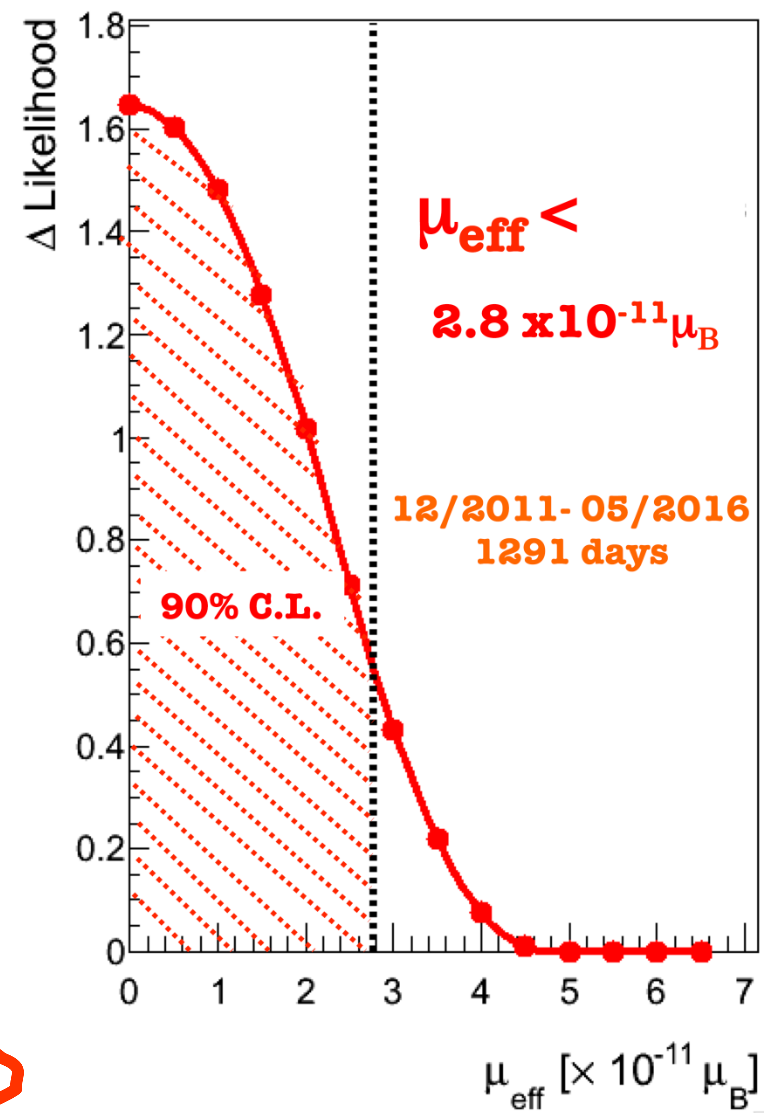
JÜLICH FORSCHUNGSZENTRUM

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.)**

Profiling μ_{eff} with σ_{EM} for pp & ^{7}Be



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	$\mu_S(E_\nu \gtrsim 5\,\mathrm{MeV}) < 1.1 \times 10^{-10}\ \mu_B$	90%	Liu *et al.* (2004)
	Borexino	$\mu_S(E_\nu \lesssim 1\,\mathrm{MeV}) < 5.4 \times 10^{-11}\ \mu_B$	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

... quite exciting claim that ν-e cross section should be increased by Atomic Ionization Effect:

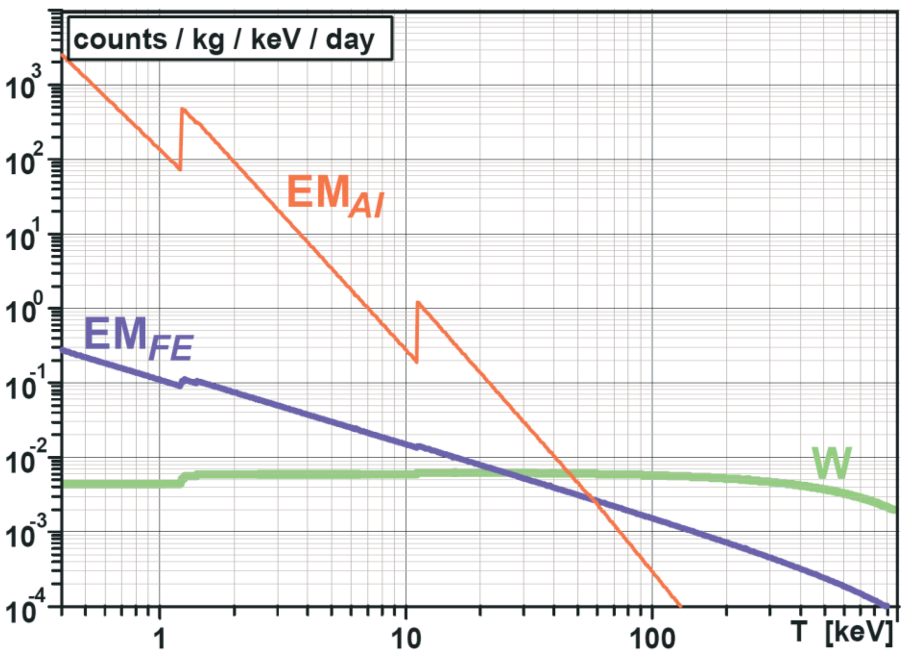
?

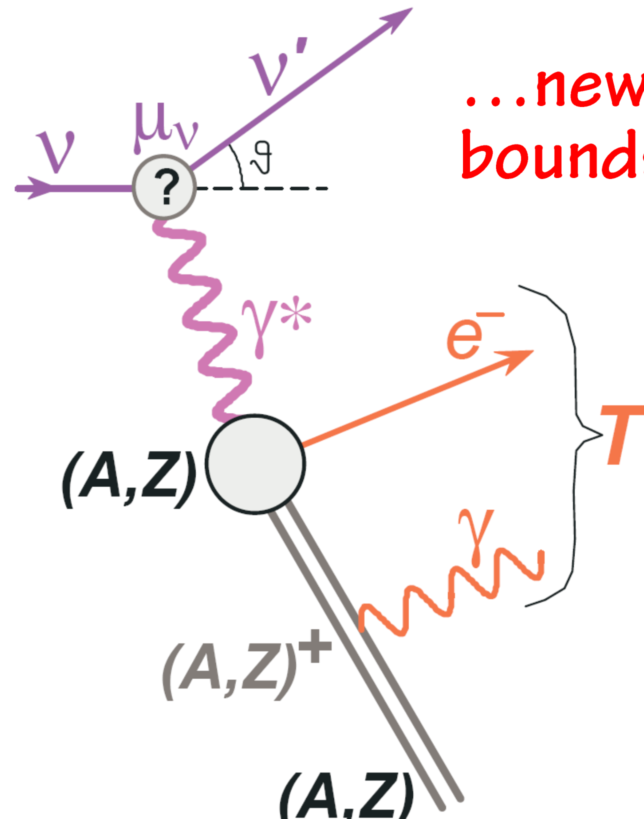
H.Wong et al. (TEXONO Coll.), PRL 105 (2010) 061801

$$\nu + (A,Z) \longrightarrow \nu\,' + (A,Z)^+ + e^-$$
$$\downarrow \text{recombination}$$
$$(A,Z) \quad + \gamma$$

(ν scattering on bound e)

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





...new bounds ...

... better limits on ν effective magnetic moment ...

$$\mu_\nu < 1.3 \times 10^{-11} \mu_B$$?

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

... atomic ionization effect accounted for ...

... however ...

$$\mu_\nu < 5.0 \times 10^{-12} \mu_B$$?

... atomic ionization effect accounted for ...

A.Beda et al. (GEMMA Coll.), arXiv: 1005.2736, 16 May 2010

$$\mu_\nu < 3.2 \times 10^{-11} \mu_B$$

... ν-e scattering on free electrons ... (without atomic ionization)

... 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[*]

Department of Nuclear Physics and Quantum Theory of Collisions, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia

Alexander I. Studenikin[†]

Department of Theoretical Physics, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia and Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia

(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

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 !

3.11

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* *dipole* *3. electric* *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

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

Editors' Suggestion

Ch – It – Ru collaboration

Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering

M. Cadeddu*
Dipartimento di Fisica, Università degli Studi di Cagliari, and INFN, Sezione di Cagliari, Complesso Universitario di Monserrato—S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy

C. Giunti†
Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Via P. Giuria 1, I–10125 Torino, Italy

K. A. Kouzakov‡
Department of Nuclear Physics and Quantum Theory of Collisions, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia

Y. F. Li§
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China and School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

A. I. Studenikin‖
Department of Theoretical Physics, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia and Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia

Y. Y. Zhang¶
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China and School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

(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

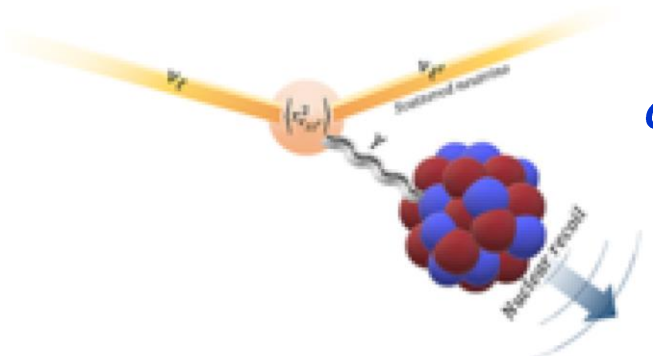
Physical Review D – Highlights 2018 – Editors' Suggestion

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

poster # xxx

- A. Studenikin, New bounds on neutrino electric millicharge from limits on neutrino magnetic moment, Europhys. Lett. 107 (2014) 21001

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

Review of Particle Physics 2014 - 2016 – 2018 (2019)
M. Tanabashi et al. (Particle Data Group) Phys. Rev. D 98 (2018) 030001

The European Physical Society Conference on High Energy Physics, 10-17 July 2019, Ghent, Belgium

Constraints on neutrino millicharge and charge radius from neutrino-atom scattering

M. Cadeddu,[1] C. Giunti,[2] K. A. Kouzakov, Y. F. Li, A. I. Studenikin,[3,5] and Y. Y. Zhang[4]
1. Dipartimento di Fisica, Università degli Studi di Cagliari, and INFN, Sezione di Cagliari, Monserrato (Cagliari), Italy
2. Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Torino, Italy
3. Faculty of Physics, Lomonosow Moscow State University, Moscow, Russia
4. Institute of High Energy Physics, Chinese Academy of Sciences and School of Physical Sciences, University of Chinese Academy of Sciences, Beijing, China
5. Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia
Correspondence: kouzakov@gmail.com; studenik@srd.sinp.msu.ru

Introduction

In the standard model neutrinos are massless left-handed fermions which very weakly interact with matter via exchange of the $W^{\pm}$ and Z^0 bosons. The development of our knowledge about neutrino masses and mixing provides a basis for exploring neutrino properties and interactions beyond the standard model (BSM). In this respect, the study of nonvanishing electromagnetic characteristics of massive neutrinos is of particular interest [1, 2]. It can help not only to shed light on whether neutrinos are Dirac or Majorana particles, but also to constrain the existing BSM theories and/or to hint at new physics. The effects of neutrino electromagnetic properties can be searched in astrophysical environments, where neutrinos propagate in strong magnetic fields and dense matter, and in laboratory measurements of neutrinos from various s ources. In the latter case, a very sensitive method is provided by the direct measurement of low-energy elastic neutrino scattering on atomic electrons and nuclei in a detector. A general strategy of such experiments consists in determining deviations of the scattering cross section differential with respect to the energy transfer from the value predicted by the standard model of the electroweak interaction. In this contribution, we present our bounds on the neutrino millicharge [7] and charge radii [9] that have been derived from the data of the **GEMMA** [3] and **COHERENT** [4] scattering experiments, respectively, and included in the *Particle Data Group's Review of Particle Physics* [5].

