Neutrino electromagnetic properties: new limits and phenomenology

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&

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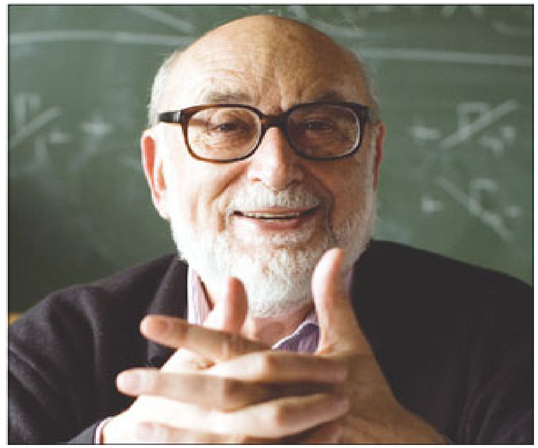
Corfu Summer School
& Workshop on Standard
Model and Beyond,
Corfu Summer Instititute,
Corfu, Greece,
04/09/2014

The last two years

- . . . has been celebrated by spectacular step further in High Energy Physics . . .

Robert Brout



François Englert

Peter Higgs

Observation of Higgs boson confirms the symmetry breaking mechanism by Brout-Englert-Higgs (BEH)

- provides final glorious triumph of Standard Model
- ... new division in particle physics with special name BEH Physics

(as it has been fixed by ICHEP in Valencia, July 2014)

What

is

next ?

ν

unique particle
that is precursor of
BSM physics

BEH physics $\Longrightarrow$ BSM physics

ν is the only known particle with properties Beyond Standard Model

… It was always like this

from the very beginning …

ν exhibits unexpected properties (puzzles)

W. Pauli, 1930

- neutral "neutron" $\Rightarrow$ ν — E. Fermi, 1933
- probably $\mu_\nu \neq 0$!?
- Pauli himself wrote to Baade:

…recent claim for new experimental bound on μ_ν (with atomic ionization effect) continue chain of puzzles…

"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* ...

- ...up to now absolute value ?

$m_\nu \neq 0$ after 80 years left !

... however ...

... an optimistic view on the present and future of ν

1913-1993

In 1946 Bruno Pontecorvo:

"... observation of neutrinos is not out of question..."

$$\nu + (A, Z) \rightarrow e^{-} + (A, Z+1)$$

$$^{37}Cl + \nu \rightarrow {}^{37}Ar + e^{-}$$

August 22, 2013

Centenary of the birth of Bruno Pontecorvo

Бруно Понтекорво

1913-1993

August 22, 2013
is the birth centenary of
Bruno Pontecorvo

- Since 1950,
  Bruno Pontecorvo
  lived in Russia and
  was staff member of
  Joint Institute for Nuclear
  Research, Dubna

- During 1966 - 1986 Bruno Pontecorvo was Head of Department of Particle Physics and member of Scientific Council at Faculty of Physics of Moscow State University

