Neutrino electromagnetic properties

(overview and new effects)

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&

JINR

(GEMMA Coll.)

"Results and Perspectives in Particle Physics",
La Thuile, Italy
06/03/2017

Outline

1. (short) review of ν electromagnetic properties
2. experimental constraints on μ_ν and q_ν
3. ν electromagnetic interactions (new effects)
4. two new aspects of spin ν (flavour) oscillations

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

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

Neutrino electromagnetic interactions: A window to new physics

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(published 16 June 2015)

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

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ν electromagnetic properties (new effects)

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

K. Kouzakov, A. Studenikin, "Theory of neutrino-atom collisions: the history, present status, and BSM physics",
Adv. in High Energy Phys. 2014 (2014) 569409 (37pp)

A. Studenikin , I. Tokarev, "Millicharged neutrino with anomalous magnetic moment in rotating magnetized matter" ,
Nucl. Phys. B 884 (2014) 396

I. Balantsev, A. Studenikin, "From electromagnetic neutrinos to new electromagnetic radiation mechanism in neutrino fluxes",
Int.J.Mod.Phys. A30 (2015) 17, 1530044

- K. Kouzakov, A. Studenikin, "Electromagnetic properties of massive neutrinos in low-energy elastic neutrino-electron scattering",
arXiv: 1703.0040 March 1, 2017, accepted by PRD

New developments in ν spin (flavour) oscillations

- A. Studenikin,
“From neutrino electromagnetic interactions to spin oscillations in transversal matter currents”, PoS (2017) NOW2016_070

R. Fabbricatore, A. Grigoriev, A. Studenikin,
“Neutrino spin-flavour oscillations derived from the mass basis”,
arXiv:1604.01245

A. Studenikin,
“Status and perspectives of neutrino magnetic moments”,
arXiv:1603.00337

A. Dmitriev, R. Fabbricatore, A. Studenikin,
“Neutrino electromagnetic properties: new approach to oscillations in magnetic fields”,
arXiv:1506.053115

… the meaning of "new physics" is twofold:

1) a massive ν neutrino have nonzero electromagnetic properties that can be considered as manifestation of physics beyond Standard Model

2) in studies of ν electromagnetic interactions new phenomena are predicted astrophysical applications…

... problem and puzzle ...

ν electromagnetic properties

up to now nothing has been seen

... in spite of reasonable efforts ...

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

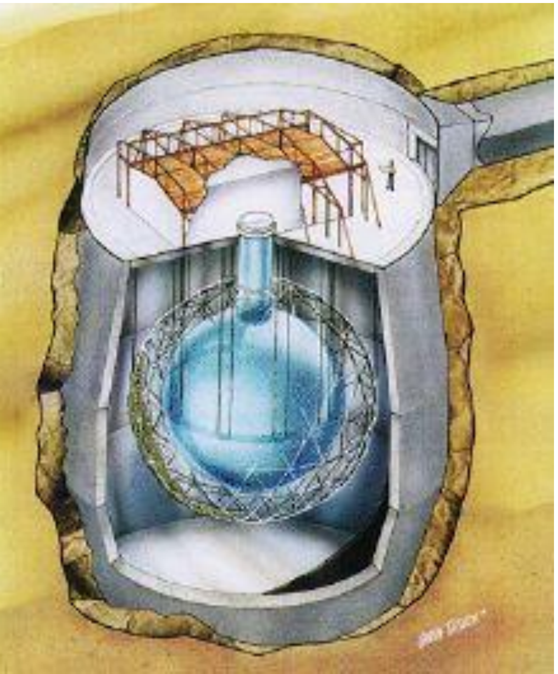
are in agreement with "ZERO" ν EM properties

... However, in course of recent development of knowledge on ν mixing and oscillations,

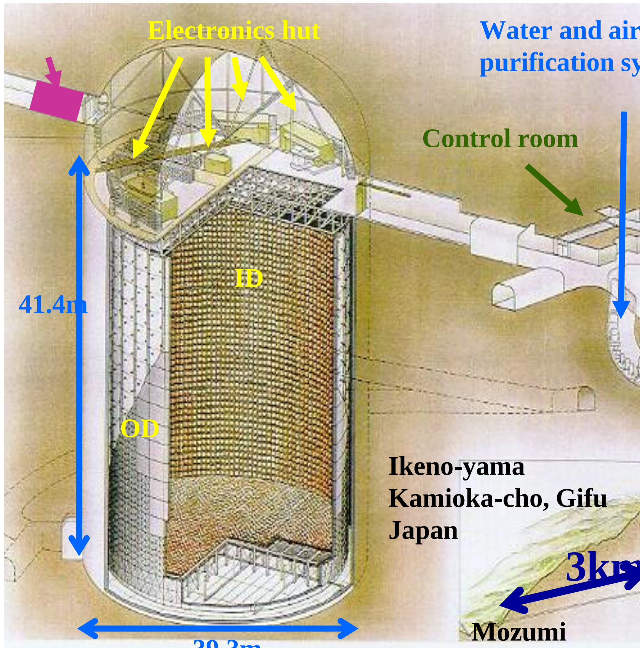
The Nobel Prize in Physics 2015

Arthur McDonald

Takaaki Kajita



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



- **Astrophysical bounds**

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

G. Raffelt (1990)

$m_\nu \neq 0$

- **Theory (Standard Model with ν_R)**

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

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

Lee, Shrock, 1977; Fujikawa, Shrok, 1980

- **Limits from reactor ν-e scattering experiments**

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

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

ν exhibits unexpected properties (puzzles)

W. Pauli, 1930

- neutral "neutron" $\Longrightarrow$ ν E.Fermi, 1933
- probably $\mu_\nu \neq 0$!?

Pauli himself wrote to Baade:

"Today I did something a physicist should never do. I predicted something which will never be observed experimentally..."

H. Bethe, R. Peierls,

«The 'neutrino'»

Nature 133 (1934) 532

- «There is no practically possible way of observing the neutrino» !

  ... puzzles ...

- ... what about electromagnetic properties of ν ?

e, ν in external electromagnetic fields

ν in dense matter

...«method of exact solutions »...

A. Studenikin

- "Quantum treatment of neutrino in background matter"
J. Phys. A: Math. Gen. 39 (2006) 6769-6776

- "Method of wave equations exact solutions in studies of neutrinos and electron interactions in dense matter"
J.Phys.A: Math.Theor. 41 (2008) 164047

- "Neutrinos and electrons in background matter: a new approach"
Ann.Fond. de Broglie 31 (2006) 289-316

Astrophysical consequences of ν electromagnetic interactions

A. Studenikin , I. Tokarev,
"Millicharged neutrino with anomalous magnetic moment in rotating magnetized matter" , Nucl. Phys. B 884 (2014) 396

C. Giunti, . K.Kouzakov, Yu-Feng Li, A. Lokhov, A. Studenikin, Shun Zhou,
"Electromagnetic neutrinos in laboratory experiments and astrophysics",
Ann. d. Phys. 528 (2016) 198-215

5

...astrophysical consequences of ν electromagnetic interactions ...

New mechanism of electromagnetic radiation

SLe_ν

I. Balantsev, A. Studenikin,

"Spin Light of Electron in dense Neutrino fluxes", arXiv: 1405.6598,

"Spin light of relativistic electrons in neutrino fluxes", arXiv: 1502.05346,

"From electromagnetic neutrinos to new electromagnetic radiation mechanism in neutrino fluxes", Int.J.Mod.Phys. A30 (2015) 17, 1530044

6 … the effect of ν helicity conversions and oscillations induced by transversal matter currents

#2 … matter effect included …

ν spin precession can be stimulated not only by e.m. interactions with e.m. field $F_{\mu\nu}$ but also by ν weak interactions with matter!

- "Neutrino in electromagnetic fields and moving matter", Phys. Atom. Nucl. 67 (2004) 993-1002
- "Neutrino in magnetic fields: from the first studies to the new effects in neutrino oscillations" arXiv: hep-ph/040701
- "The four new effects in neutrino oscillations", Nucl.Phys.B (Proc.Suppl.) 143 (2005) 570
- "Neutrino spin and spin-flavour oscillations in transversally moving or polarized matter", arXiv:1610.06563
- "From neutrino electromagnetic interactions to spin oscillations in transversal matter currents", PoS (NOW 2016) 070

37th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

ICHEP 2014 VALENCIA

2 - 9 - JULY - 2014 - VALENCIA

Nuclear & Particle Physics Proc. 273-275 (2016)

- A.Studenikin,
  "Electromagnetic neutrino: a short review", p. 1711-1718

- K.Kouzakov, A.Studenikin,
  "Theory of ionizing neutrino-atom collisions:
  The role of atomic recoil", p. 2609-2611

- V. Brudanin, D. Medvedev, A. Starostin, A. Studenikin (GEMMA Coll.)
  "New bounds on neutrino electric millicharge from
  GEMMA experiment on neutrino magnetic moment", p. 2605-2608

- A.Studenikin, I.Tokarev,
  "New astrophysical limit on neutrino millicharge", p. 2332-2334

- I.Balantsev, A.Studenikin,
  "Spin light of relativistic electrons in neutrino fluxes", p. 2335-2338

6 … the effect of ν helicity conversions and oscillations induced by transversal matter currents

- A.Studenikin, "Status and perspectives of neutrino magnetic moments"
  J.Phys. (Conf.Ser.) TAUP 2015 (2016)
  arXiv:1603.00337

#2 … matter effect included …

ν spin precession can be stimulated not only by e.m. interactions with e.m. field $F_{\mu\nu}$ but also by ν weak interactions with matter!