Electromagnetic properties of massive neutrinos

Here we briefly outline the general form of the electromagnetic interactions of Dirac and Majorana neutrinos. There are at least three massive neutrino fields ν_i with respective masses m_i ($i = 1, 2, 3$), which are mixed with the three active flavor neutrinos ν_e, ν_μ, ν_τ. Therefore, the effective electromagnetic interaction Hamiltonian can be presented as [1, 2]

$$\mathcal{H}_{em}^{(\nu)} = j_\mu^{(\nu)} A^\mu = \sum_{i,f=1}^{3} \overline{\nu}_f \Lambda_\mu^{fi} \nu_i A^\mu, \qquad (1)$$

where we take into account possible transitions between different massive neutrinos. The physical effect of $\mathcal{H}_{em}^{(\nu)}$ is described by the effective electromagnetic vertex, which in momentum-space representation depends only on the four-momentum $q = p_i - p_f$ transferred to the photon and can be expressed as follows:

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right)\left[f_Q(q^2) + f_A(q^2)q^2\gamma_5\right] - i\sigma_{\mu\nu}q^\nu\left[f_M(q^2) + i f_E(q^2)\gamma_5\right]. \qquad (2)$$

Here $\Lambda_\mu(q)$ is a 3×3 matrix in the space of massive neutrinos expressed in terms of the four Hermitian 3×3 matrices of form factors

$$f_Q = f_Q^\dagger, \quad f_M = f_M^\dagger, \quad f_E = f_E^\dagger, \quad f_A = f_A^\dagger, \qquad (3)$$

where Q, M, E, A refer respectively to the real charge, magnetic, electric, and anapole neutrino form factors. The Lorentz-invariant form of the vertex function (2) is also consistent with electromagnetic gauge invariance that implies four-current conservation.

For the coupling with a real photon in vacuum ($q^2 = 0$) one has

$$f_Q^{fi}(0) = e_{fi}, \quad f_M^{fi}(0) = \mu_{fi}, \quad f_E^{fi}(0) = \epsilon_{fi}, \quad f_A^{fi}(0) = a_{fi}, \qquad (4)$$

where $e_{fi}, \mu_{fi}, \epsilon_{fi}$ and a_{fi} are, respectively, the neutrino charge, magnetic moment, electric moment and anapole moment of diagonal ($f = i$) and transition ($f \neq i$) types. Even if the electric charge of a neutrino is zero, the electric form factor $f_Q(q^2)$ can still contain nontrivial information about neutrino electrostatic properties. A neutral particle can be characterized by a superposition of two charge distributions of opposite signs, so that the particle form factor $f_Q(q^2)$ can be nonzero for $q^2 \neq 0$. The mean charge radius (in fact, it is the squared charge radius) of an electrically neutral neutrino is given by

$$\langle r_\nu^2 \rangle = \frac{1}{6} \left.\frac{df_Q(q^2)}{dq^2}\right|_{q^2=0}, \qquad (5)$$

which is determined by the second term in the power-series expansion of the neutrino charge form factor.

Elastic neutrino-electron scattering

Here we consider the process $\nu + e^- \to e^- + \nu$ where an ultrarelativistic neutrino with energy E_ν elastically scatters on an atomic electron in a detector at energy transfer T. The simplest model of the electron system in the detector is a free-electron model, where it is assumed that electrons are free and at rest. In the scattering experiments the observables are the kinetic energy T_e of the recoil electron and/or its solid angle Ω_e. From the energy-momentum conservation one gets

$$T_e = T, \qquad \cos\theta_e = \left(1 + \frac{m_e}{E_\nu}\right)\sqrt{\frac{T}{T + 2m_e}}, \qquad (6)$$

where θ_e is the angle of the recoil electron with respect to the neutrino beam. The cross section, which is differential with respect to the electron kinetic energy T_e, can be presented in the form of a sum of *helicity-conserving* (w, Q) and *helicity-flipping* (μ) components [6]:

$$\frac{d\sigma}{dT_e} = \frac{d\sigma_{(w,Q)}}{dT_e} + \frac{d\sigma_{(\mu)}}{dT_e}, \qquad (7)$$

where $d\sigma_{(w,Q)}/dT_e$ is the electroweak cross section modified by the effect of the neutrino millicharge, charge radius and anapole moment, and $d\sigma_{(\mu)}/dT_e$ is the magnetic cross section due to the neutrino dipole magnetic and electric moments.

At small T_e values the contributions to the recoil-electron spectrum due to the weak, millicharge, and magnetic scattering channels exhibit qualitatively different T_e dependencies, namely

$$\mathcal{N}_{e^-}^{(w,Q)}(T_e) \propto \begin{cases} \text{const} & (e_\nu = 0), \\ \frac{2\pi\alpha^2}{m_e T_e^2}\left(\frac{e_\nu}{e_0}\right)^2 & (e_\nu \neq 0), \end{cases} \quad \text{and} \quad \mathcal{N}_{e^-}^{(\mu)}(T_e) \propto \frac{\pi\alpha^2}{m_e^2 T_e}\left(\frac{\mu_\nu}{\mu_B}\right)^2, \qquad (8)$$

where α is the fine structure constant, e_ν and μ_ν are the neutrino (effective) millicharge and magnetic moment, and e_0 and μ_B are an elementary electric charge and a Bohr magneton, respectively. For the ratio $\mathcal{R}$ of the millicharge and magnetic-moment contributions to the recoil-electron energy spectrum one thus has

$$\mathcal{R} = \frac{\mathcal{N}_{e^-}^{(Q)}(T_e)}{\mathcal{N}_{e^-}^{(\mu)}(T_e)} = \frac{2m_e}{T_e}\frac{(e_\nu/e_0)^2}{(\mu_\nu/\mu_B)^2}. \qquad (9)$$

In case there are no observable deviations from the weak contribution to the electron spectrum it is possible to get the upper bound for the neutrino millicharge demanding that a possible effect due to e_ν does not exceed one due to the neutrino (anomalous) magnetic moment μ_ν. This implies that $\mathcal{R} < 1$ and from the relation (9), using the **GEMMA** data [3], namely the detector energy threshold ~ 2.8 keV and the μ_ν bound $\mu_\nu < 2.9 \times 10^{-11}\mu_B$, one obtains the following upper limit on the neutrino millicharge [7]:

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

The e_ν range that expected to be probed in a few years with the **GEMMA-II** experiment (an effective threshold of 1.5 keV and the μ_ν sensitivity at the level of $1 \times 10^{-11}\mu_B$) is $|e_\nu| < 3.7 \times 10^{-13} e_0$.

Coherent elastic neutrino-nucleus scattering

Here we consider the process $\nu_\ell + a(Z,N) \to a(Z,N) + \nu_{\ell'=e,\mu,\tau}$ where an utrarelativistic neutrino with energy E_ν elastically scatters on an atomic nucleus, having Z protons and N neutrons, in a detector at energy-momentum transfer $q = (T, \vec{q})$. For a spin-zero nucleus and $T_a \ll E_\nu$, where $T_a = T$ is the nuclear recoil kinetic energy, the differential cross section due to the weak and charge-radius scattering channels is given by [6, 9]

$$\frac{d\sigma_{(w,r_\nu)}}{dT_a} \simeq \frac{G_F^2 M_a}{\pi}\left(1 - \frac{M_a T_a}{2E_\nu^2}\right)\left\{\left[\left(g_V^p - \delta_{\ell\ell}\right)F_Z(|\vec{q}|^2) + g_V^n F_N(|\vec{q}|^2)\right]^2 + F_Z^2(|\vec{q}|^2)\sum_{\ell' \neq \ell}|\delta_{\ell\ell'}|^2\right\}, \qquad (10)$$

where M_a is the nuclear mass, $g_V^p = 1/2 - 2\sin^2\theta_W$ and $g_V^n = -1/2$ (the neglected radiative corrections are too small to affect the results). $F_{Z,N}(|\vec{q}|^2)$, such that $F_Z(0) = Z$ and $F_N(0) = N$, are the nuclear form factors, which are the Fourier transforms of the corresponding nucleon density distribution in the nucleus and describe the loss of coherence for $|\vec{q}|R \gtrsim 1$, where R is the nuclear radius. The effect of the neutrino charge radii is accounted for through

$$\delta_{\ell\ell'} = \frac{2}{3} m_W^2 \sin^2\theta_W \langle r_{\nu_{\ell\ell'}}^2 \rangle, \qquad \text{with} \qquad \langle r_{\nu_{\ell\ell'}}^2 \rangle = \sum_{i,j} U_{\ell i}^* U_{\ell' j} \langle r_{\nu_{ij}}^2 \rangle,$$

where U is the neutrino mixing matrix. The diagonal ($\ell = \ell'$) charge radii are already predicted in the standard model [8]:

$$\langle r_{\nu_e}^2 \rangle_{SM} = -0.83 \times 10^{-32}\,\text{cm}^2, \quad \langle r_{\nu_\mu}^2 \rangle_{SM} = -0.48 \times 10^{-32}\,\text{cm}^2, \quad \langle r_{\nu_\tau}^2 \rangle_{SM} = -0.30 \times 10^{-32}\,\text{cm}^2. \qquad (11)$$

However, the transition ($\ell \neq \ell'$) charge radii are essentially the BSM quantities.

Fig. 1 shows the results of our fit [9] of the time-dependent **COHERENT** data [4]. In the analysis, we used the Helm parametrization of the nuclear form factors $F_{Z,N}(|\vec{q}|^2)$ and the rms radii of the proton distribution $R_p(^{133}\text{Cs}) = 4.804$ fm and $R_p(^{127}\text{I}) = 4.749$ fm that have been determined with high accuracy with muonic atom spectroscopy [10].

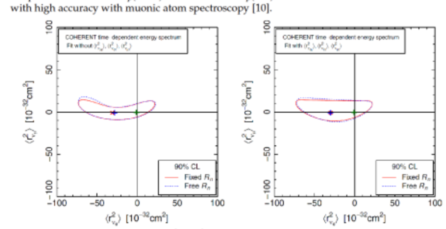


Figure 1: 90% CL allowed regions in the $\langle r_{\nu_e}^2 \rangle - \langle r_{\nu_\mu}^2 \rangle$ plane obtained from the fit of the time-dependent COHERENT energy spectrum without (left panel) and with (right panel) the transition charge radii. The red and blue points indicate the best-fit values, and the green point near the origin indicates the standard model values in Eq. (11).
Fixed R_n: We used the theoretical values $R_n(^{133}\text{Cs}) = 5.01$ fm and $R_n(^{127}\text{I}) = 4.94$ fm from the relativistic mean field NL-Z2 nuclear model calculations [11].
Free R_n: $R_n(^{133}\text{Cs})$ and $R_n(^{127}\text{I})$ are allowed to vary in suitable intervals, with the lower bounds given by the corresponding experimental R_p values (see above) and the upper bound of 6 fm.

In addition to the customary, diagonal charge radii, from the **COHERENT** data we have obtained for the first time limits on the neutrino transition charge radii [9]:

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

at 90% CL, marginalizing over reliable allowed intervals of the rms radii $R_n(^{133}\text{Cs})$ and $R_n(^{127}\text{I})$. This is an interesting information on the BSM physics which can generate the neutrino transition charge radii [12].