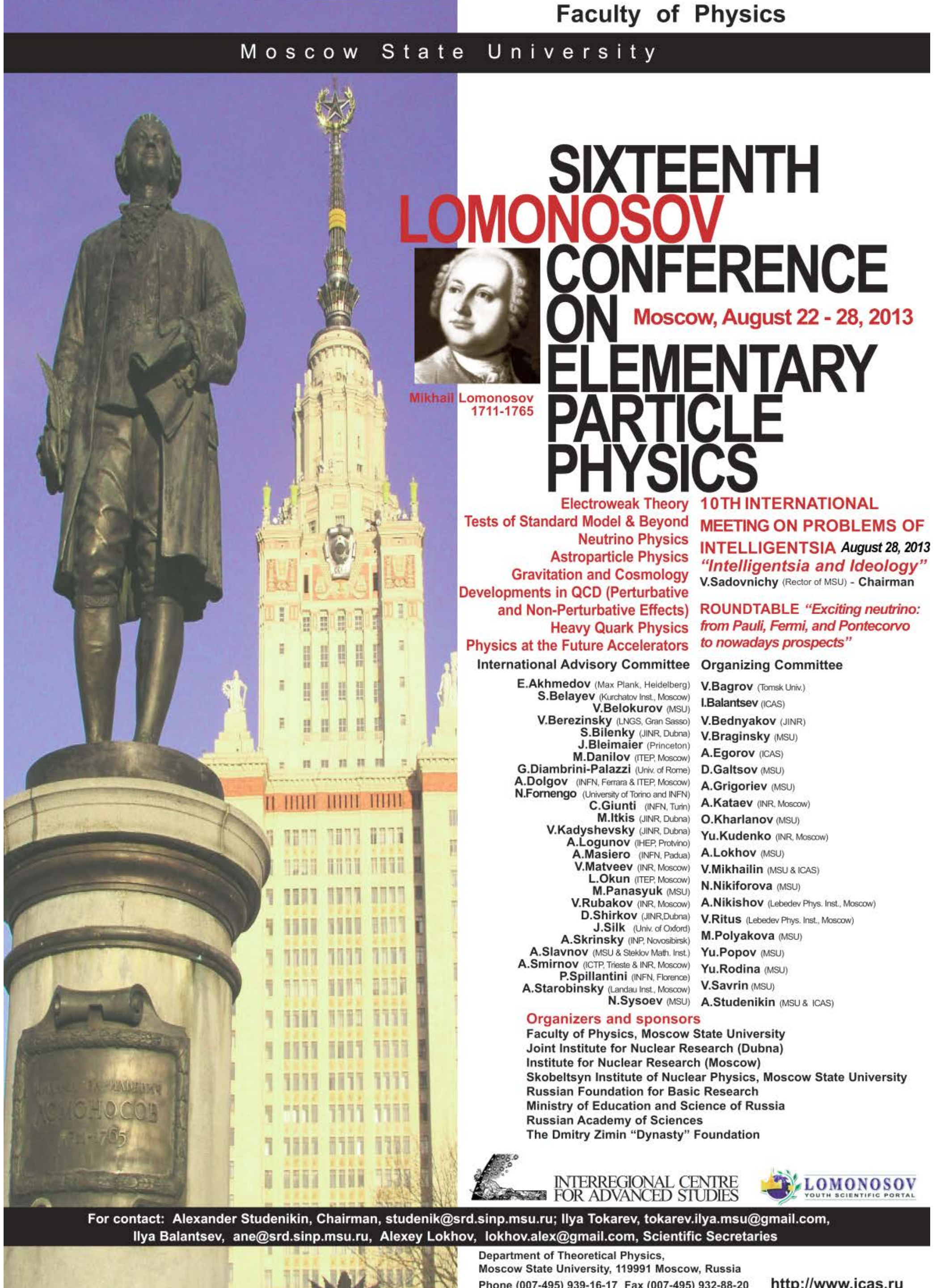
16th Lomonosov Conference on Elementary Particle Physics,

www.icas.ru

Moscow State University,

August 22-28, 2013

Dedicated to the birth centenary of Bruno Pontecorvo



... problem and puzzle

ν is quite

invisible

particle

weak interactions are indeed weak

$L \sim 10^{15} km$

$\bar{\nu} + p \to e^{+} + n$

$E_\nu \sim 3MeV$

... *free path in water*... $\sigma \sim 10^{-43}\ cm^2$

ν manifests itself most clearly under the influence of

extreme external conditions:

- strong external electromagnetic fields

and

- dense background matter

Outline (I)

ν electromagnetic properties

(short review)

1. C.Giunti, A.Studenikin : "Neutrino electromagnetic properties" Phys.Atom.Nucl. 73 (2009) 2089-2125
2. A.Studenikin : "Neutrino magnetic moment: a window to new physics" Nucl.Phys.B (Proc.Supl.) 188, 220 (2009)
3. C. Giunti, A. Studenikin : "Electromagnetic properties of neutrino" J.Phys.: Conf.Series. 203 (2010) 012100
4. C.Broggini, C.Giunti, A.Studenikin : "Electromagnetic properties of neutrinos", Adv. in High Energy Phys. 2012 (2012) 459526 (49 pp)
5. C.Giunti, A.Studenikin : "Electromagnetic interactions of neutrinos: a window to new physics", arXiv:1403.6344, submt to Rev.Mod.Phys. ●
6. 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)
7. A.Studenikin : "New bounds on neutrino electric millicharge from limits on neutrino magnetic moment", Eur.Phys.Lett. 107 (2014) 21001

● Outline ●

0. Introduction
1. ν magnetic moment in experiments
2. New experimental result on μ_ν
3. ν electromagnetic properties - theory
   - 3.1 ν vertex function
   - 3.2 μ_ν (arbitrary masse)
   - 3.3 relationship between m_ν and μ_ν
   - 3.4 ν vertex function in case of flavour mixing
   - 3.5 ν dipole moments in case of mixing
   - 3.6 μ_ν in left-right symmetry models
   - 3.7 astrophysical bounds on μ_ν
   - 3.8 ν millicharge (Red Gaints cooling etc)
   - 3.9 ν charge radius and anapole moment
   - 3.10 ν electromagnetic properties in matter and e.m.f.
4. Effects of ν electromagnetic properties
   - 3.11 ν radiative decay, *Ch* radiation and *Spin Light of* ν in matter
   - 3.12 ν radiative $2\times\gamma$ - decay
   - 3.13 ν spin-flavour oscillations
5. Direct-Indirect influence of e.m.f. on ν
6. Conclusion