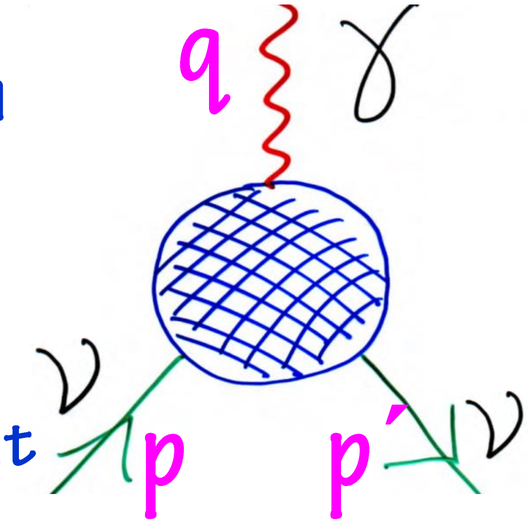
1

ν electromagnetic properties

(short review)

$m_\nu \neq 0$

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

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

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

Matrix element of electromagnetic current between neutrino states

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

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

dipole

2. magnetic

3. electric

4. anapole

- Hermiticity and discrete symmetries of EM current $J_\mu^{\rm EM}$ put constraints on form factors

Dirac ν

1) CP invariance + Hermiticity $\Longrightarrow f_E = 0$,

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 $\Longrightarrow$ three form factors are real: $Imf_Q = Imf_M = Imf_A = 0$

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 $\Longrightarrow$ 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

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

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

... beyond SM...

and

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

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

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

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

Dipole magnetic $\boxed{f_M(q^2)}$ and electric $\boxed{f_E(q^2)}$

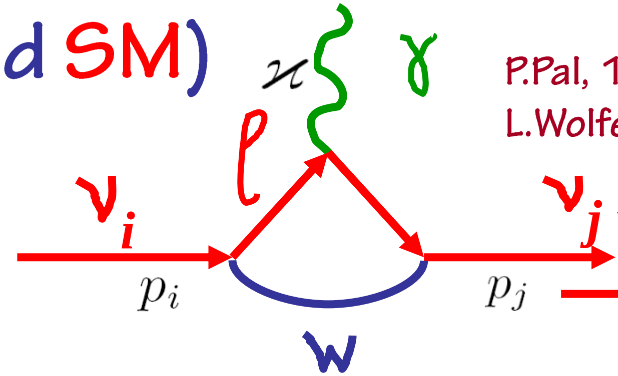
are most well studied and theoretically understood among form factors

...because in the limit $\boxed{q^2 \to 0}$ they can have nonvanishing values

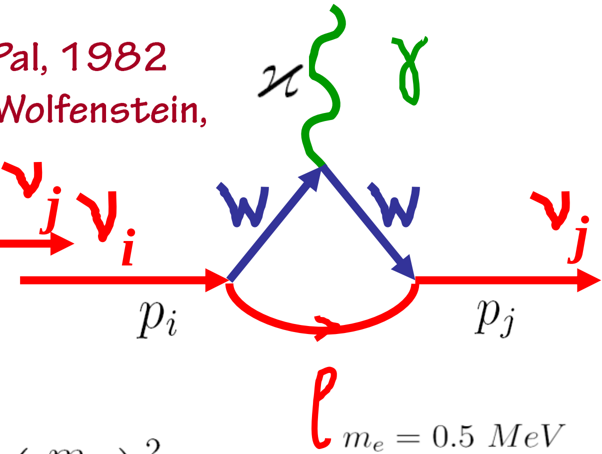
$$\boxed{\mu_\nu \;=\; f_M(0)} \Leftarrow \quad \nu \text{ magnetic moment}$$

$$\boxed{\epsilon_\nu \;=\; f_E(0)} \Leftarrow \quad \nu \text{ electric moment ???}$$

Neutrino (beyond SM) dipole moments
(+ transition moments)



P.Pal, 1982
L.Wolfenstein,



- **Dirac neutrino**

$$\left.\begin{matrix}\mu_{ij}\\ \epsilon_{ij}\end{matrix}\right\} = \frac{eG_F m_i}{8\sqrt{2}\pi^2}\left(1 \pm \frac{m_j}{m_i}\right) \sum_{l=\,e,\ \mu,\ \tau} f(r_l) U_{lj} U^*_{li}$$

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

$m_e = 0.5\ MeV$
$m_\mu = 105.7\ MeV$
$m_\tau = 1.78\ GeV$
$m_W = 80.2\ GeV$

- $m_i, m_j \ll m_l, m_W$

$$f(r_l) \approx \frac{3}{2}\left(1 - \frac{1}{2} r_l\right), \quad r_l \ll 1$$

transition moments vanish because unitarity of U implies that its rows or columns represent orthogonal vectors

- transition moments are suppressed, Glashow-Iliopoulos-Maiani cancellation,
- for diagonal moments there is no GIM cancellation

- **Majorana neutrino** only for $\boxed{i \neq j}$

$$\boxed{\mu^M_{ij} = 2\mu^D_{ij} \quad and \quad \epsilon^M_{ij} = 0}$$

or

$$\boxed{\mu^M_{ij} = 0 \quad and \quad \epsilon^M_{ij} = 2\epsilon^D_{ij}}$$

… depending on relative CP phase of ν_i and ν_j

The first nonzero contribution from neutrino transition moments

$$f_{r_l} \to \cancel{-\frac{3}{2}} + \frac{3}{4}\left(\frac{m_l}{m_W}\right)^2 \ll 1$$

GIM cancellation

$$\left.\begin{array}{l}\mu_{ij}\\ \epsilon_{ij}\end{array}\right\} = \frac{3eG_F m_i}{32\sqrt{2}\pi^2}\left(1 \pm \frac{m_j}{m_i}\right)\left(\frac{m_\tau}{m_W}\right)^2 \sum_{l=e,\,\mu,\,\tau}\left(\frac{m_l}{m_\tau}\right)^2 U_{lj}U_{li}^*$$

$$\mu_B = \frac{e}{2m_e}$$

- $$\left.\begin{array}{l}\mu_{ij}\\ \epsilon_{ij}\end{array}\right\} = 4\times 10^{-23}\mu_B\left(\frac{m_i \pm m_j}{1\ eV}\right) \sum_{l=e,\,\mu,\,\tau}\left(\frac{m_l}{m_\tau}\right)^2 U_{lj}U_{li}^*$$

… neutrino radiative decay is very slow

- Dirac ν diagonal (i=j) magnetic moment

$$\boxed{\epsilon_{ii}^D = 0}$$ for CP-invariant interactions

$$\boxed{\mu_{ii}^M = \epsilon_{ii}^M = 0}$$

$$\mu_{ii} = \frac{3eG_F m_i}{8\sqrt{2}\pi^2}\left(1 - \frac{1}{2}\sum_{l=e,\mu,\tau} r_l \mid U_{li}\mid^2\right) \approx 3.2\times 10^{-19}\left(\frac{m_i}{1\ eV}\right)\mu_B$$

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

Lee, Shrock, Fujikawa, 1977

- no GIM cancellation
- μ_{ii}^D - to leading order - independent on U_{li} and $m_{\,l=e,\,\mu,\,\tau}$
- $$\boxed{\mu_e^2 = \sum_{i=1,2,3} \mid U_{ie}\mid^2 \mu_{ii}^2}$$ …possibility to measure fundamental μ_{ii}^D

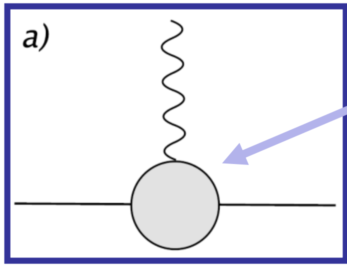
$\mu_{ii}^D = 0$ for massless ν (in the absence of right-handed charged currents)

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

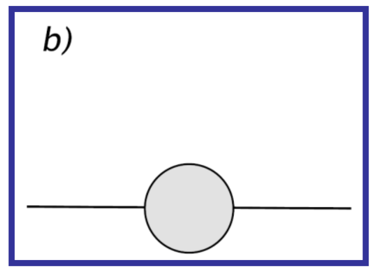


then

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

…combination of constants and loop factors…

contribution to m_ν given by



, then

$$\boxed{m_\nu \sim G\Lambda}$$

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

Voloshin, 1988;
Barr, Freire,
Zee, 1990

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:

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

where the Standard Model contribution

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

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

K. Kouzakov, A. Studenikin,

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

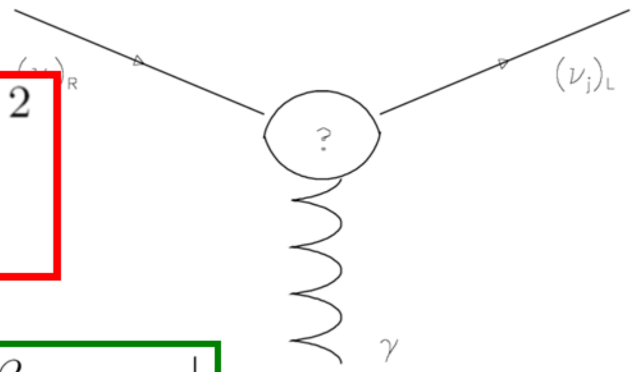
Abstract

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 arriving 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.

arXiv: 1703.0040 Mar 2017, accepted by PRD

Effective ν magnetic moment in experiments

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



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

where U_{li}: neutrino mixing matrix

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

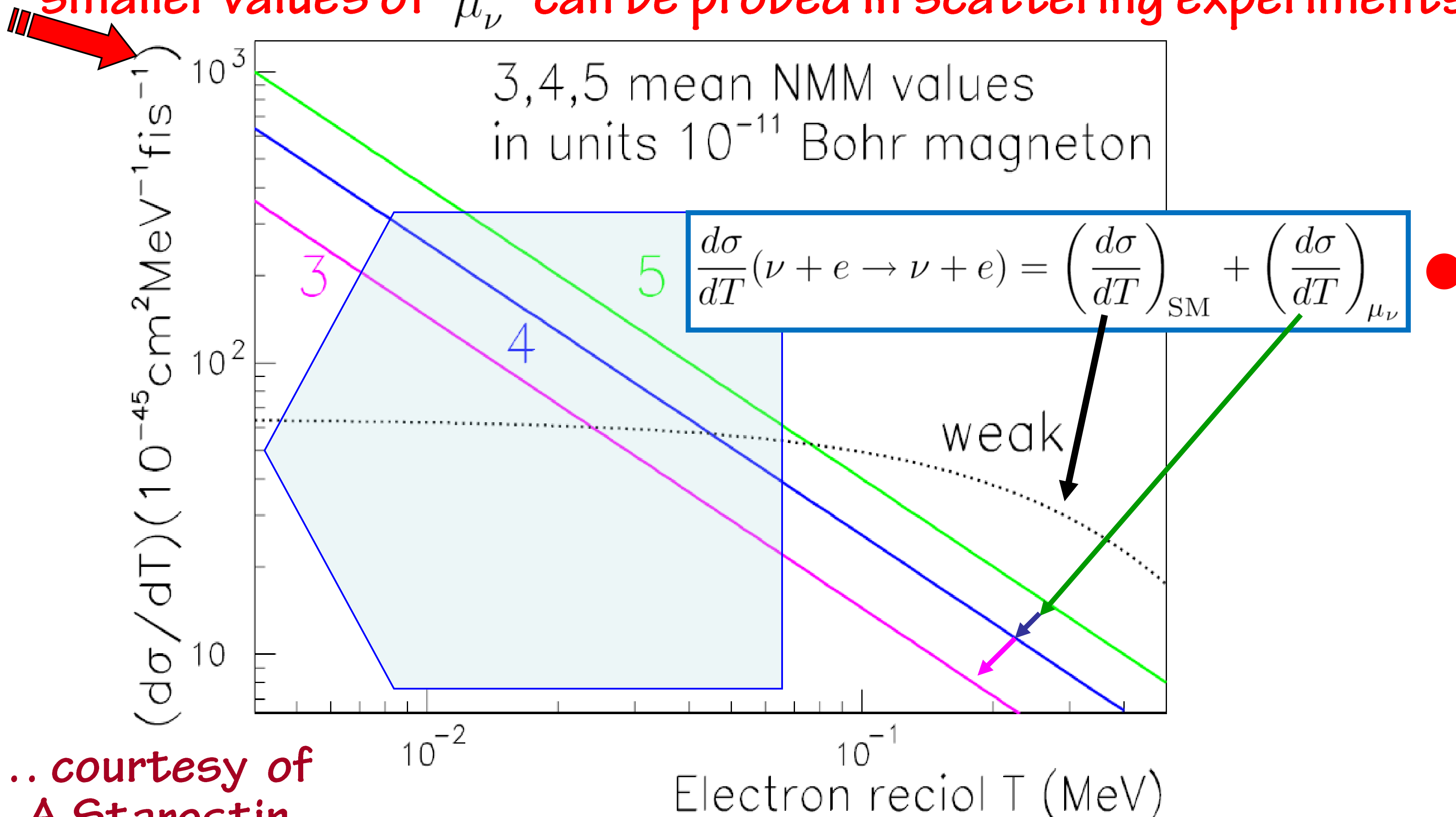
magnetic and **electric** moments

- 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}B and ^{7}Be) are different.

Magnetic moment contribution dominates at low electron recoil energies when $\boxed{\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} > \left(\frac{d\sigma}{dT}\right)_{SM}}$ and $\boxed{\frac{T}{m_e} < \frac{\pi^2 \alpha_{em}}{G_F^2 m_e^4}\mu_\nu^2}$

... 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...

MUNU experiment at Bugey reactor (2005)

$$\boxed{\mu_\nu \le 9 \times 10^{-11} \mu_B}$$

TEXONO collaboration at Kuo-Sheng power plant (2006)

$$\boxed{\mu_\nu \le 7 \times 10^{-11} \mu_B}$$

GEMMA (2007) $\boxed{\mu_\nu \le 5.8 \times 10^{-11} \mu_B}$

GEMMA I 2005 - 2007

BOREXINO (2008) $\boxed{\mu_\nu \le 5.4 \times 10^{-11} \mu_B}$

...was considered as the world best constraint...

$$\boxed{\mu_\nu \le 8.5 \times 10^{-11} \mu_B \quad (\nu_\tau,\ \nu_\mu)}$$

based on first release of BOREXINO data

Montanino, Picariello, Pulido, PRD 2008

...attempts to improve bounds

GEMMA (2005-2012)

Germanium Experiment for Measurement of Magnetic Moment of Antineutrino

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

World best experimental limit

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

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

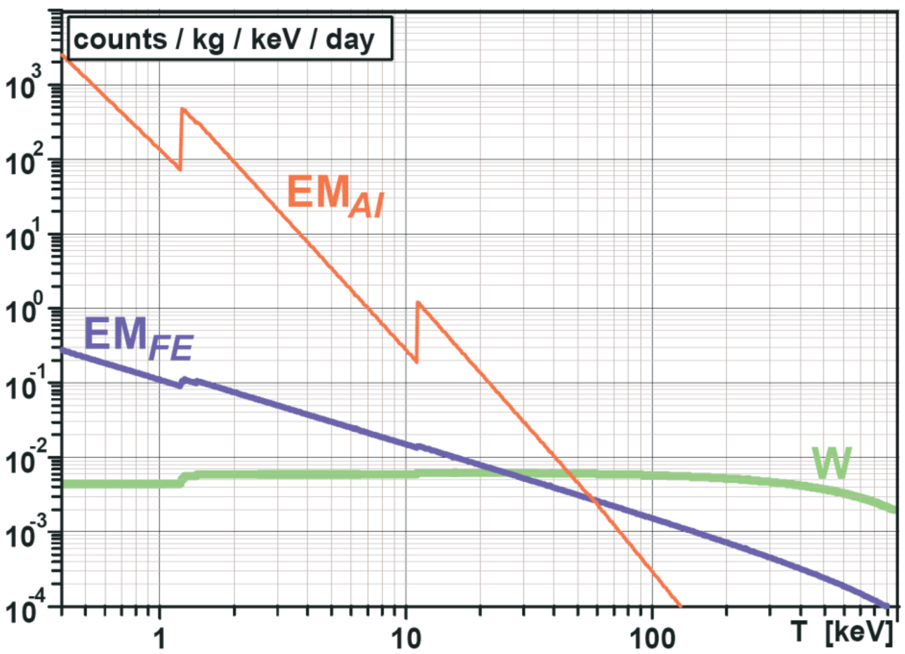
$$\boxed{\mu_\nu \sim 1 \times 10^{-11} \mu_B}$$

(V. Brudanin, A. Starostin, private communication)

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

?