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③

Experimental limits on ν charge radius $<r_\nu^2>$

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	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3 \times 10^{-32}$	90%	Vidyakin *et al.* (1992)
	TEXONO	$-4.2 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 6.6 \times 10^{-32}$	90%	Deniz *et al.* (2010)[a]
Accelerator ν_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 ν_μ-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	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2 \times 10^{-32}$	90%	Vilain *et al.* (1995)[a]

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

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

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

… if one trusts ν

to be precursor for

BESM physics …

… 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:

- In SM :

$SU(2)_L \times U(1)_Y$

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

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

- *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 ≠ 0** are included : in the absence of Y quantization electric charges **Q** gets dequantized* ⇒ **millicharged ν**

②

Experimental limits on 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
$\vert q_{\nu_\tau}\vert \lesssim 3\times10^{-4}\,e$	SLAC e^- beam dump	Davidson *et al.* (1991)
$\vert q_{\nu_\tau}\vert \lesssim 4\times10^{-4}\,e$	BEBC beam dump	Babu *et al.* (1994)
$\vert q_{\nu}\vert \lesssim 6\times10^{-14}\,e$	Solar cooling (plasmon decay)	Raffelt (1999a)
$\vert q_{\nu}\vert \lesssim 2\times10^{-14}\,e$	Red giant cooling (plasmon decay)	Raffelt (1999a)
$\vert q_{\nu_e}\vert \lesssim 3\times10^{-21}\,e$ ●	Neutrality of matter ●	Raffelt (1999a)
$\vert q_{\nu_e}\vert \lesssim 3.7\times10^{-12}\,e$	Nuclear reactor	Gninenko *et al.* (2007)
$\vert q_{\nu_e}\vert \lesssim 1.5\times10^{-12}\,e$	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 $\mu_\nu^a < 2.9 \times 10^{-11} \mu_B$ ($T \sim 2.8\ keV$)

2019 (expected)

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

Constraints on q_ν

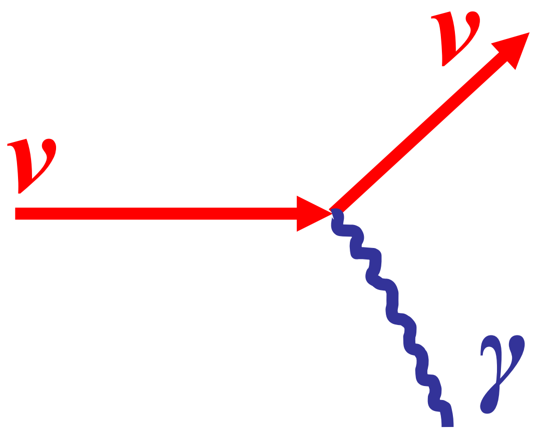
$|q_\nu| < 1.5 \times 10^{-12} e_0$

... unprecedentedly low threshold ...

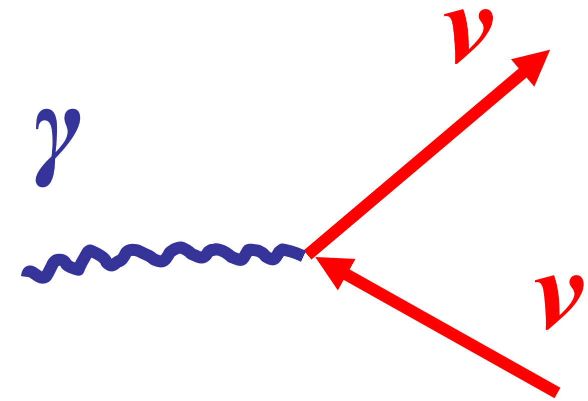
$|q_\nu| < 1.1 \times 10^{-13} e_0$

! !

③ ν electromagnetic interactions

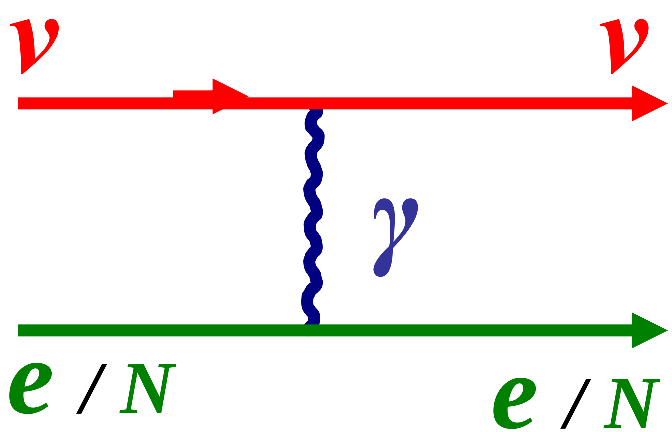


ν decay, Cherenkov radiation

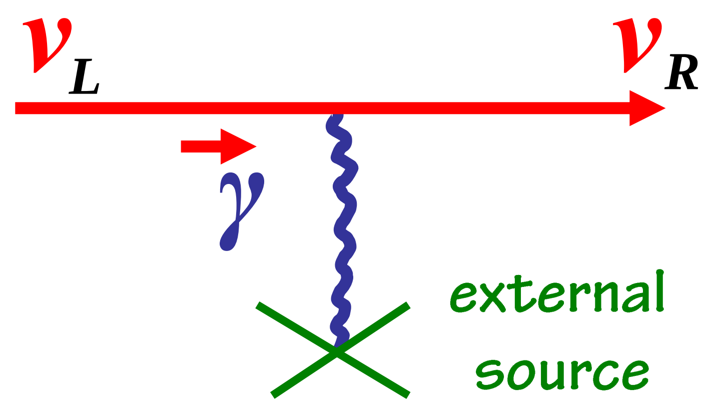


γ decay in plasma

!!!



Scattering



Spin precession

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.
$\mu_\nu \leq 3 \cdot 10^{-12} \mu_B$
G. Raffelt, D. Dearborn, J. Silk, 1989.

Bounds depend on
- modeling of astrophysical systems
- on assumptions on ν properties

Generic assumptions:
- absence of other nonstandard interactions other than μ_ν

A global treatment would be desirable, incorparating oscillations and matter effects as well as 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

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

... 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

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

new developments in ν spin and flavour scillations

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

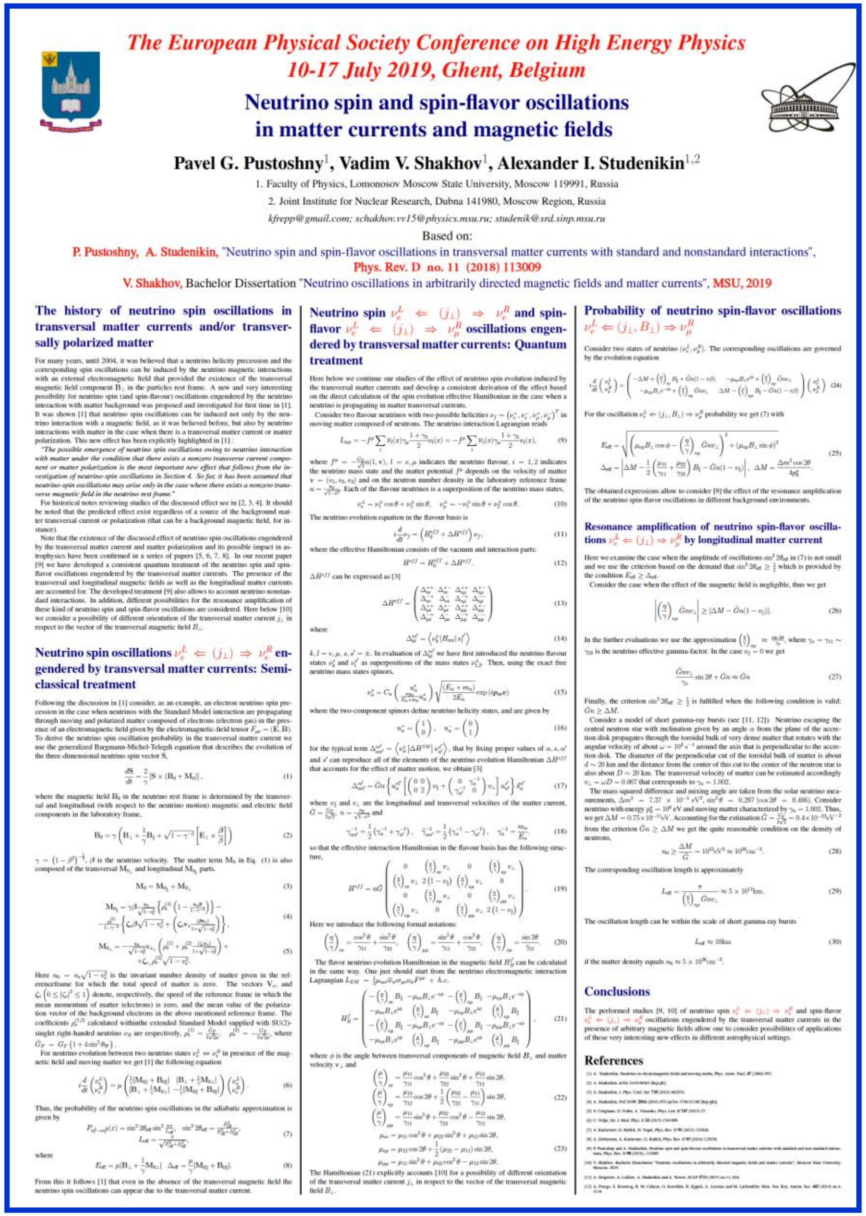
   P. Pustoshny, A. Studenikin,
   "Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions"
   - Phys. Rev. D98 (2018) no. 11, 113009

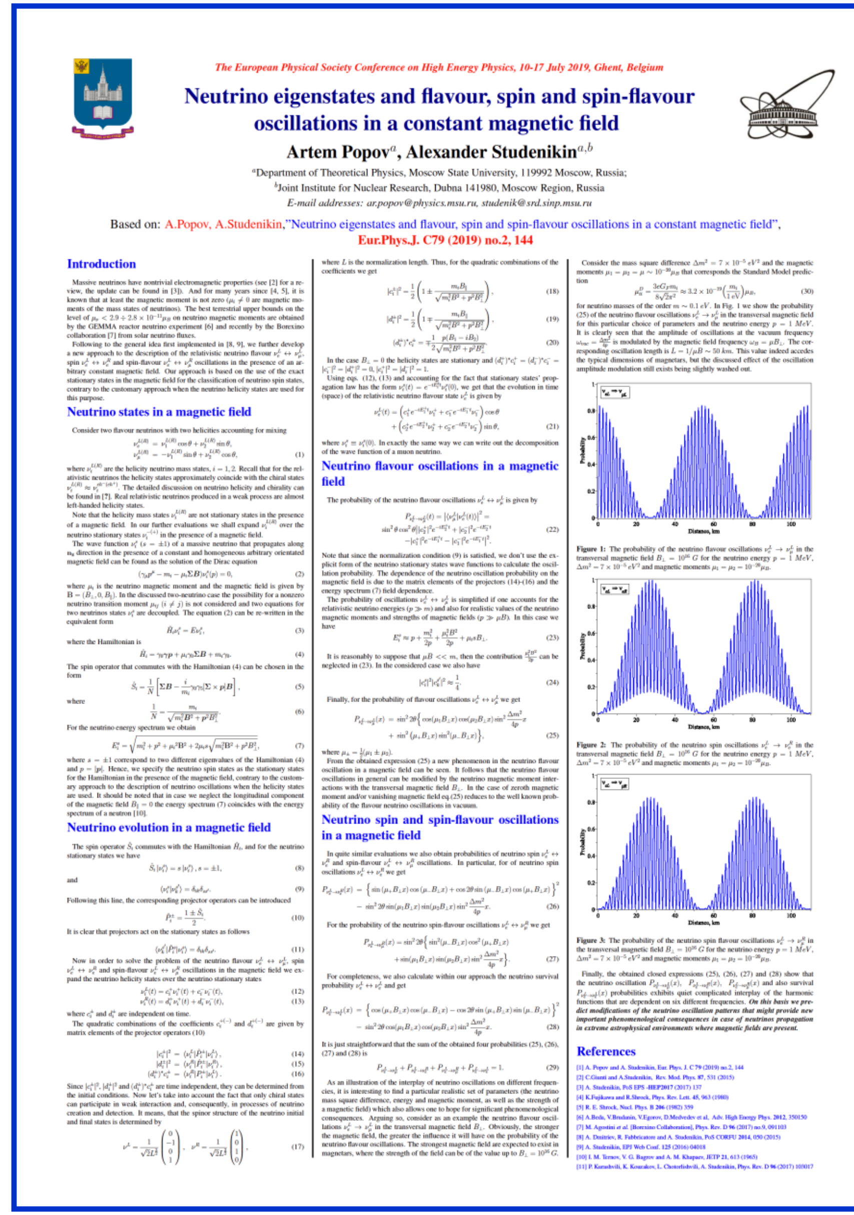
2. inherent interplay of ν spin and flavour oscillations in B

   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





A. Pustoshny, V. Shakhov, A. Studenikin
"Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions" poster # xxx

poster # xxx A. Popov, A. Studenikin
"Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field"

Main steps in ν oscillations

62 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 !