Outline (II)

- ν quantum states in magnetized matter

… new effect of …

Spin Light of ν in matter

$SL\nu$

$\Rightarrow$

… pheno-meno-logical consequences in astrophysics (pulsars)

ν energy quantization in rotating matter

ν in matter treated within «method of exact solutions» of quantum wave equations for wave function

Astrophysical consequences of ν electromagnetic interactions

① A. Studenikin , I.Tokarev,

"Millicharged neutrino with anomalous magnetic moment in rotating magnetized matter" ,

Nucl. Phys. B 884 (2014) 396

② I.Balantsev, A.Studenikin,

"Spin light of electron in dense neutrino fluxes" ,

arXiv: 1405.6598

ν electromagnetic properties

(short review)

$m_\nu \neq 0$

…Why

electromagnetic properties of ν

provide a kind of

window / bridge

to

NEW Physics ?

… simple answer …

Why

magnetic moment

of ν ?

… simple answer …

... in spite of

- results of terrestrial laboratory experiments on ν EM properties and μ_ν

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,

... a tool for studying physics
Beyond Standard Model...

$m_\nu \neq 0$

Theory (Standard Model with ν_R)

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

Lee Shrock, 1977; Fujikawa Shrock, 1980

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

... much greater values are desired

for astrophysical or cosmology

visualization of μ_ν

$\nu_\odot$

- **Astrophysical bounds**

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

G. Raffelt, D. Dearborn, J. Silk, 1989.

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

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

Lee Shrock, 1977; Fujikawa Shrok, 1980

- **Limits from reactor** ν-e **scattering experiments** A.Beda et al. (GEMMA Coll.) (2012):

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

ν electromagnetic properties

(up to now nothing has been seen)

is a tool for studying

Beyond

Extended

Standard

Model physics…

BEH physics $\Rightarrow$ BSM physics $\Rightarrow$ BESM physics

...the present status...

to have visible $m_\nu \neq 0$

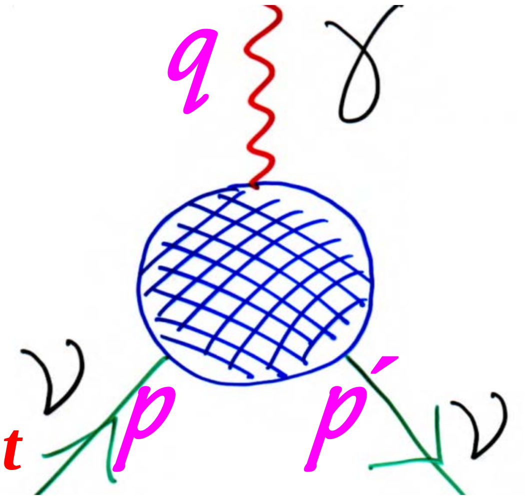
is not an easy task for

theoreticians

and experimentalists

… a bit of ν electromagnetic properties theory …

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) ⟹

Vertex function $\Lambda_\mu(q,l)$ → there are three sets of operators:

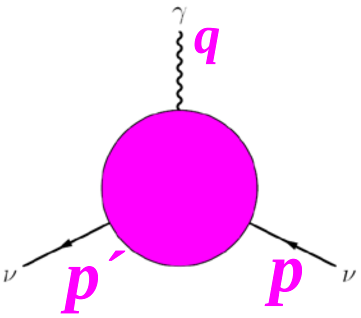
- $\hat{\mathbf{1}} q_\mu, \quad \hat{\mathbf{1}} l_\mu, \quad \gamma_5 q_\mu, \quad \gamma_5 l_\mu$

  $\not{q} q_\mu, \quad \not{l} q_\mu, \quad \gamma_5 q_\mu, \quad \gamma_5 \not{q} q_\mu, \quad \gamma_5 \not{l} q_\mu, \quad \sigma_{\alpha\beta} q^\alpha l^\beta q_\mu, \quad \{q_\mu \leftrightarrow l_\mu\}$

- $\gamma_\mu, \quad \gamma_5 \gamma_\mu, \quad \sigma_{\mu\nu} q^\nu, \quad \sigma_{\mu\nu} l^\nu.$

- $\epsilon_{\mu\nu\sigma\gamma} \sigma^{\alpha\beta} q^\nu, \quad \epsilon_{\mu\nu\sigma\gamma} \sigma^{\alpha\beta} l^\nu, \quad \epsilon_{\mu\nu\sigma\gamma} \sigma^{\nu\beta} q_\beta q^\sigma l^\gamma,$