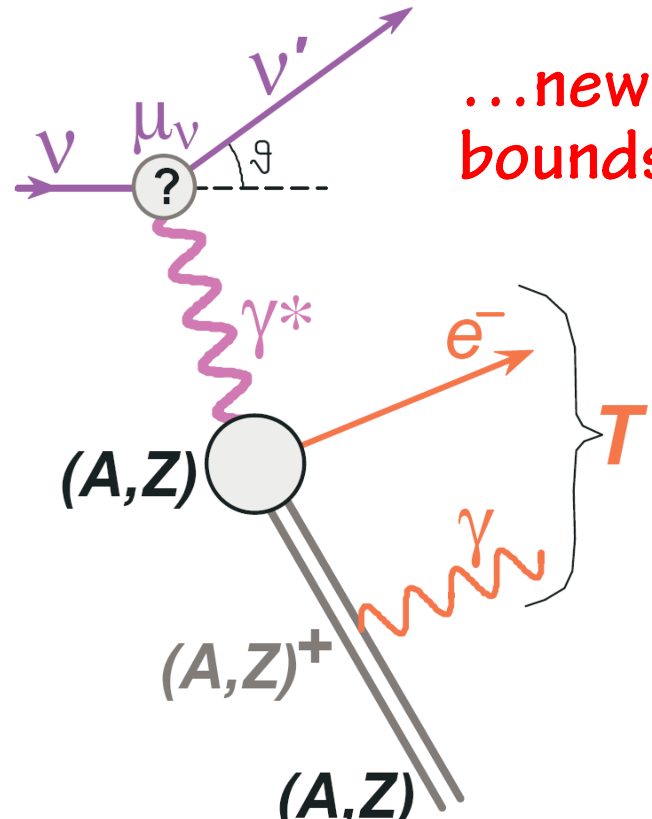
$$\boxed{\begin{array}{l} \nu + (A,Z) \longrightarrow \nu\,' + (A,Z)^{+} + e^{-} \\ \qquad\qquad\qquad\qquad \downarrow \text{recombination} \\ \qquad\qquad\qquad\qquad (A,Z) \quad + \gamma \end{array}}$$



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 …

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

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

… atomic ionization effect accounted for …

… however …

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

… atomic ionization effect accounted for …

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

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

… 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

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Experimental limits for different effective μ_ν

Method		Experiment	Limit	CL	Reference
		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)
Reactor $\bar{\nu}_e$-e^-	●	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

… 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

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

- ***…General proof:***

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

- ***In SM :***

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

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

$\boxed{Q=0}$

- $\boxed{Q=0}$ ***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*** $\Rightarrow$ **millicharged** ν

2

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

A. Studenikin: "New bounds on neutrino electric millicharge from limits on neutrino magnetic moment", Eur.Phys.Lett. 107 (2014) 2100, arXiv:1302.1168

C. Patrignani et al (Particle Data Group), "The Review of Particle Physics 2016" Chinese Physics C 40, No. 10 (2016) 100001)

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

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

Bounds on q_ν from

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

… not observable effects of New Physics

- Studenikin, arXiv:1302.1168, Eur. Phys. Lett. 107 (2014) 21001
- Brudanin, Medvedev, Starostin, Studenikin, Nucl. Part.Phys. Proc. 2016, ICHEP 2014

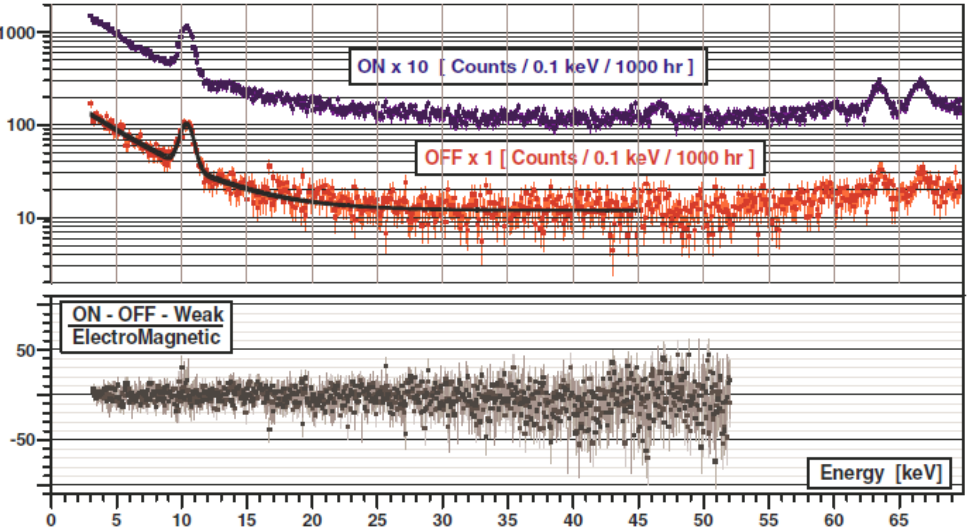
Constraints on μ_ν from GEMMA:

Constraints on q_ν

now $\mu_\nu^a < 2.9 \times 10^{-11}\mu_B$ $(T \sim 2.8\ keV)$ $\boxed{|\, q_\nu \,| < 1.5 \times 10^{-12} e_0}$

2017 (expected) $\mu_\nu^a \sim 1.5 \times 10^{-11}\mu_B$ $(T = 1.5\ keV)$ $\boxed{|\, q_\nu \,| < 3.7 \times 10^{-13} e_0}$

2018 (expected) $\mu_\nu^a \sim 0.9 \times 10^{-12}\mu_B$ $\boxed{T = 350\ eV}$ $\boxed{|q_\nu| < 1.8 \times 10^{-13} e_0}$



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

A. Beda et al, Adv. High Energy Phys. 2012(2012) 350150

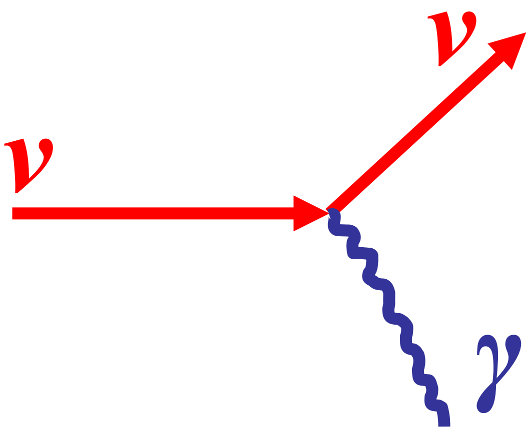
- Limit evaluated using statistical procedures is of the same order as previously discussed

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

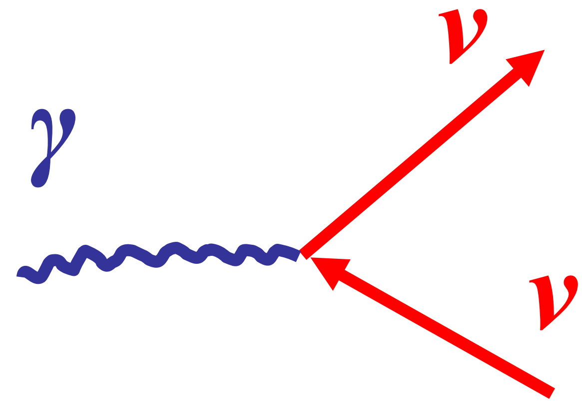
A.Studenikin : "New bounds on neutrino electric millicharge from limits on neutrino magnetic moment", Eur.Phys.Lett. 107 (2014) 2100, arXiv:1302.1168

- V.Brudanin, D.Medvedev, A.Starostin, A.Studenikin : "New bounds on neutrino electric millicharge from GEMMA experiment on neutrino magnetic moment", arXiv: 1411.2279

③ ν electromagnetic interactions

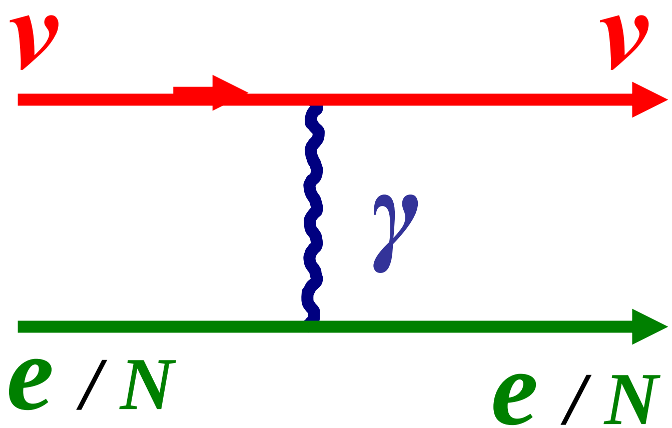


ν decay, Cherenkov radiation

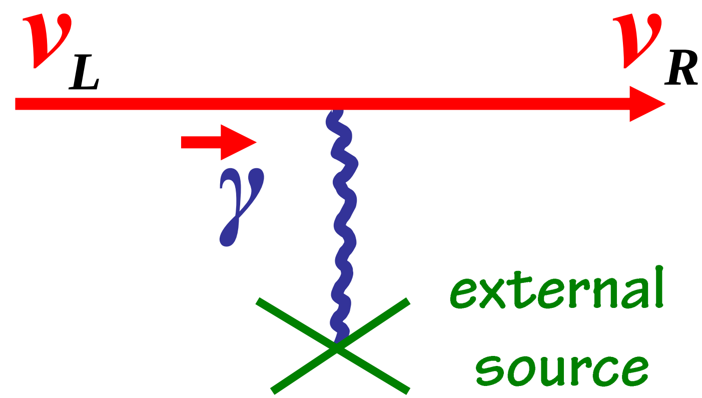


γ decay in plasma

!!!