Bruno Pontecorvo

1913-1993

only in $B_\perp$ and matter at rest

② ν spin and spin-flavour oscillations in $B_\perp$

Consider two different neutrinos: $\nu_{e_L}, \quad \nu_{\mu_R}, \quad m_L \neq m_R$

with magnetic moment interaction

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

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

ν evolution equation

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

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

$$\tilde{H} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \frac{V_{\nu_e}}{2} & \mu_{e\mu}Be^{-i\phi} \\ \mu_{e\mu}Be^{+i\phi} & \frac{\Delta m^2}{4E} - \frac{V_{\nu_e}}{2} \end{pmatrix}$$

Probability of $\nu_{e_L} \leftrightarrow \nu_{\mu_R}$ oscillations in $B = |\mathbf{B}_\perp| e^{i\phi(t)}$

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

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

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

- Resonance amplification of oscillations in matter:

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

Akhmedov, 1988
Lim, Marciano

... similar to MSW effect

In magnetic field

$\nu_{e_L} \;\; \nu_{\mu_R}$

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

$$i\frac{d}{dz}\nu_{\mu_L} = \frac{\Delta_{LR}}{4E}\nu_{\mu_L} + \mu_{e\mu}B\nu_{e_R}$$

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 $j_\perp$

$(\mu_\nu B)$

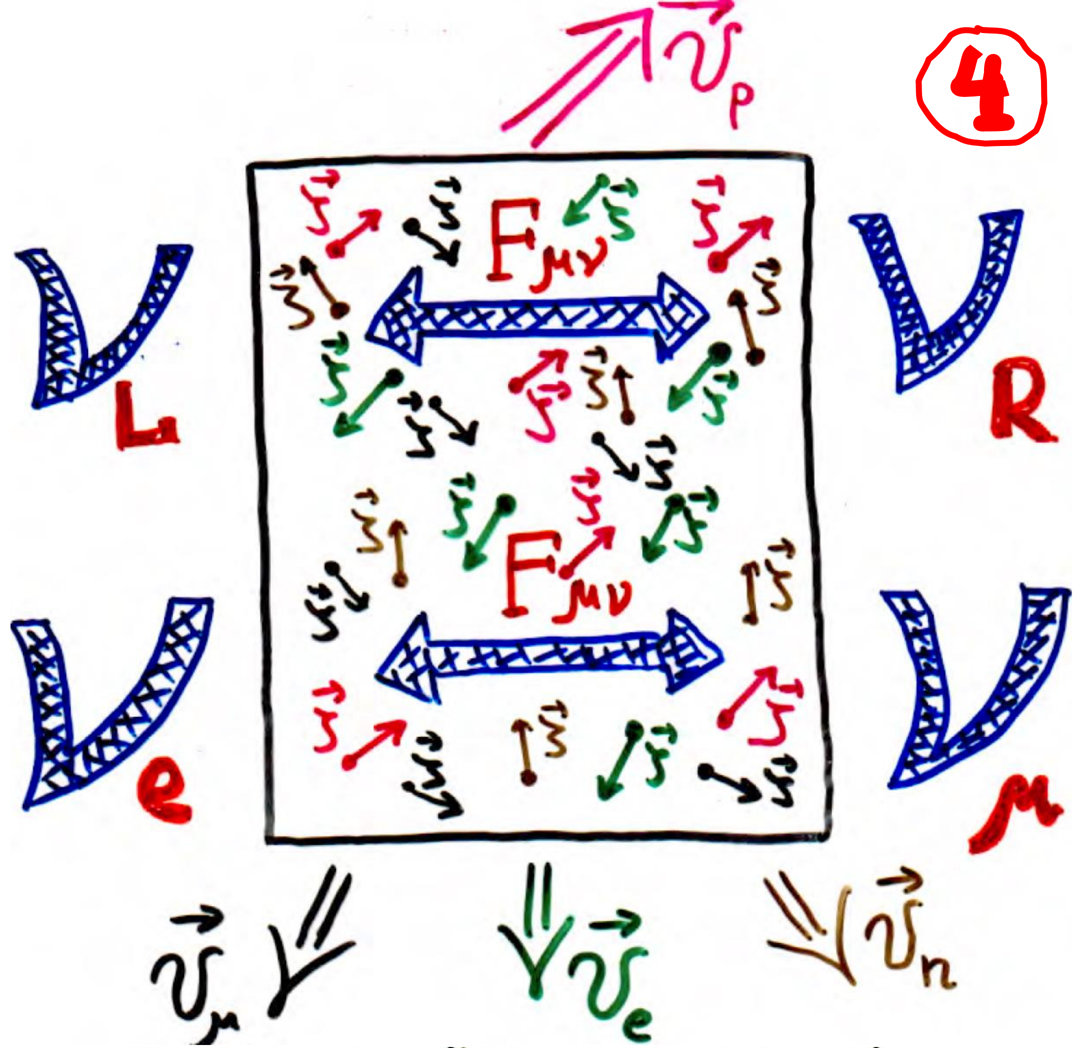
P. Pustoshny, A. Studenikin,
"Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions"
Phys. Rev. D98 (2018) no. 11, 113009

neutrino spin and flavor oscillations in moving matter

A.Egorov, A.Lobanov, A.Studenikin, Phys.Lett.B 491 (2000) 137

A.Lobanov, A.Studenikin, Phys.Lett.B 515 (2001) 94

A.Lobanov, A.Grigoriev, A.Studenikin, Phys.Lett.B 535 (2002) 187



moving matter components

$f = e, n, p, \mu$, etc

with polarizations

$\vec{\zeta}, \vec{\zeta}, \vec{\zeta}, \vec{\zeta}$, etc

ν spin evolution in presence of general external fields

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

General types non-derivative interaction with external fields

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

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

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

Relativistic equation (quasiclassical) for ν spin vector:

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

- ***Neither s nor π nor V contributes to spin evolution***

- **Electromagnetic interaction**

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

- **SM weak interaction**

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

$$\vec{M} = \gamma(A^0\vec{\beta} - \vec{A})$$
$$\vec{P} = -\gamma[\vec{\beta} \times \vec{A}],$$

… once more…

For SM+SU(2)-singlet ν_R and matter $f=e$

Bargmann-Michel-Telegdi eq →

$$\frac{d\vec{S}_\nu}{dt} = \frac{2\mu_\nu}{\gamma_\nu}\left[\vec{S}_\nu \times (\vec{B}_0 + \vec{M}_0)\right],$$

interaction of neutrino with an electromagnetic field →

in rest frame of neutrino

$$\vec{B}_0 = \gamma_\nu\left(\vec{B}_\perp + \frac{1}{\gamma_\nu}\vec{B}_\parallel + \sqrt{1-\frac{1}{\gamma_\nu^2}}\left[\vec{E}_\perp \times \vec{n}\right]\right),$$

interaction of neutrino with matter →

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

$$\rho_e^{(1)} = \frac{G_F}{2\mu\sqrt{2}}(1 + 4\sin^8\theta_W),$$

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

matter density; $\parallel$; $\perp$

→ ν spin procession in moving matter !!!

without any magnetic field !!!

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 $\mathbf{j}_\perp$

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

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*

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

- 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: $n = \dfrac{n_0}{\sqrt{1-v^2}}$ neutron number density in laboratory reference frame

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

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

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

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

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

ν flavour and mass states

P. Pustoshny, A. Studenikin,

Phys. Rev. D98 (2018) no. 11, 113009

Two flavour ν with two helicities in moving matter

$$i\frac{d}{dt}\begin{pmatrix}\nu_e^+\\ \nu_e^-\\ \nu_\mu^+\\ \nu_\mu^-\end{pmatrix} = \left\{H_{vac}^{eff} + \Delta H^{eff}\right\}\begin{pmatrix}\nu_e^+\\ \nu_e^-\\ \nu_\mu^+\\ \nu_\mu^-\end{pmatrix}$$

$$\Delta H^{eff} = \Delta H^{eff}_{v=0} + \Delta H^{eff}_{\vec{j}_\parallel + \vec{j}_\perp}$$

$\vec{j}_\perp + \vec{j}_\parallel$

Contribution of matter currents

$$\Delta H^{eff} = \begin{pmatrix}\Delta_{ee}^{++} & \Delta_{ee}^{+-} & \Delta_{e\mu}^{++} & \Delta_{e\mu}^{+-}\\ \Delta_{ee}^{-+} & \Delta_{ee}^{--} & \Delta_{e\mu}^{-+} & \Delta_{e\mu}^{--}\\ \Delta_{\mu e}^{++} & \Delta_{\mu e}^{+-} & \Delta_{\mu\mu}^{++} & \Delta_{\mu\mu}^{+-}\\ \Delta_{\mu e}^{-+} & \Delta_{\mu e}^{--} & \Delta_{\mu\mu}^{-+} & \Delta_{\mu\mu}^{--}\end{pmatrix}$$

$$\Delta_{kl}^{ss'} = \langle \nu_k^s | \Delta H^{SM} | \nu_l^{s'} \rangle \quad k,l = e,\mu \qquad s,s' = \pm$$

$$\Delta H^{SM} = -\frac{G_F}{2\sqrt{2}}\frac{n}{\sqrt{1-v^2}}\left(1-\gamma_0\boldsymbol{\gamma}\mathbf{v}\right)\left(1+\gamma_5\right)$$

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

$$\gamma_{\alpha\alpha'}{}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} + \gamma_{\alpha'}^{-1}\right) \qquad \widetilde{\gamma}_{\alpha\alpha'}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} - \gamma_{\alpha'}^{-1}\right)$$

$$\Delta_{\alpha\alpha'}^{ss'} = \frac{G_F}{2\sqrt{2}}\frac{n_0}{\sqrt{1-v^2}}\left\{u_\alpha^{s\,T}\left[\left(1-\sigma_3\right)\left(v_\parallel - 1\right) + \left(\gamma_{\alpha\alpha'}{}^{-1}\sigma_1 + i\widetilde{\gamma}_{\alpha\alpha'}^{-1}\sigma_2\right)v_\perp\right] u_{\alpha'}^{s'}\right\} \alpha = 1,2$$

$$\Delta_{\alpha\alpha'}^{ss'} = \frac{G_F}{2\sqrt{2}}\frac{n_0}{\sqrt{1-v^2}}\left\{u_\alpha^{s\,T}\left[\begin{pmatrix}0 & 0\\ 0 & 2\end{pmatrix}\left(v_\parallel - 1\right) + \begin{pmatrix}0 & \gamma_\alpha^{-1}\\ \gamma_{\alpha'}^{-1} & 0\end{pmatrix} v_\perp\right] u_{\alpha'}^{s'}\right\}$$

$$u^+ = \begin{pmatrix}1\\0\end{pmatrix}, \qquad u^- = \begin{pmatrix}0\\1\end{pmatrix}$$

two helicity states $s,s' = \pm$

$$\gamma_\alpha^{-1} = \frac{m_\alpha}{E_\alpha}$$

!