  $\epsilon_{\mu\nu\sigma\gamma} \sigma^{\nu\beta} l_\beta q^\sigma l^\gamma, \quad \epsilon_{\mu\nu\sigma\gamma} \gamma^\nu q^\sigma l^\gamma \hat{\mathbf{1}}, \quad \epsilon_{\mu\nu\sigma\gamma} \gamma^\nu q^\sigma l^\gamma \gamma_5$



ν vertex function (using Gordon-like identities)

$$\Lambda_\mu(q,l) = f_1(q^2) q_\mu + f_2(q^2) q_\mu \gamma_5 + f_3(q^2) \gamma_\mu + f_4(q^2) \gamma_\mu \gamma_5 + f_5(q^2) \sigma_{\mu\nu} q^\nu + f_6(q^2) \epsilon_{\mu\nu\rho\gamma} \sigma^{\rho\gamma} q^\nu,$$

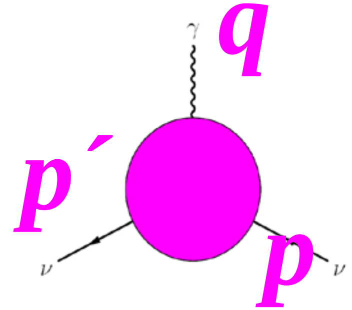
the only dependence on q^2 remains because $p^2 = p'^2 = m^2, \; l^2 = 4m^2 - q^2$

Gordon-like identities

$$
\begin{aligned}
\bar{u}(\mathbf{p}_1)\gamma^\mu u(\mathbf{p}_2) &= \frac{1}{2m}\bar{u}(\mathbf{p}_1)[l^\mu + i\sigma^{\mu\nu}q_\nu]u(\mathbf{p}_2) \\
\bar{u}(\mathbf{p}_1)\gamma^\mu\gamma_5 u(\mathbf{p}_2) &= \frac{1}{2m}\bar{u}(\mathbf{p}_1)[\gamma_5 q^\mu + i\gamma_5\sigma^{\mu\nu}l_\nu]u(\mathbf{p}_2) \\
\bar{u}(\mathbf{p}_1)i\sigma^{\mu\nu}l_\nu u(\mathbf{p}_2) &= -\bar{u}(\mathbf{p}_1)q^\nu u(\mathbf{p}_2) \\
\bar{u}(\mathbf{p}_1)i\sigma^{\mu\nu}q_\nu u(\mathbf{p}_2) &= \bar{u}(\mathbf{p}_1)[2m\gamma^\mu l^\mu]u(\mathbf{p}_2)
\end{aligned}
$$

$$
\begin{aligned}
\bar{u}(\mathbf{p}_1)i\sigma^{\mu\nu}\gamma_5 q_\nu u(\mathbf{p}_2) &= -\bar{u}(\mathbf{p}_1)l^\mu\gamma_5 u(\mathbf{p}_2) \\
\bar{u}(\mathbf{p}_1)[\epsilon^{\alpha\mu\nu\beta}\gamma_5\gamma_\beta q_\mu l_\nu]u(\mathbf{p}_2) &= \bar{u}(\mathbf{p}_1)\{-i[q^\alpha \not{l} - l^\alpha \not{q}] + i(q^2 - 4m^2)\gamma^\alpha + \\
&\quad 2im(l^\alpha + q^\alpha)\}u(\mathbf{p}_2) \\
\bar{u}(\mathbf{p}_1)[\epsilon^{\alpha\mu\nu\beta}\gamma_\beta q_\mu l_\nu]u(\mathbf{p}_2) &= \bar{u}(\mathbf{p}_1)\{i[q^\alpha \not{l} - l^\alpha \not{q}]\gamma_5 + iq^2\gamma_5\gamma^\alpha - \\
&\quad 2im(l^\alpha + q^\alpha)\gamma_5\}u(\mathbf{p}_2) \\
\bar{u}(\mathbf{p}_1)[\epsilon^{\mu\nu\alpha\beta}q_\alpha l_\beta\gamma_\nu\gamma_5]u(\mathbf{p}_2) &= \frac{i}{2m}\bar{u}(\mathbf{p}_1)[\epsilon^{\mu\nu\alpha\beta}q_\alpha l_\beta\sigma_{\nu\rho}q^\rho]u(\mathbf{p}_2) \\
\bar{u}(\mathbf{p}_1)[\epsilon^{\mu\nu\alpha\beta}q_\alpha l_\beta\sigma_{\nu\rho}l^\rho]u(\mathbf{p}_2) &= 0
\end{aligned}
$$