Scattering

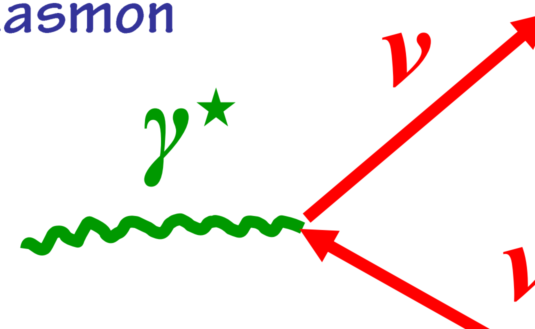


Spin precession

2 Astrophysical bound on μ_ν

G.Raffelt, PRL 1990

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



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

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

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

= 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

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

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

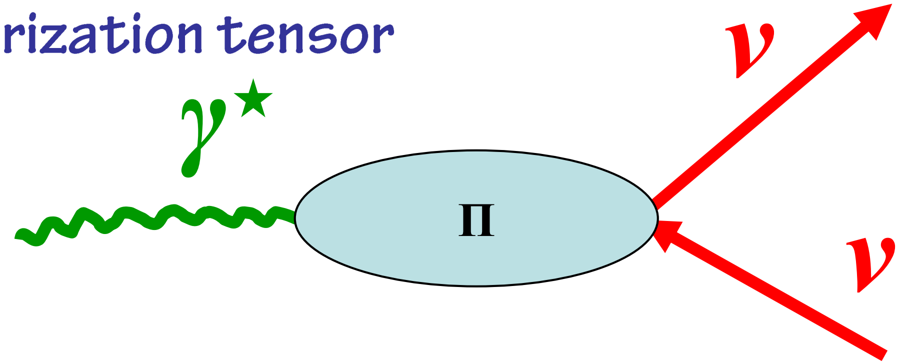
distribution function of plasmons

Astrophysical bound on μ_ν

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

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...

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

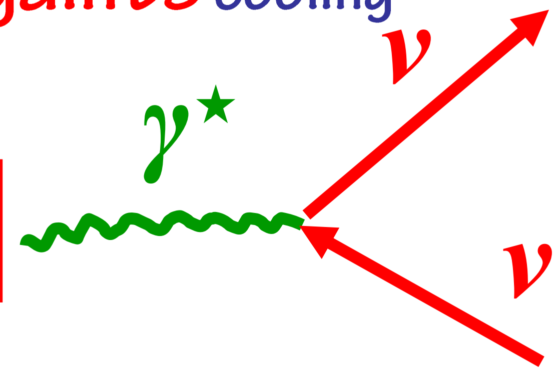
G.Raffelt, PRL 1990

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

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

- Constraints on neutrino millicharge from red gaints cooling

$\gamma^\star \longrightarrow \nu\nu$



Interaction Lagrangian

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

millicharge

Decay rate

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

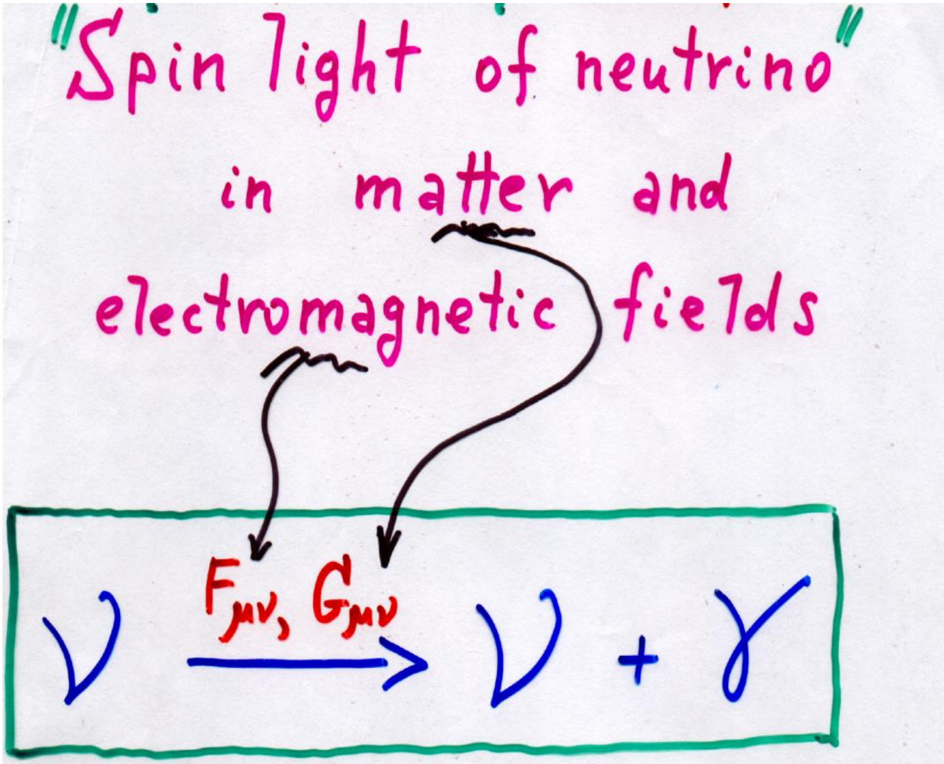
- $\boxed{q_\nu \leq 2 \times 10^{-14} e}$ ...to avoid helium ignition in low-mass red gaints — Halt, Raffelt, Weiss, PRL1994

- $\boxed{q_\nu \leq 3 \times 10^{-17} e}$ ... absence of anomalous energy-dependent dispersion of SN198'ν... signal, most model independ

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

• New mechanism of electromagnetic radiation

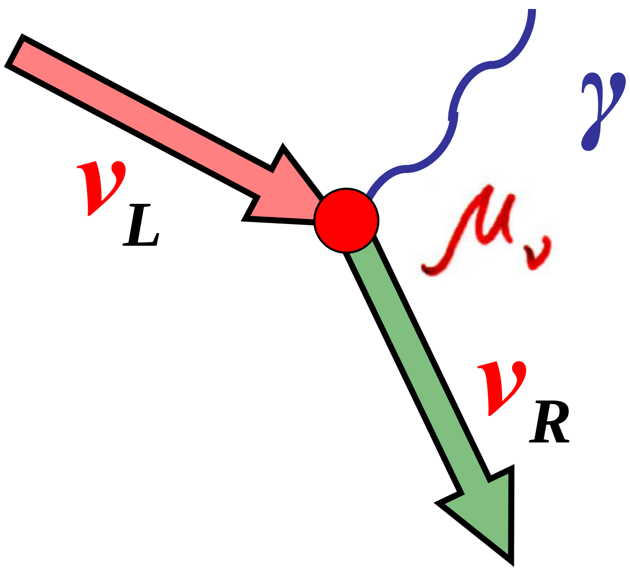
$SL\nu$



A. Egorov, A. Lobanov, A. Studenikin,
Phys.Lett. B 491 (2000) 137
Lobanov, Studenikin,
Phys.Lett. B 515 (2001) 94
Phys.Lett. B 564 (2003) 27
Phys.Lett. B 601 (2004) 171
Studenikin, A.Ternov,
Phys.Lett. B 608 (2005) 107
A. Grigoriev, Studenikin, Ternov,
Phys.Lett. B 622 (2005) 199
Studenikin,
J.Phys.A: Math.Gen. 39 (2006) 6769
J.Phys.A: Math.Theor. 41 (2008) 16402

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

Neutrino – photon coupling



broad neutrino lines
account for interaction
with environment

"Spin light of neutrino in matter"

$SL\nu$

- … within the quantum treatment based on method of exact solutions …

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

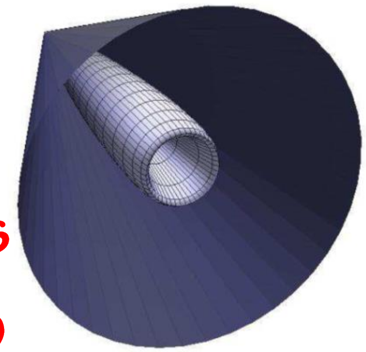


Figure 1: 3D representation of the radiation power distribution.

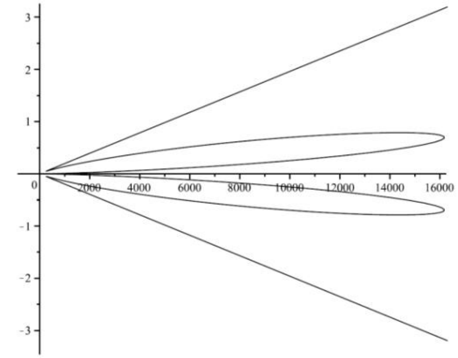


Figure 2: The two-dimensional cut along the symmetry axis. Relative units are used.