- longitudinal currents $j_\parallel$ do not change ν helicity
- transversal currents $j_\perp$ do change ν helicity

Studenikin, PoS (2017) NOW2016_070, arXiv:1610.06563
J.Phys.Conf.Ser. 888 (2017) 012221

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

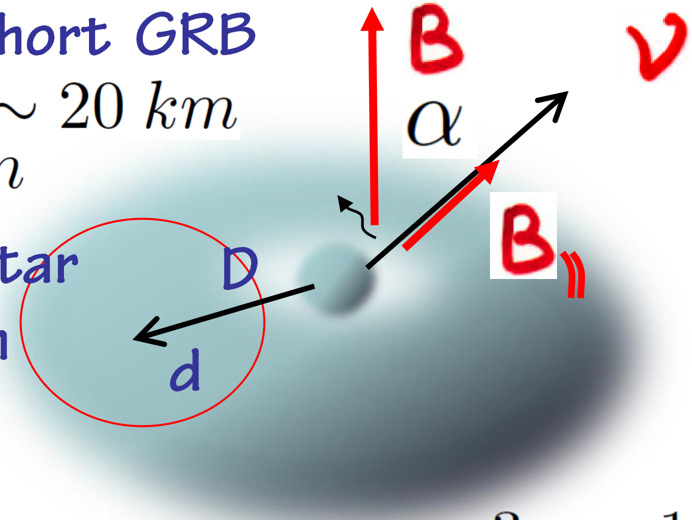
P. Pustoshny, A. Studenikin, Phys. Rev. D98 (2018) no. 11, 113009

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

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

$$v_\perp = \omega D = 0.067 \quad \text{and} \quad \gamma_n = 1.002$$

- Perego et al, Mon.Not.Roy.Astron.Soc. 443 (2014) 3134

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

- Grigoriev, Lokhov, Studenikin, Ternov, JCAP 1711 (2017) 024

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

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

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

resonance condition

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

-

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

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

$\vec{B} = \vec{B}_\perp + \vec{B}_\| \to 0$

Criterion – oscillations are important:

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

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

neglecting $\vec{B} = \vec{B}_\perp + \vec{B}_\| \to 0$:

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

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

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

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

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

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

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

- $L_{eff} \approx 10 \ km$ (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 $(\gamma_\mu p^\mu - m_i - \mu_i \boldsymbol{\Sigma B})\nu_i^s(p) = 0$ in a constant B

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

$\mu_{ij}(i \neq j) = 0$ •

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

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

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

"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)

$\nu_e^L \leftrightarrow \nu_\mu^L$ $\quad P_{\nu_e^L \to \nu_\mu^L}(t) = \left|\langle \nu_\mu^L | \nu_e^L(t)\rangle\right|^2$

$\mu_\pm = \frac{1}{2}(\mu_1 \pm \mu_2)$ 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

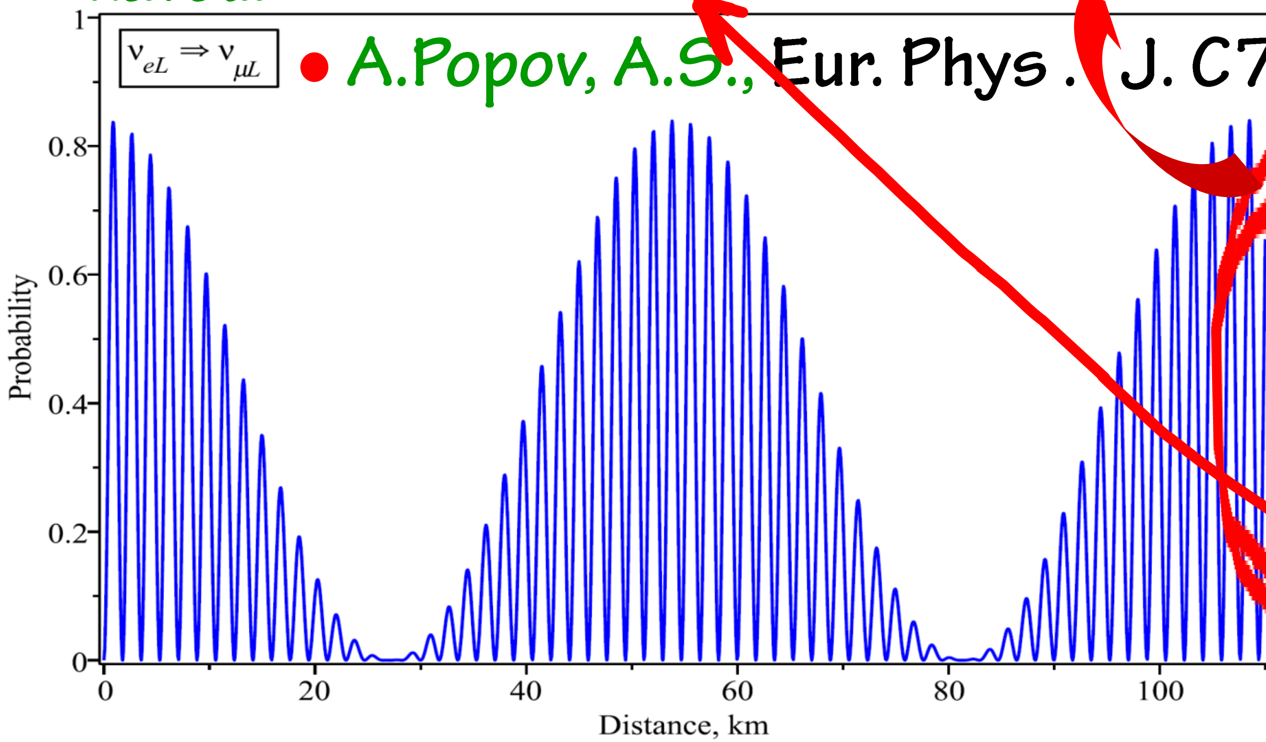


Fig. 1 The probability of the neutrino flavour oscillations $\nu_e^L \to \nu_\mu^L$ in the transversal magnetic field

• $B_\perp = 10^{16}\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

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

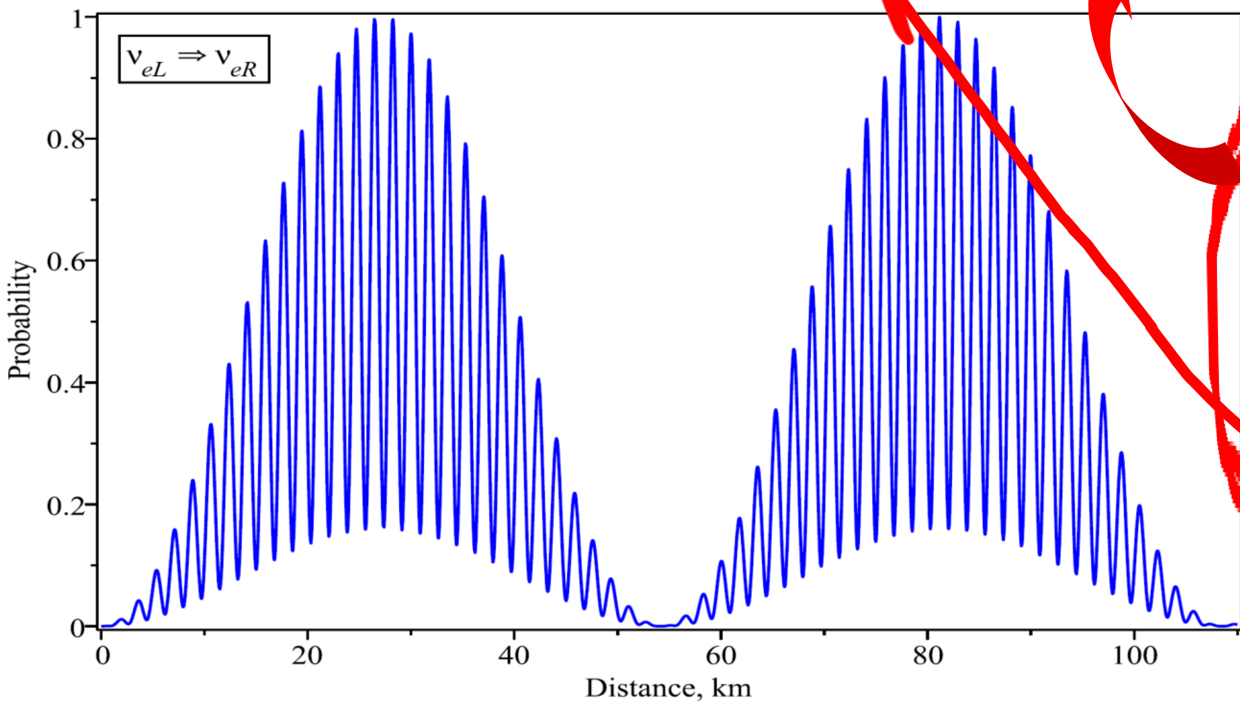
Chotorlishvili, Kouzakov, Kurashvili, Studenikin, Spin-flavor oscillations of ultrahigh-energy cosmic neutrinos in interstellar space: The role of neutrino magnetic moments, Phys. Rev. D96 (2017) 103017

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 $\omega_{vac} = \frac{\Delta m^2}{4p}$

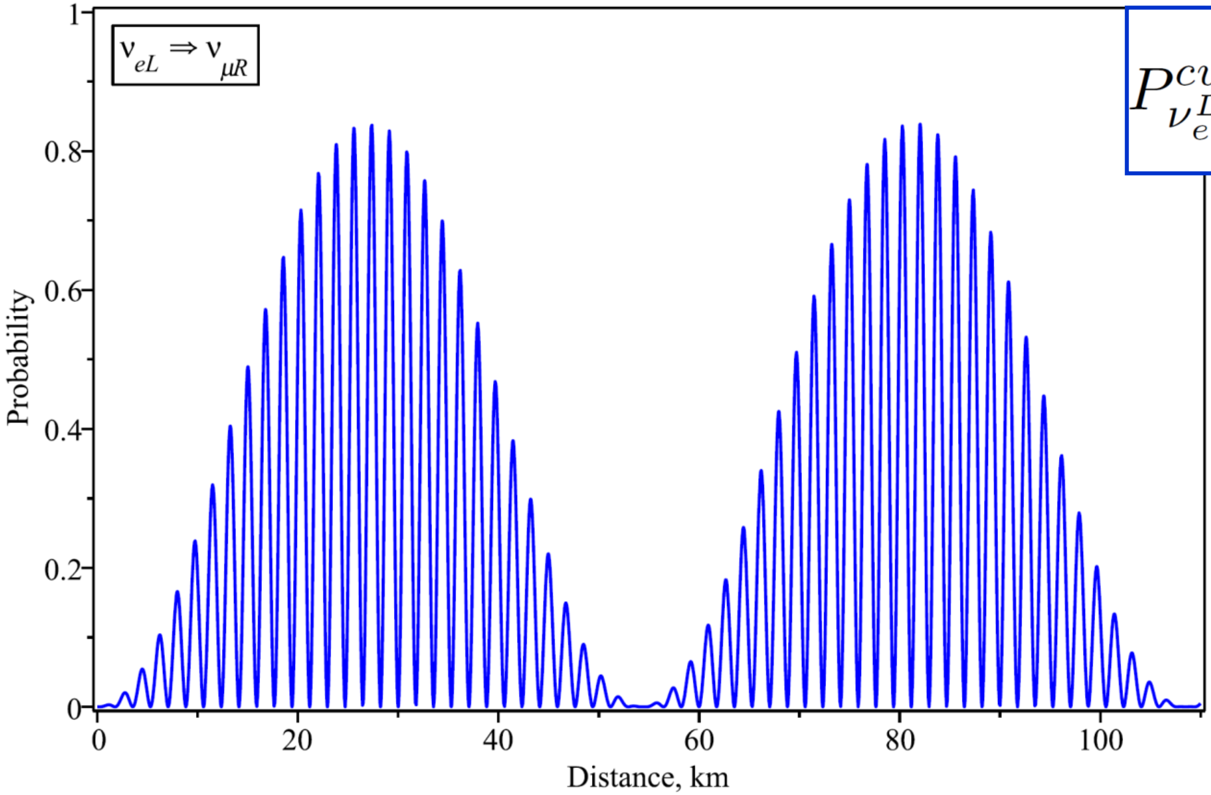
Fig. 2 The probability of the neutrino spin oscillations $\nu_e^L \to \nu_e^R$ in the transversal magnetic field $B_\perp = 10^{16}\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

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

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

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

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:

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

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

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

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

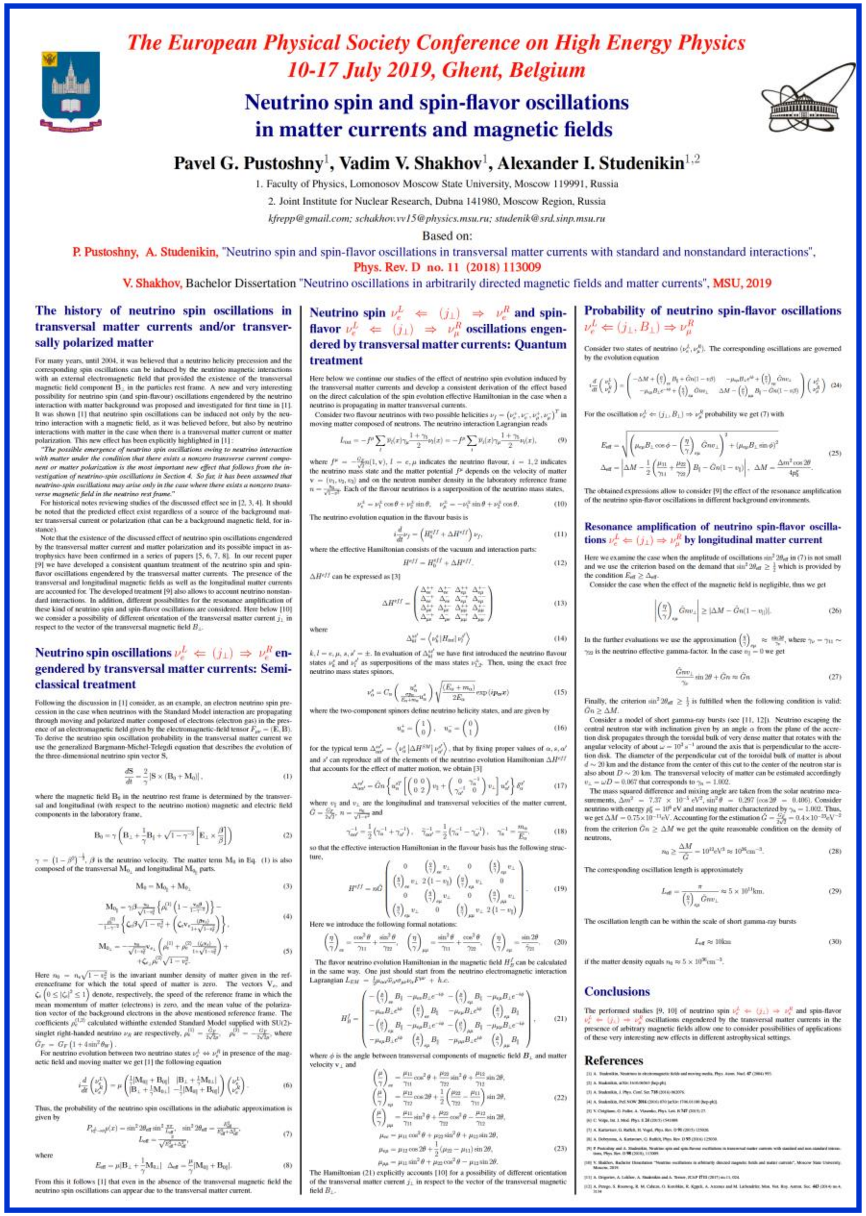
... depends on μ_ν and B

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

Σ 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 European Physical Society Conference on High Energy Physics
10-17 July 2019, Ghent, Belgium

Neutrino spin and spin-flavor oscillations in matter currents and magnetic fields

Pavel G. Pustoshny[1], Vadim V. Shakhov[1], Alexander I. Studenikin[1,2]

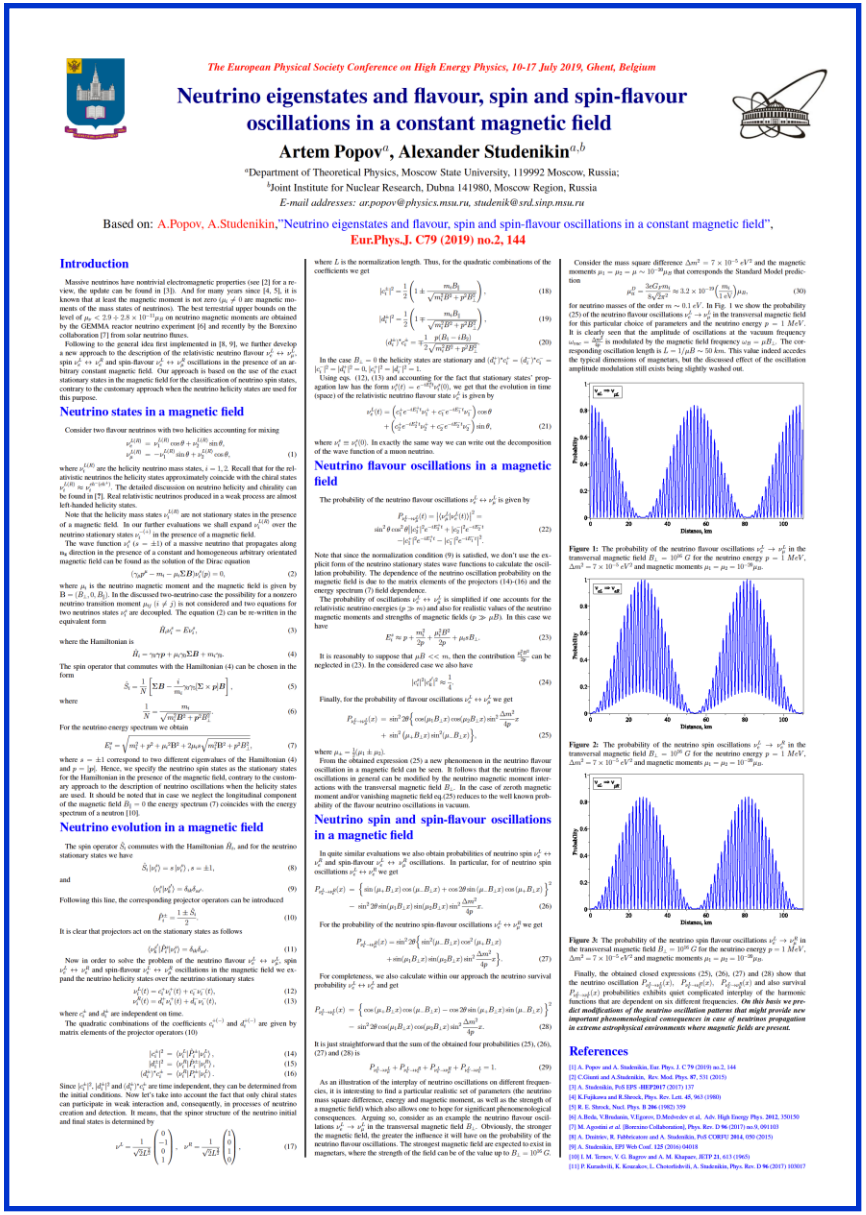
1. Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
2. Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia

kfrepp@gmail.com; schakhov.vv15@physics.msu.ru; studenik@srd.sinp.msu.ru

Based on:

P. Pustoshny, A. Studenikin, "Neutrino spin and spin-flavor oscillations in transversal matter currents with standard and nonstandard interactions", Phys. Rev. D no. 11 (2018) 113009

V. Shakhov, Bachelor Dissertation "Neutrino oscillations in arbitrarily directed magnetic fields and matter currents", MSU, 2019



The European Physical Society Conference on High Energy Physics, 10-17 July 2019, Ghent, Belgium

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

Artem Popov[a], Alexander Studenikin[a,b]

[a]Department of Theoretical Physics, Moscow State University, 119992 Moscow, Russia;
[b]Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia
E-mail addresses: ar.popov@physics.msu.ru, studenik@srd.sinp.msu.ru

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

A. Pustoshny, V. Shakhov, A. Studenikin
"Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions" poster # 25

poster # 34 A. Popov, A. Studenikin
"Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field"

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 $j_{\perp}$

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

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

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

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

Thank you

Since 1992

19th Lomonosov Conference on Elementary Particle Physics

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Back up slides

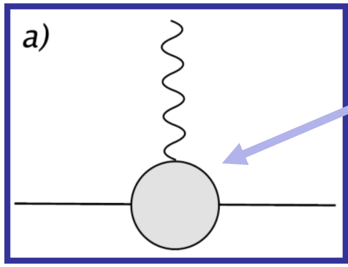
Large magnetic moment μ_ν

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

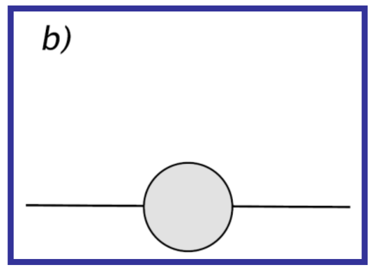


then

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

…combination of constants and loop factors…

contribution to m_ν given by



, then

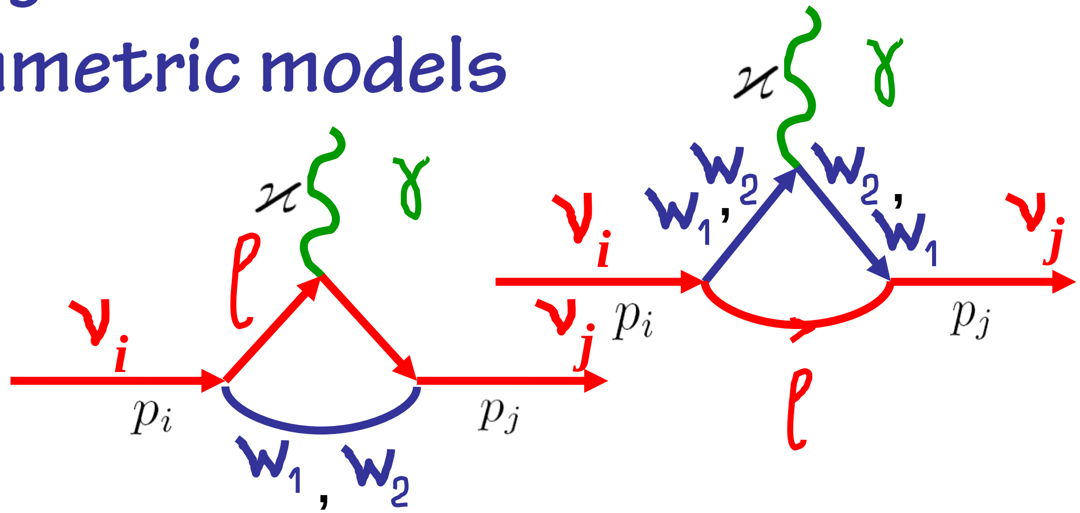
$$m_\nu \sim G\Lambda$$

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

Voloshin, 1988;
Barr, Freire,
Zee, 1990

3.6 Neutrino magnetic moment in left-right symmetric models

$$SU_L(2) \times SU_R(2) \times U(1)$$



Gauge bosons mass states $W_1 = W_L \cos\xi - W_R \sin\xi$

$W_2 = W_L \sin\xi + W_R \cos\xi$

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

Kim, 1976; Marciano, Sanda, 1977;
Beg, Marciano, Ruderman, 1978

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

... charged lepton mass ... ... neutrino mass ...

Large magnetic moment

$\mu_\nu = \mu_\nu(m_\nu, m_{B^+}, m_{e^-})$

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

Kim, 1976
Beg, Marciano, Ruderman, 1978

- Voloshin, 1988
  "On compatibility of small m_ν with large μ_ν neutrino",
  Sov.J.Nucl.Phys. 48 (1988) 512

  … there may be $SU(2)_\nu$ symmetry that forbids m_ν but not μ_ν

Z.Z.Xing, Y.L.Zhou,
"Enhanced electromagnetic transition dipole moments and radiative decays of massive neutrinos due to the seesaw-induced non-unitary effects"
Phys.Lett.B 715 (2012) 178

- Bar, Freire, Zee, 1990
- supersymmetry
- extra dimensions

considerable enhancement of μ_ν to experimentally relevant range

- model-independent constraint μ_ν

$\mu_\nu^D \leq 10^{-15}\mu_B$

$\mu_\nu^M \leq 10^{-14}\mu_B$

for BSM ($\Lambda \sim 1$ TeV) without fine tuning and under the assumption that $\delta m_\nu \leq 1$ eV

Bell, Cirigliano, Ramsey-Musolf, Vogel, Wise, 2005

. . . Atomic Ionization Effect . . .