Electromagnetic gauge invariance (2)
(requirement of current conservation)



$$\partial_\mu j^\mu = 0$$

$$f_1(q^2)q^2 + f_2(q^2)q^2\gamma_5 + 2mf_4(q^2)\gamma_5 = 0,$$

$$f_1(q^2) = 0, \qquad f_2(q^2)q^2 + 2mf_4(q^2) = 0$$

vertex function

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

charge

dipole electric and magnetic

anapole

… consistent with Lorentz-covariance (1) + electromagnetic gauge invariance (2)

4 Form Factors

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

dipole

2. magnetic

3. electric

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_μ^{EM} can be considered between different initial $\psi_i(p)$ and final $\psi_j(p')$ states of different masses $p^2 = m_i^2,\ p'^2 = m_j^2$:

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

… beyond

and **beyond SM…**

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

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* $\epsilon_{ij}^M = 2\epsilon_{ij}^D$

... importance of μ_ν studies...

If diagonal $\mu_\nu \neq 0$

were confirmed

then ν^{Dirac}

... for $\nu^{Majorana}$
non-diagonal = transitional
$\mu_\nu \neq 0$

... progress
in experimental
studies of μ_ν $\Longrightarrow$

ν magnetic moment in experiments

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

Dipole magnetic $f_M(q^2)$ **and electric** $f_E(q^2)$

are most well studied and theoretically understood among form factors

…because even in the limit $q^2 \to 0$ **they may have nonvanishing values**

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

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

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

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

$$\mu_\nu^2 = \sum_{j=\nu_e,\nu_\mu,\nu_\tau} |\mu_{ij} - \epsilon_{ij}|^2$$

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

for anti-neutrinos $g_A \to -g_A$

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

Effective ν_e magnetic moment measured in ν-e scattering experiments ?

$$\mu_e^2$$

Two steps:

1) consider ν_e as superposition of mass eigenstates ($i=1,2,3$) at some distance L from the source, and then sum up magnetic moment contributions to ν-e scattering amplitude (of each of mass components) induced by their magnetic moments

$$A_j \sim \sum_i U_{ei} e^{-iE_i L} \mu_{ji}$$

J.Beacom, P.Vogel, 1999

2) amplitudes combine incoherently in total cross section

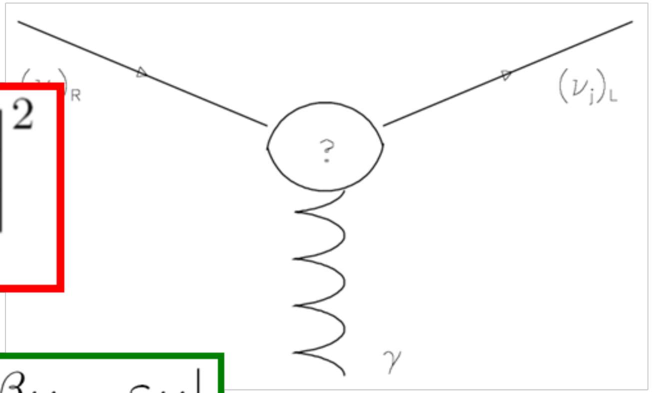
$$\sigma \sim \mu_e^2 = \sum_j \left| \sum_i U_{ei} e^{-iE_i L} \mu_{ji} \right|^2$$

C.Giunti, A.Studenikin, 2009

NB! Summation over $j=1,2,3$ is outside the square because of **incoherence** of different final mass states contributions to cross section.