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].

New mechanism of electromagnetic radiation

SLe_{ν}

I. Balantsev, A. Studenikin,
"Spin Light of Electron in dense Neutrino fluxes", arXiv: 1405.6598,
"Spin light of relativistic electrons in neutrino fluxes", arXiv: 1502.05346,

"From electromagnetic neutrinos to new electromagnetic radiation mechanism in neutrino fluxes", Int.J.Mod.Phys. A30 (2015) 17, 1530044

2015
the YEAR of LIGHT . . .
(United Nations)

3 I. Balantsev, A. Studenikin

"From electromagnetic neutrinos to new electromagnetic radiation mechanism in neutrino fluxes" Int. J. Mod. Phys. A 30 (2015) 1530044

$\boxed{SL\nu} \Longrightarrow SLe_{\nu}$

$SL\nu$

Spin light of electron in dense neutrino fluxes

SLe_ν

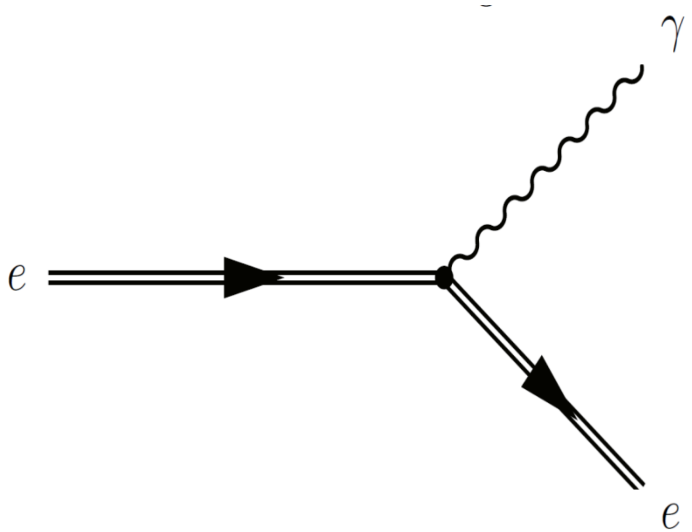
I.Balantsev, A.Studenikin, I

Int.J.Mod.Phys. A 30 (2015) 17, 1530044,
arXiv: 1405.6598, arXiv: 1502.05346

- Electrons in background matter potential (ultra-relativistic ν flux)

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

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



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

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

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

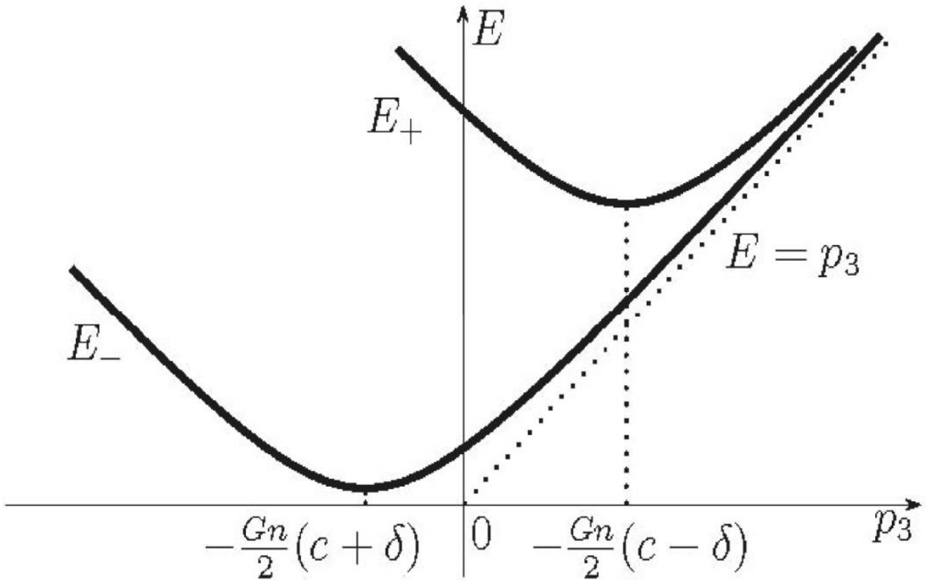


Fig. 1. The dependence of the electron energies in two different spin states, $E_+(\boldsymbol{p})$ and $E_-(\boldsymbol{p})$, on the momentum component p_3.

Energy spectrum of electrons in relativistic ν flux

$$\boldsymbol{p} = (\boldsymbol{p}_\perp, p_3)$$

$$\boxed{E_s^\varepsilon(\boldsymbol{p}) = \varepsilon\sqrt{m^2 + \boldsymbol{p}_\perp^2 + \Big(p_3 + A\Big)^2} - A} \quad A = \frac{Gn}{2}(c - s\delta),\ \delta = |\delta_e|$$

Wave function of electrons

$$\psi_i(\boldsymbol{r}, t) = \mathrm{e}^{i(-E_+ t + \boldsymbol{p}\boldsymbol{r})}\tilde{\psi}_i, \qquad \psi_f(\boldsymbol{r}, t) = \mathrm{e}^{i(-E_- t + \boldsymbol{p}\boldsymbol{r})}\tilde{\psi}_f$$

$$\tilde{\psi}_i = \frac{1}{L^{\frac{3}{2}} C_+}\begin{pmatrix} 0 \\ m \\ p_\perp \mathrm{e}^{-i\phi} \\ E_+ - p_3 \end{pmatrix}, \quad \tilde{\psi}_f = \frac{1}{L^{\frac{3}{2}} C_-}\begin{pmatrix} E_- - p_3 \\ -p_\perp e^{i\phi} \\ m \\ 0 \end{pmatrix} \quad C_\pm = \sqrt{m^2 + p_\perp^2 + (E_\pm - p_3)^2}$$

SLe_ν in case of relativistic electrons in dense ν fluxes at supernovae environment

C. Frohlich, P. Hauser, M. Liebendorfer, G. Martinez-Pinedo, F.-K. Thielemann *et al.*, Composition of the innermost supernova ejecta, *Astrophys.J.* **637**, 415 (2006).

H.-T. Janka, K. Langanke, A. Marek, G. Martinez-Pinedo and B. Mueller, Theory of core-collapse supernovae, *Phys.Rept.* **442**, 38 (2007).

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

I.Balantsev, A.Studenikin,
Int.J.Mod.Phys. A 30 (2015) 17, 1530044

- new mechanism of electromagnetic radiation in the Year of Light

SLe_ν in case of relativistic electrons in dense ν fluxes at supernovae environment

C. Frohlich, P. Hauser, M. Liebendorfer, G. Martinez-Pinedo, F.-K. Thielemann *et al.*, Composition of the innermost supernova ejecta, *Astrophys.J.* **637**, 415 (2006).
H.-T. Janka, K. Langanke, A. Marek, G. Martinez-Pinedo and B. Mueller, Theory of core-collapse supernovae, *Phys.Rept.* **442**, 38 (2007).

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I.Balantsev, A.Studenikin,
Int.J.Mod.Phys. A 30 (2015) 17, 1530044

- new mechanism of electromagnetic radiation in the Year of Light
    - Journal of Physics: Conference Series **718** (2016) 062057

Conclusion and phenomenology

It is interesting to apply the considered SLe_ν of nonmoving and relativistic electrons in dense neutrino fluxes to an environment peculiar for supernovae phenomena. As it is shown in [17], one can estimate the effective neutrino matter density to be $n \sim 10^{35}\, cm^{-3}$, thus the characteristic parameter $\frac{Gn}{m} \sim 10^{-8}$. The surrounding interstellar medium can contain regions with reasonably high electron density relativistically moving towards the neutrino flux [18, 19]. Under these conditions, the spin light can be emitted by the relativistic electrons in the quantum transition from the energy states E_+ to the states E_-.

From Eq. (12) it follows that for nonmoving initial electron the SLe_ν photon energy is

$$\omega \sim 1\ eV. \tag{18}$$

From (16) we also find for the SLe_ν rate and power

$$\Gamma \sim 10^{-19}\, eV \sim 10^{-4}\, s^{-1}, \qquad I \sim 10^{-7} eV\, s^{-1}. \tag{19}$$

The corresponding characteristic time of the SLe_ν process is rather big, $\tau \sim 10^4 s$. It means that SLe_ν from a single electron is hardly observable.