… quite exciting claim that ν-e cross section should be increased by Atomic Ionization Effect:

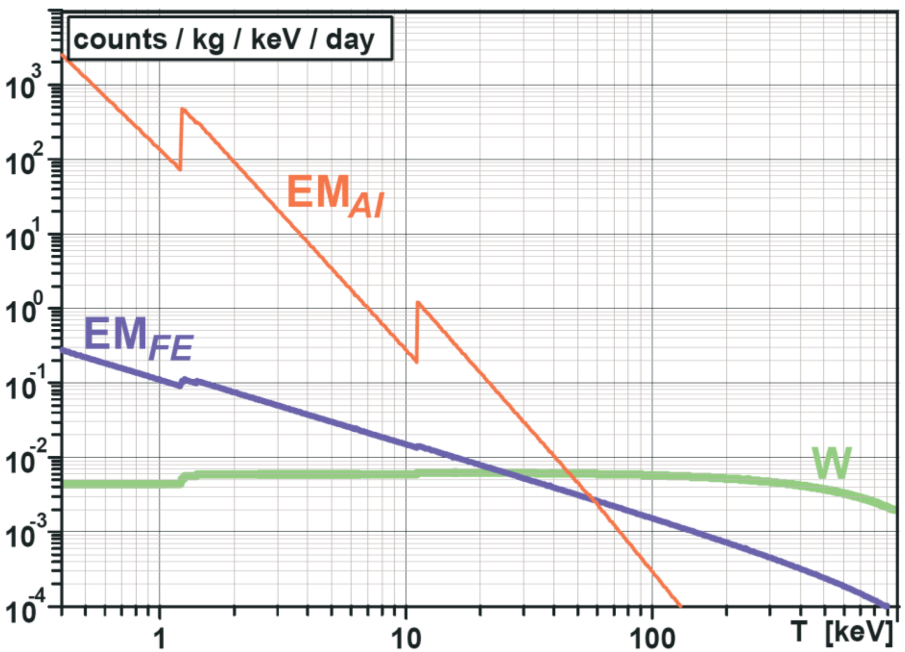
$$\nu + (A,Z) \longrightarrow \nu' + (A,Z)^+ + e^-$$
$$\downarrow \text{recombination}$$
$$(A,Z) \quad + \gamma$$

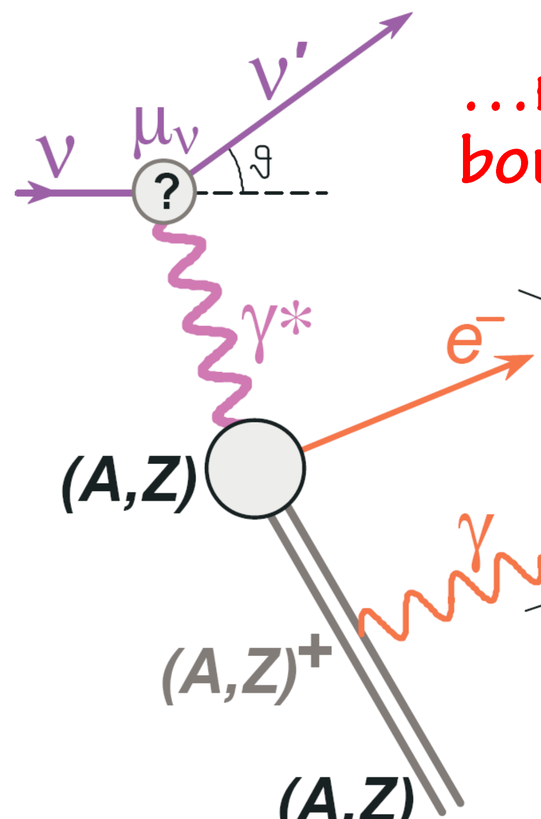
?

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

(ν scattering on bound e)

… an interesting hypothetical possibility to improve bounds…





…new bounds …

... better limits on ν effective magnetic moment ...

$$\mu_\nu < 1.3 \times 10^{-11} \mu_B$$?

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

... atomic ionization effect accounted for ...

... however ...

$$\mu_\nu < 5.0 \times 10^{-12} \mu_B$$?

... atomic ionization effect accounted for ...

A.Beda et al. (GEMMA Coll.), arXiv: 1005.2736, 16 May 2010

$$\mu_\nu < 3.2 \times 10^{-11} \mu_B$$

... ν-e scattering on free electrons ... (without atomic ionization)

K.Kouzakov, A.Studenikin,

- “Magnetic neutrino scattering on atomic electrons revisited” **Phys.Lett. B** 105 (2011) 061801,
- “Electromagnetic neutrino-atom collisions: The role of electron binding” **Nucl.Phys.** (Proc.Suppl.) 217 (2011) 353

K.Kouzakov, A.Studenikin, M.Voloshin,

- “Neutrino electromagnetic properties and new bounds on neutrino magnetic moments” **J.Phys.: Conf.Ser**. 375 (2012) 042045
- “Neutrino-impact ionization of atoms in search for neutrino magnetic moment”, **Phys.Rev.D** 83 (2011) 113001
- “On neutrino-atom scattering in searches for neutrino magnetic moments” **Nucl.Phys.B** (Proc.Supp.) 2011 (Proc. of Neutrino 2010 Conf.)
- “Testing neutrino magnetic moment in ionization of atoms by neutrino impact”, **JETP Lett.** 93 (2011) 699

M.Voloshin,

- “Neutrino scattering on atomic electrons in search for neutrino magnetic moment” **Phys.Rev.Lett.** 105 (2010) 201801

K. Kouzakov, A. Studenikin,

"Theory of neutrino-atom collisions:
the history, present status, and BSM physics",

in: Special issue

"Through Neutrino Eyes: The Search for New Physics",

Adv. in High Energy Phys. 2014 (2014) 569409 (37pp)

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

Astrophysical bound on q_ν

- ... astrophysical bound on millicharge q_ν from ②

ν energy quantization in rotating magnetized media

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 ν in rotating magnetized matter

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

Modified Dirac equation for ν wave function

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

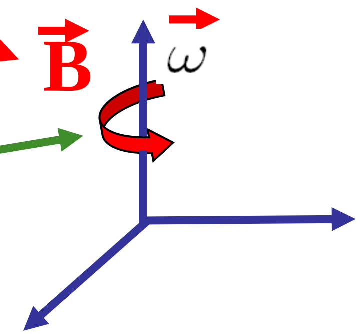
external magnetic field

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

matter potential

rotating matter

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



rotation angular frequency

ν energy is quantized in rotating matter

A.Studenikin, I.Tokarev, Nucl.Phys.B (2014)

$$G = \frac{G_F}{\sqrt{2}}$$

$$p_0 = \sqrt{p_3^2 + 2N|2Gn_n\omega - \epsilon q_\nu B| + m^2} - Gn_n - q\phi$$

$$N = 0, 1, 2, ...$$

integer number

matter rotation frequency

scalar potential of electric field

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

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

In quasi-classical approach

- ν quantum states in rotating matter
- ν 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

A.Studenikin, I.Tokarev, Nucl.Phys.B (2014)

... we predict :

$E \sim 1$ eV

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

$$R = \sqrt{\frac{2N}{Gn\omega}} < R_{NS} = 10\ km$$

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

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

$$T_{\nu} \sim 10^{-4}\ \mathrm{eV}$$

- ν Star Turning mechanism (ν ST)

A. Studenikin, I. 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 νST impact with observational data on pulsars ...

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

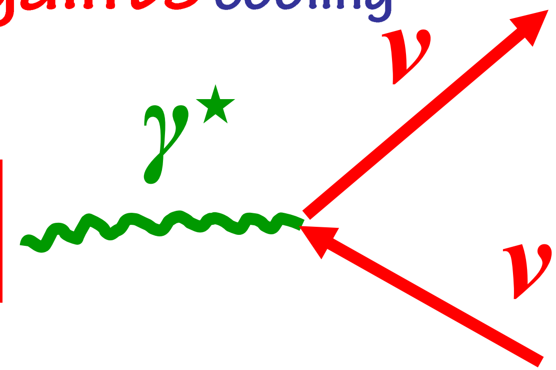
- ... best astrophysical bound ...

Dobroliubov, Ignatiev (1990); Babu, Volkas (1992); Mohapatra, Nussinov (1992) ...

- Constraints on neutrino millicharge from red gaints cooling

$\gamma^{\star} \rightarrow \nu\nu$

$$L_{int} = -iq_\nu \bar{\psi}_\nu \gamma^\mu \psi_\nu A^\mu$$



Interaction Lagrangian

millicharge

Decay rate

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

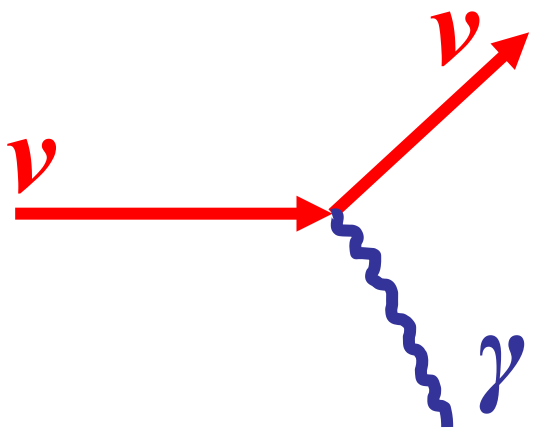
- $q_\nu \leq 2 \times 10^{-14} e$ ...to avoid helium ignition in low-mass red gaints Halt, Raffelt, Weiss, PRL1994

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

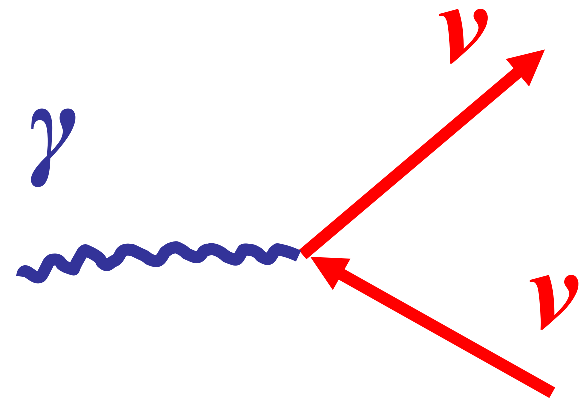
- ... from "charge neutrality" of neutron... $q_\nu \leq 3 \times 10^{-21} e$

Astrophysical bound on μ_ν

③ ν electromagnetic interactions

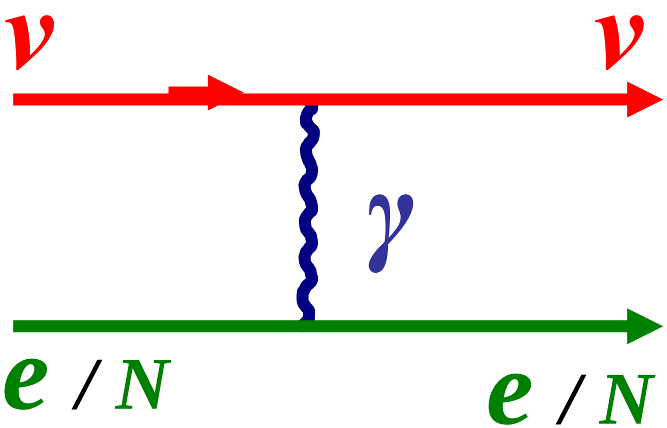


ν decay, Cherenkov radiation

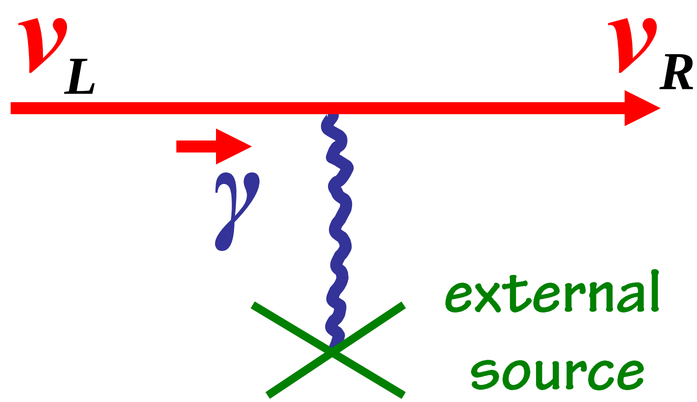


γ decay in plasma

!!!