Effective ν magnetic moment in experiments

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



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

where neutrino mixing matrix

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

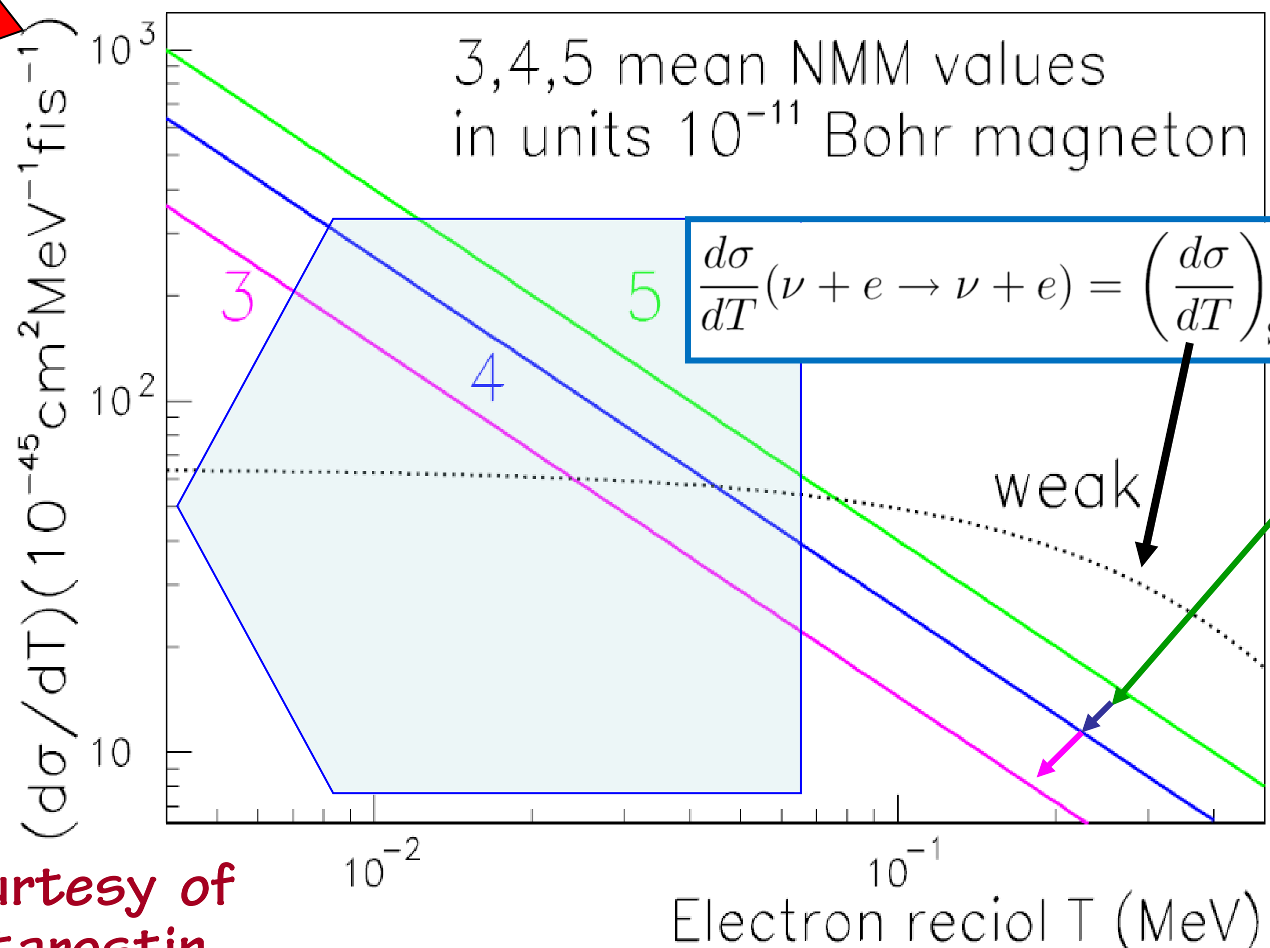
magnetic and **electric** moments

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

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

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 …*



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

… courtesy of A.Starostin…

MUNU experiment at Bugey reactor (2005)

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

TEXONO collaboration at Kuo-Sheng power plant (2006)

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

GEMMA (2007)

$$\mu_\nu \leq 5.8 \times 10^{-11} \mu_B$$

GEMMA I 2005 - 2007

BOREXINO (2008)

$$\mu_\nu \leq 5.4 \times 10^{-11} \mu_B$$

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

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

based on first release of BOREXINO data

Montanino, Picariello, Pulido, PRD 2008

... attempts to improve bounds

GEMMA (2005-2012)

Germanium Experiment for Measurement of Magnetic Moment of Antineutrino

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

World best experimental limit

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

June 2012

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

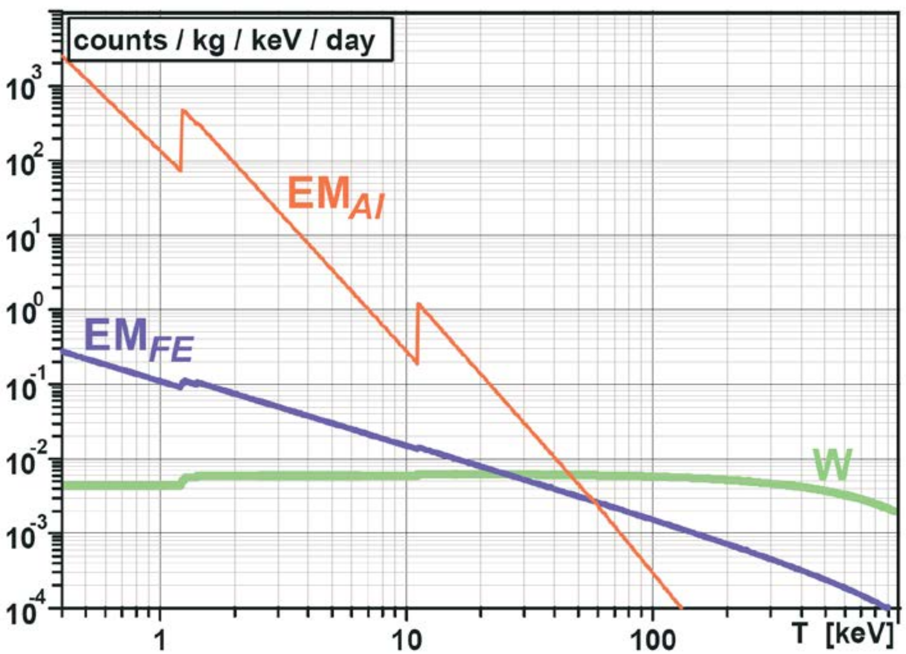
$$\mu_\nu \sim 1 \times 10^{-11} \mu_B$$