From (13) and (17) for the relativistic electrons characterized by $\frac{|\tilde{p}_3|}{m} = 10^7$ we get the following estimations for the SLe_ν photon energy, rate and power, respectively,

$$\omega \sim 10^{14}\ eV, \quad \Gamma \sim 10^{10}\ s^{-1}, \quad I \sim 10^{21} eV\, s^{-1}. \tag{20}$$

The electron number density at the distance $R = 10\ km$ from the star center can be of order $N_e \sim 10^{19}\ cm^{-3}$. Thus, the amount of SLe_ν flashes per second from 1 cm^3 of the electron matter under the influence of a dense neutrino flux is $N \sim 10^{28}\ cm^{-3}\ s^{-1}$. For the energy release of 1 cm^3 per one second we get

$$\frac{\delta E}{\delta t \delta V} = I N_e \sim 10^{40}\ eV\ cm^{-3}\ s^{-1}. \tag{21}$$

- ... 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

ν in extreme environments

A. Studenikin,

- "Quantum treatment of neutrino in background matter",
  J. Phys. A: Math. Gen. 39 (2006) 6769-6776
- "Method of wave equations exact solutions in studies of neutrinos and electron interactions in dense matter",
  J.Phys.A: Math.Theor. 41 (2008) 164047
- "Neutrinos and electrons in background matter: a new approach",
  Ann.Fond. de Broglie 31 (2006) 289-316

...«method of exact solutions»

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

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

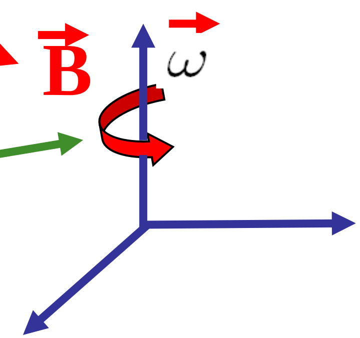
external magnetic field

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

matter potential

rotating matter

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



rotation angular frequency

ν energy is quantized in rotating matter

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

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

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

$\boxed{N = 0, 1, 2, \ldots}$

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):

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

In quasi-classical approach

- quantum states in rotating matter
- motion in circular orbits

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

due to effective Lorentz force

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

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

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 ?

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

. . . we predict :

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

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

M.Ageron et al,
Nucl.Instrum.Meth. A692 (2012) 184

• Millicharged ν as star rotation engine

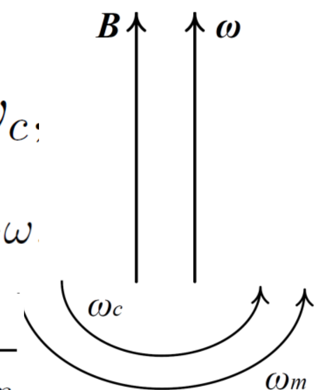
- Single ν generates feedback force with projection on rotation plane

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

$$\Omega = \omega_m + \omega_c,$$

$$\omega_m = \frac{2Gn_n}{p_0 + Gn_n}\omega,$$

$$\omega_c = \frac{q_0 B}{p_0 + Gn_n}$$

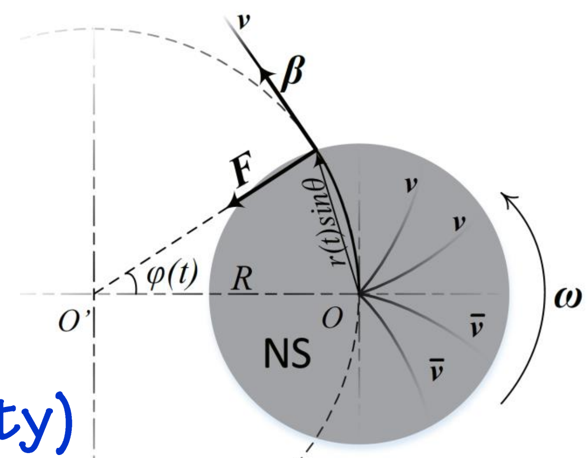


single ν torque

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

total N_ν torque

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



- Should effect initial star rotation (shift of star angular velocity)

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

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

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

- ν Star Turning mechanism (ν ST)

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

Escaping ν s 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

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

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

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

- ... best astrophysical bound ...

Main steps in ν oscillations:

60 years!

1. $\nu_e \xleftrightarrow{vac} \bar{\nu}_e$, B. Pontecorvo, 1957

2. $\nu_e \xleftrightarrow{vac} \nu_\mu$, Z. Maki, M. Nakagava, S. Sakata, 1962

3. $\nu_e \xleftrightarrow{matter,\ \rho = const} \nu_\mu$, L. Wolfenstein, 1978

4. $\nu_e \xleftrightarrow{matter,\ \rho \neq const} \nu_\mu$, S. Mikheev, A. Smirnov, 1985

- resonances in ν flavour oscillations $\Rightarrow$ MSW-effect, solution for $\nu_\odot$ - problem

5. $\nu_{e_L} \xleftrightarrow{B_\perp} \nu_{e_R}$, A. Cisneros, 1971; M. Voloshin, M. Vysotsky, L. Okun, 1986, $\nu_\odot$

6. $\nu_{e_L} \xleftrightarrow{B_\perp} \nu_{e_R}, \nu_{\mu_R}$, E. Akhmedov, 1988; C.-S. Lim & W. Marciano, 1988

- resonances in ν spin (spin-flavour) oscillations in matter

only in $B_\perp$ and matter at rest

④ 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

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

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

ν evolution equation

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

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

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

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

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

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

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

- Resonance amplification of oscillations in matter:

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

Akhmedov, 1988
Lim, Marciano

... similar to MSW effect

In magnetic field

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

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

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

Neutrino conversions and oscillations in magnetic field

- $\circledast$ $\nu_\odot$ problem

$$\nu_L \overset{B}{\longleftrightarrow} \nu_R$$

...for recent analysis see J.Pulido, 2006, TAUP-09; A.Balantekin, C.Volpe, 2005

Cisneros, 1971

* { Voloshin, Vysotsky, Okun, 1986
Barbieri, Fiorentini, 1988

$\odot$ twisting B { Smirnov, 1991
Akhmedov, Petcov, Smirnov, 1993

...subdominant contribution to LMA – MSW solution...

$\nu_\odot$

- $\circledast$ Supernova $\nu_L \overset{B}{\longleftrightarrow} \nu_R$

- Dar, 1987

Fujikawa, Shrock, 1988

Voloshin, 1988

$\circledast$ Spin-flavour oscillations in early universe – strong $B_\perp$ → population of ν wrong-helicity states (r.h.) would accelerate expansion of universe (???)

ν spin and flavor oscillations in arbitrary magnetic fields $\vec{B} = \vec{B}_{\perp} + \vec{B}_{\parallel}$

4

- A. Grigoriev, R. Fabbricatore, A. Studenikin — "Neutrino spin-flavour oscillations derived from the mass basis" arXiv:1604.01245, TAUP 2015 (2016)

- A. Dmitriev, R. Fabbricatore, A. Studenikin — "Neutrino electromagnetic properties: new approach to oscillations in arbitrary magnetic field" arxXiv: 1506.05311

Two ν mass states with two helicities in $\vec{B} = \vec{B}_{\perp} + \vec{B}_{\parallel}$

For two ν mass states ($\alpha, \alpha' = 1,2$) with two helicities ($s = \pm 1$) in $\vec{B} = \vec{B}_\perp + \vec{B}_{||}$

- Evolution equation (ν mass states)

arXiv:1604.01245

$$i\frac{d}{dt}\begin{pmatrix} \nu_{1,s=1} \\ \nu_{1,s=-1} \\ \nu_{2,s=1} \\ \nu_{2,s=-1} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} E_1 + \mu_{11}\frac{B_{||}}{\gamma_{11}} & \mu_{11}B_\perp & \mu_{12}\frac{B_{||}}{\gamma_{12}} & \mu_{12}B_\perp \\ \mu_{11}B_\perp & E_1 - \mu_{11}\frac{B_{||}}{\gamma_{11}} & \mu_{12}B_\perp & -\mu_{12}\frac{B_{||}}{\gamma_{12}} \\ \mu_{12}\frac{B_{||}}{\gamma_{12}} & \mu_{12}B_\perp & E_2 + \mu_{22}\frac{B_{||}}{\gamma_{22}} & \mu_{22}B_\perp \\ \mu_{12}B_\perp & -\mu_{12}\frac{B_{||}}{\gamma_{12}} & \mu_{22'}B_\perp & E_2 - \mu_{22}\frac{B_{||}}{\gamma_{22}} \end{pmatrix}\begin{pmatrix} \nu_{1,s=1} \\ \nu_{1,s=-1} \\ \nu_{2,s=1} \\ \nu_{2,s=-1} \end{pmatrix}$$

$$E_\alpha = \sqrt{\mathbf{p}^2 + m_\alpha^2} \approx |\mathbf{p}| + \frac{m_\alpha^2}{2|\mathbf{p}|}, \quad \alpha = 1,2. \qquad \gamma_{\alpha\alpha'}^{-1} = \frac{1}{2}\left(\frac{m_\alpha}{E_\alpha} + \frac{m_{\alpha'}}{E_{\alpha'}}\right)$$