Scattering

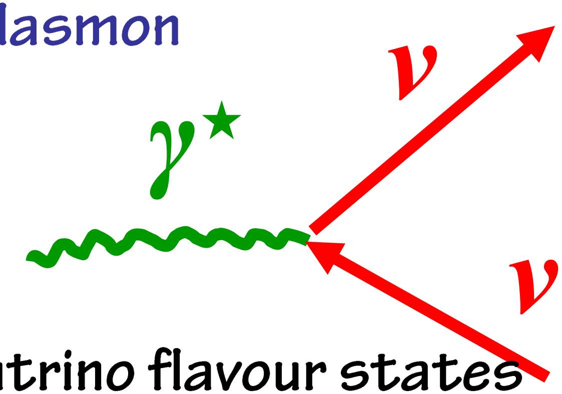


Spin precession

② Astrophysical bound on μ_ν

G.Raffelt, PRL 1990

comes from cooling of red gaint stars by plasmon decay $\gamma^\star \longrightarrow \nu\nu$



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

neutrino flavour states

$$\epsilon_\alpha k^\alpha = 0$$

Matrix element

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

Decay rate

$$\Gamma_{\gamma\to\nu\bar{\nu}} = \frac{\mu^2}{24\pi}\frac{(\omega^2 - k^2)^2}{\omega}$$

= 0 in vacuum $\omega = k$

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

Energy-loss rate per unit volume

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

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

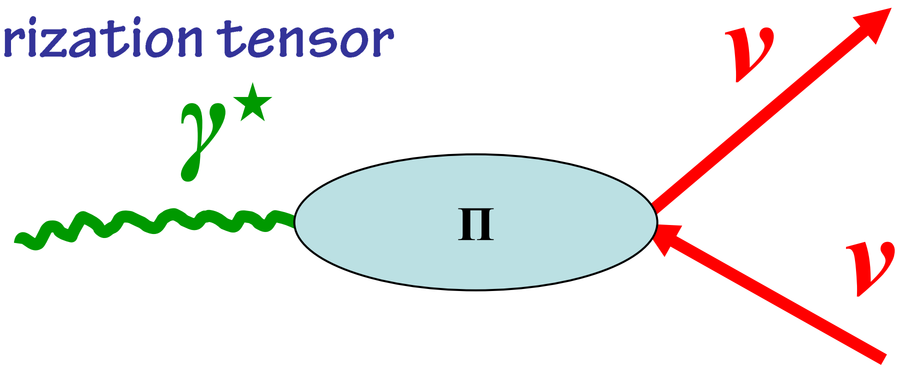
distribution function of plasmons

Astrophysical bound on μ_ν

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

Energy-loss rate per unit volume

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



more fast star cooling

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

… best astrophysical limit on ν magnetic moment…

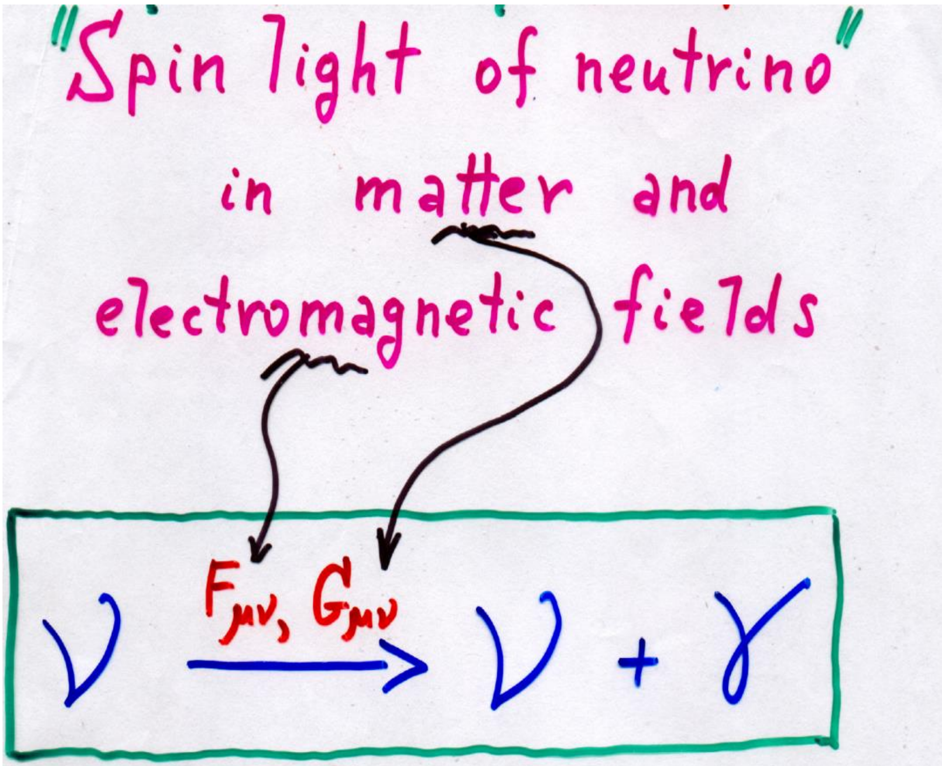
$$\mu \le 3 \times 10^{-12} \mu_B$$

G.Raffelt, PRL 1990

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

• New mechanism of electromagnetic radiation

$SL\nu$



A. Egorov, A. Lobanov, A. Studenikin,
Phys.Lett. B 491 (2000) 137

Lobanov, Studenikin,
Phys.Lett. B 515 (2001) 94
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Phys.Lett. B 601 (2004) 171

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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
J. Cosm. Astropart. Phys. 11 (2017) 024

Осцилляции нейтрино

флейворные: $\nu_e \leftrightarrow \nu_\mu$

спиновые: $\nu_L \leftrightarrow \nu_R$

flavour **oscillations** **spin**

$$P_{\nu_e \nu_\mu}(x) = \sin^2 2\theta \cdot \sin^2 \frac{\Delta m^2}{4E} x$$

$$\Delta m^2 = m_2^2 - m_1^2$$

$$P_{\nu_L \nu_R} = \sin^2 \beta \cdot \sin^2 \Omega x$$

$$\Omega = \left((\mu B)^2 + \left(\frac{\Delta_{LR}}{4E} \right)^2 \right)^{1/2}$$

$$\sin^2 \beta = \frac{(\mu B)^2}{(\mu B)^2 + (\Delta_{LR}/4E)^2}$$

resonance amplification of ν oscillation probabilities amplitudes

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

E. Akhmedov
C.-S. Lim, W. Marciano
(1988)

{Neutrino spin $\nu_L \overset{B_\perp}{\longleftrightarrow} \nu_R$ oscillations

(mixing due to $\frac{\Delta m_\nu^2}{2E_\nu} \sin 2\theta_{vac} \to 2\mu B_\perp$)

$$P(\nu_L \leftrightarrow \nu_R) = \sin^2 2\theta_{eff} \sin^2 \frac{\pi x}{L_{eff}},$$

$$\sin^2 2\theta_{eff} = \frac{(2\mu B_\perp)^2}{(2\mu B_\perp)^2 + \Omega^2},$$

$$* \quad \Omega = \frac{\Delta m_\nu^2}{2E_\nu} A(\theta_{vac}) - \sqrt{2} G_F n_{eff},$$

n_{eff} — particle number density

$$L_{eff} = \frac{2\pi}{\sqrt{\Omega^2 + (2\mu B_\perp)^2}}$$

$\Omega^2 \to 0$: resonance in $\nu_L \leftrightarrow \nu_R$ neutrino spin oscillations

$\Downarrow$

Spin and spin-flavour oscillations for $\nu_\odot$ and ν_{SN}

Bruno Pontecorvo,
«Mesonium and anti-mesonium»,
Sov.Phys.JETP 6 (1957) 429
Zh.Eksp.Teor.Fiz. 33 (1957) 549-551:

if $m_\nu \neq 0$
then
$\nu \leftrightarrow \bar{\nu}$
In vacuum

«It was assumed above that there exists a conservation law for the neutrino charge, according to which a neutrino cannot change into an antineutrino in any approximation. This law has not yet been established; evidently it has been merely shown that the neutrino and antineutrino are not identical particles.

If the two-component neutrino theory should turn out to be incorrect … and if the conservation law of neutrino charge would not apply, then in principle neutrino – antineutrino transitions could take place in vacuo»

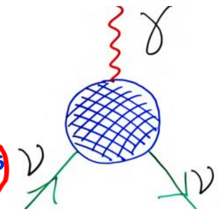
Electromagnetic Properties of ν

(effects of magnetic moments)

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 $q^2 = 0$ static EP of ν

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

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

$$\mu^{D}_{jj} = \frac{3e_0 G_F m_j}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19}\mu_B \left(\frac{m_j}{1\ \text{eV}}\right)$$

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

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

- 2.9 — GEMMA Coll. 2012
- 2.8 — Borexino Coll. 2017
- ~0.1 — Astrophysics, Raffelt ea 1988, Arcoa Dias ea 2015

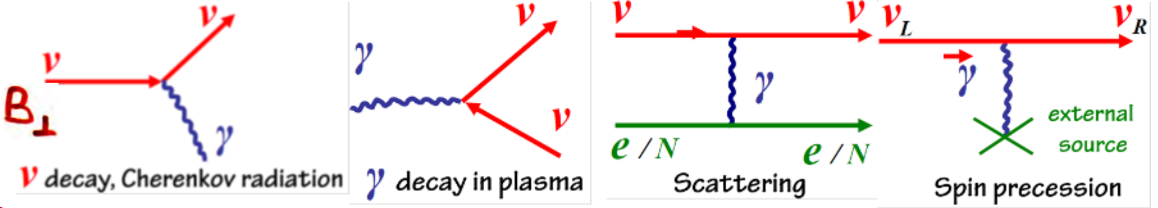
$q_{\nu_e} <\sim 10^{-12},\ 10^{-19},\ \sim 10^{-21}\ e_0$

- $\sim 10^{-12}$ — reactor ν scattering: AS '14, Chen ea '14
- 10^{-19} — AS '14 (astrophysics)
- $\sim 10^{-21}$ — neutrality of matter

Effects of ν magnetic moment:

- spin precession and oscillations in $B_\perp$

Cisneros, Okun, Voloshin, Vysotsky, Valle, Raffelt, Schechter, Petkov, Akhmedov, Lim, Marciano, Smirnov, Pulido, Dvornikov, Grigoriev, Lobanov, Lokhov, Kouzakov, Ternov, Studenikin et al



1 Electromagnetic interactions and oscillations of ultrahigh-energy cosmic ν in interstellar space

Kouzakov & AS, **PRD 96 (2017)**

$$L_B = \pi/\mu_\nu B$$

$$P_{\nu^L \to \nu^R}(x) = \sin^2\left(\frac{\pi x}{L_B}\right)$$

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

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

2 ν flavour, spin and spin-flavour oscillations and consistent account for constant magnetic field

Popov & AS, Eur. Phys .J. C 79 (2019) no.2, 144

probability of spin oscillations depends on Δm^2

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

3 ν spin and spin-flavour oscillations engendered by transversal matter current

Pustoshny & AS, Phys. Rev. D98 (2018) 113009

Studenikin 2004, 2017

- **transversal matter currents $j_\perp$ do change ν helicity !**

4 Spin-light of ν in Gamma-Ray Bursts

Grigoriev, Lokhov, Studenikin, Ternov

new mechanism of EM radiation by ν

JCAP 1711 (2017) no. 11, 024

"SL ν in astrophysical environments"