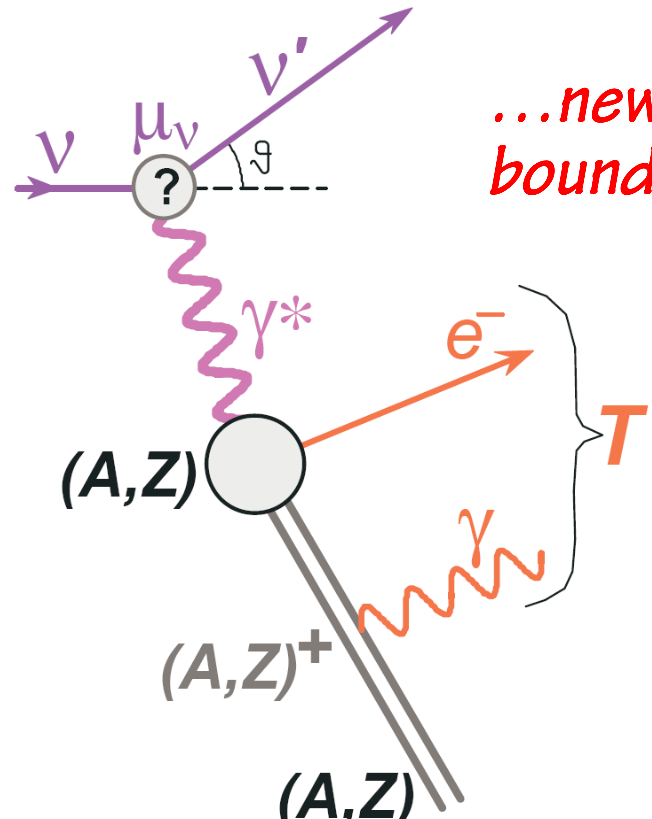
(V.Brudanin, A.Starostin, priv. comm.)

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

H.Wong et al. (TEXONO Coll.), arXiv: 1001.2074, 13 Jan 2010, reported at **Neutrino 2010 Conference (Athens, June 2010),** PRL 105 (2010) 061801

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





...new bounds ...

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

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

... atomic ionization effect accounted for ...

H.Wong et al., (TEXONO Coll.), arXiv: 1001.2074, 13 Jan 2010, PRL 105 (2010) 061801

Neutrino 2010 Conference, Athens

... however ...

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

... atomic ionization effect accounted for ...

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

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

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

- K.Kouzakov, A.Studenikin,
  "Magnetic neutrino scattering on atomic electrons revisited" •
  Phys.Lett. B 105 (2011) 061801, arXiv: 1011.5847

- "Electromagnetic neutrino-atom collisions: The role of electron binding"
  to appear in **Nucl.Phys.B** (Proc.Suppl.) 217 (2011) 353
  arXiv: 1108.2872, 14 Aug 2011

- K.Kouzakov, A.Studenikin, M.Voloshin,
  "Neutrino-impact ionization of atoms in search for neutrino magnetic moment", arXiv: 1101.4878, 25 Jan 2011
  Phys.Rev.D 83 (2011) 113001
- "On neutrino-atom scattering in searches for neutrino magnetic moments" arXiv: 1102.0643, 3 Feb 2011
  Nucl.Phys.B (Proc.Supp.) 2011 (*Proc. of Neutrino 2010 Conference*)
- "Testing neutrino magnetic moment in ionization of atoms by neutrino impact", arXiv: 1105.5543, 27 May 2011
  JETP Lett. 93 (2011) 699

- M.Voloshin,
  "Neutrino scattering on atomic electrons in search for neutrino magnetic moment"
  Phys.Rev.Lett. 105 (2010) 201801, arXiv: 1008.2171

No important effect of Atomic Ionization on cross section in μ_ν experiments once all possible final electronic states accounted for

...free electron approximation ...