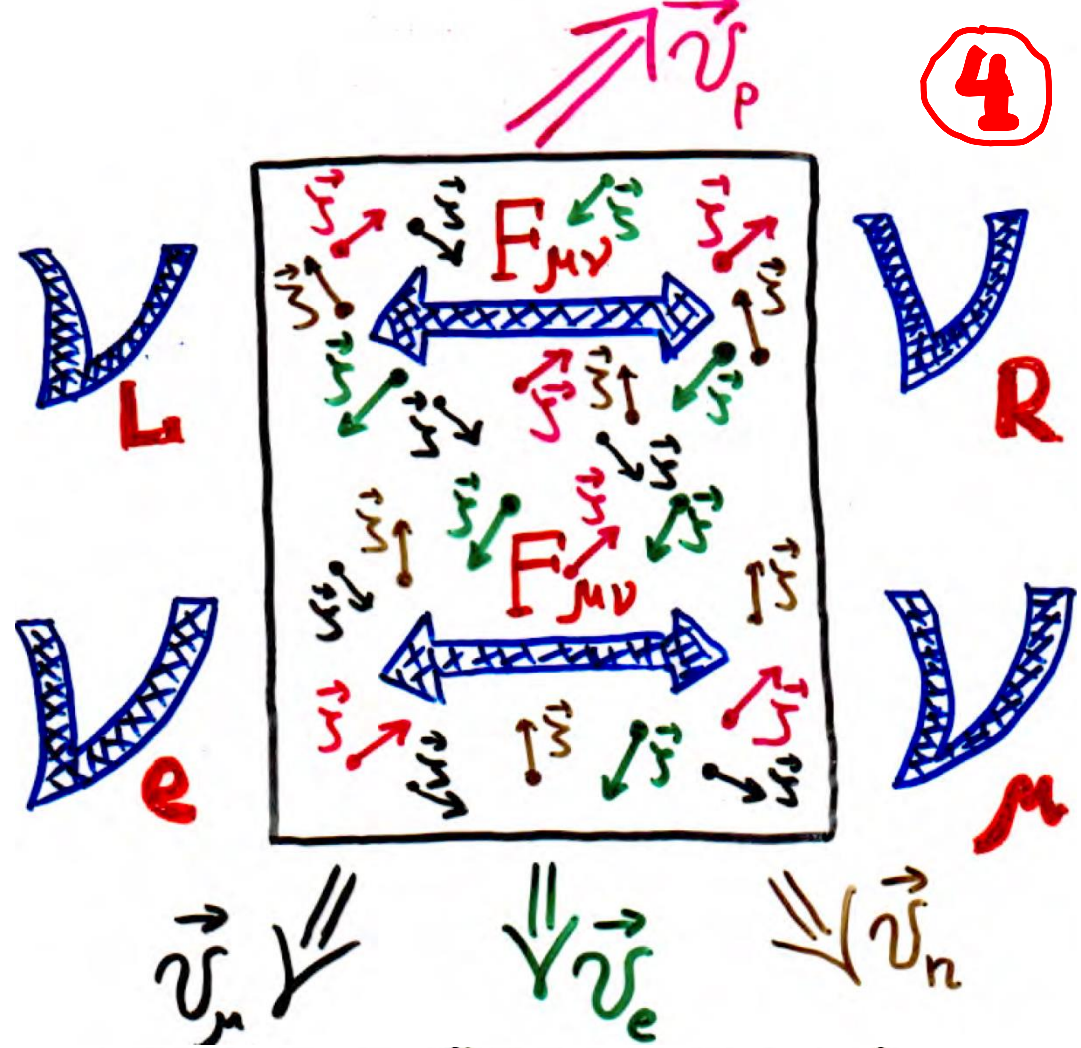
- mixings between two different helicity states are due to $B_\perp$
- couplings with $B_{||}$ shift ν energies
- mixing between different mass states is due to transition magnetic moment interactions with $B_{||}$

- **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

$\vec{\xi}, \vec{\xi}, \vec{\xi}, \vec{\xi}$, etc

[Neutrino spin evolution in arbitrary electromagnetic field $F_{\mu\nu}$ and moving and polarized matter

$\boxed{\text{START}}$

Bargmann-Michel-Telegdi equation for spin vector S_μ of neutral particle:

$$\frac{dS^\mu}{d\tau} = 2\mu\left[F^{\mu\nu}S_\nu - u^\mu\left(u_\nu F^{\nu\lambda}S_\lambda\right)\right] + \underbrace{2\epsilon\left[\tilde{F}^{\mu\nu}S_\nu - u^\mu\left(u_\nu \tilde{F}^{\nu\lambda}S_\lambda\right)\right]}_{\cancel{\text{T-invariance}}}$$

magnetic

dipole moments

electric

- direct interaction of ~~ν~~ spin with $F_{\mu\nu}$
- P invariant theory

arbitrary e.m. field

Substitution $\boxed{F_{\mu\nu} \to F_{\mu\nu} + G_{\mu\nu}}$

implies:

$$\boxed{\begin{array}{l} \vec{B} \to \vec{B} + \vec{M} \\ \vec{E} \to \vec{E} - \vec{P} \end{array}}$$

effects of ν interaction with moving and polarized matter

... once more...

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

Bargmann-Michel-Telegdi eq

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

in rest frame of neutrino

interaction of neutrino with an electromagnetic field

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

interaction of neutrino with matter

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

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

matter density

$\parallel$ $\perp$

ν spin procession in moving matter !!!

without any magnetic field !!!

Consider

$$\boxed{\nu_{e_L} \to \nu_{e_R}, \qquad \nu_{e_L} \to \nu_{\mu_R}}$$

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

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

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

- A.Studenikin, "Status and perspectives of neutrino magnetic moments" arXiv:1603.00337

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

matter density

$\parallel$

$\perp$

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

where

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

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

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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.

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

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

- 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
- A. Dobrynina, A. Kartavtsev, and G. Raffelt, "Helicity oscillations of Dirac and Majorana neutrinos", Phys. Rev. D93 (2016) 125030

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

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

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:

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

- *Neither* ***s*** *nor* $\boldsymbol{\pi}$ *nor* ***V*** *contributes to spin evolution*

- **Electromagnetic interaction**

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

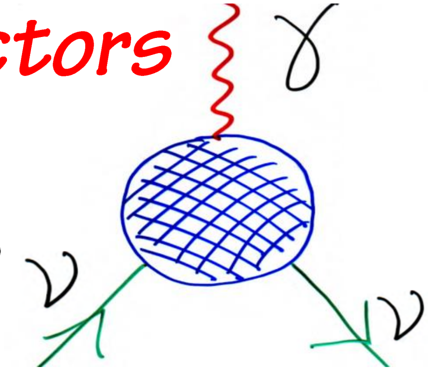
- **SM weak interaction**

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

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

Conclusions

ν e.m. vertex function $\Rightarrow$ 4 form factors



charge dipole magnetic and electric

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

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

- Standard Model with ν_R ($m_\nu \neq 0$): $\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e} \sim 3 \cdot 10^{-19} \mu_B \left(\frac{m_{\nu_e}}{1\,eV}\right)$

- In extensions of SM $\Rightarrow$ enhancement of ν magnetic moment , even electrically millicharged ν

- Limits from reactor ν-e scattering experiments (2012):

$\boxed{\mu_\nu < 2.9 \times 10^{-11}\mu_B}$ A.Beda et al. (GEMMA Coll.)

$\boxed{|\, q_\nu \,| < 1.5 \times 10^{-12} e_0}$ A.Studenikin, 2013

- Limits from astrophysics, star cooling (1990):

$\boxed{\mu_\nu < 3 \times 10^{-12}\mu_B}$ G.Raffelt

$\boxed{q_0 < 1.3 \times 10^{-19} e_0}$ νST , 2014 mechanism

μ_ν is "presently known" to be in the range

$$\boxed{10^{-20}\mu_B \leq \mu_\nu \leq 10^{-\mathbf{11}}\mu_B}$$

μ_ν provides a tool for exploration possible physics beyond the Standard Model

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

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

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

Beyond Extended Standard Model

μ_ν interactions could have important effects in astrophysical and cosmological environments

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

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

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

... Accounting for the predicted unprecedented sensitivity to μ_ν we develop a new (more precise than the usual one) approach to description of ν spin (spin-flavor) oscillations in B.

Dmitriev, Fabbricatore, Studenikin, Neutrino electromagnetic properties: new approach to oscillations in magnetic fields, arXiv:1506.053115

Our approach is based on ν stationary states in B for classification of ν spin states, contrary to the customary approach when ν helicity states are used.

- Future experiments can be sensitive to difference $$\boxed{\Delta P_{\nu_L \to \nu_R}(t) = P^{new}_{\nu_L \to \nu_R}(t) - P^{old}_{\nu_L \to \nu_R}(t)}$$

25 years of running since 1992

XVIII Lomonosov Conference on Elementary Particle Physics

Moscow State University,
24-30 August 2017,
Moscow, Russia

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