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)

Experimental limits for different effective μ_ν

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

C. Giunti, A. Studenikin, arXiv: 1403.6344

… if one trusts ν

to be precursor for

BSM 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

- *…General proof:*

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

- *In SM :*

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

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

Q=0

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

Bardeen, Gastmans, Lautrup, 1972;
Cabral-Rosetti, Bernabeu, Vidal, Zepeda, 2000;
Beg, Marciano, Ruderman, 1978;
Marciano, Sirlin, 1980; Sakakibara, 1981;
- *M.Dvornikov, A.S., 2004 (for extended SM in one-loop calculations)*

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

Experimental and astrophysics limits for different effective q_ν

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)

C.Giunti, A.Studenikin, arXiv: 1403.6344

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

... best limit from astrophysics...

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

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

A.S., arXiv: 1302.1168

ν-e cross-section

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

two not seen contributions:

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

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

Bounds on q_ν from

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

... no observable effects of New Physics

Constraints on μ_ν from GEMMA: Constraints on q_ν

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

2015 (expected) $\mu_\nu^a \sim 1.5 \times 10^{-11}\mu_B$ ($T = 1.5\ keV$) $\quad | q_\nu | < 3.7 \times 10^{-13} e_0$

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

... the obtained constraint on neutrino millicharge q_ν

- rough order-of-magnitude estimation,
- exact values should be evaluated using the corresponding statistical procedures

this is because limits on neutrino μ_ν are derived from GEMMA experiment data taken over an extended energy range 2.8 keV --- 55 keV, rather than at a single electron energy-bin at threshold

- limit evaluated using statistical procedures

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

is of the same order as previously discussed

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

3

… a bit of ν electromagnetic properties theory

3.1 ν vertex function

The most general study of the massive neutrino vertex function (including electric and magnetic form factors) in arbitrary R_ξ gauge in the context of the SM + SU(2)-singlet ν_R accounting for masses of particles in polarization loops

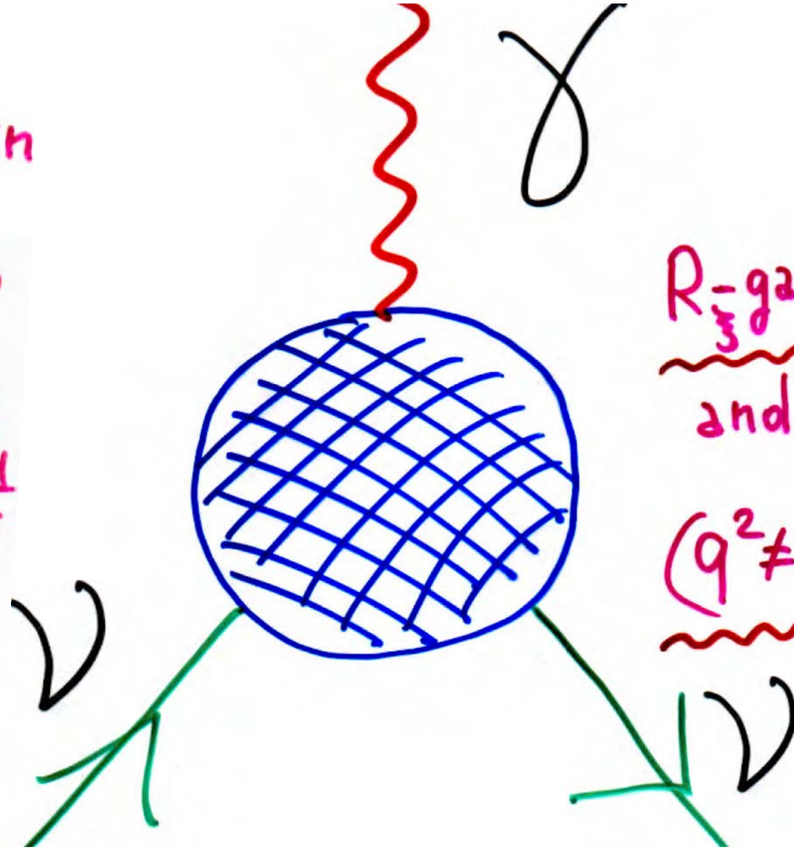
M. Dvornikov, A. Studenikin

(*) Phys. Rev. D 63, 073001, 2004,

"Electric charge and magnetic moment of massive neutrino";

JETP 126 (2004), N8, 1

(*) "Electromagnetic form factors of a massiv neutrino."



R_ξ-gauge

and

$(q^2 \neq 0)$

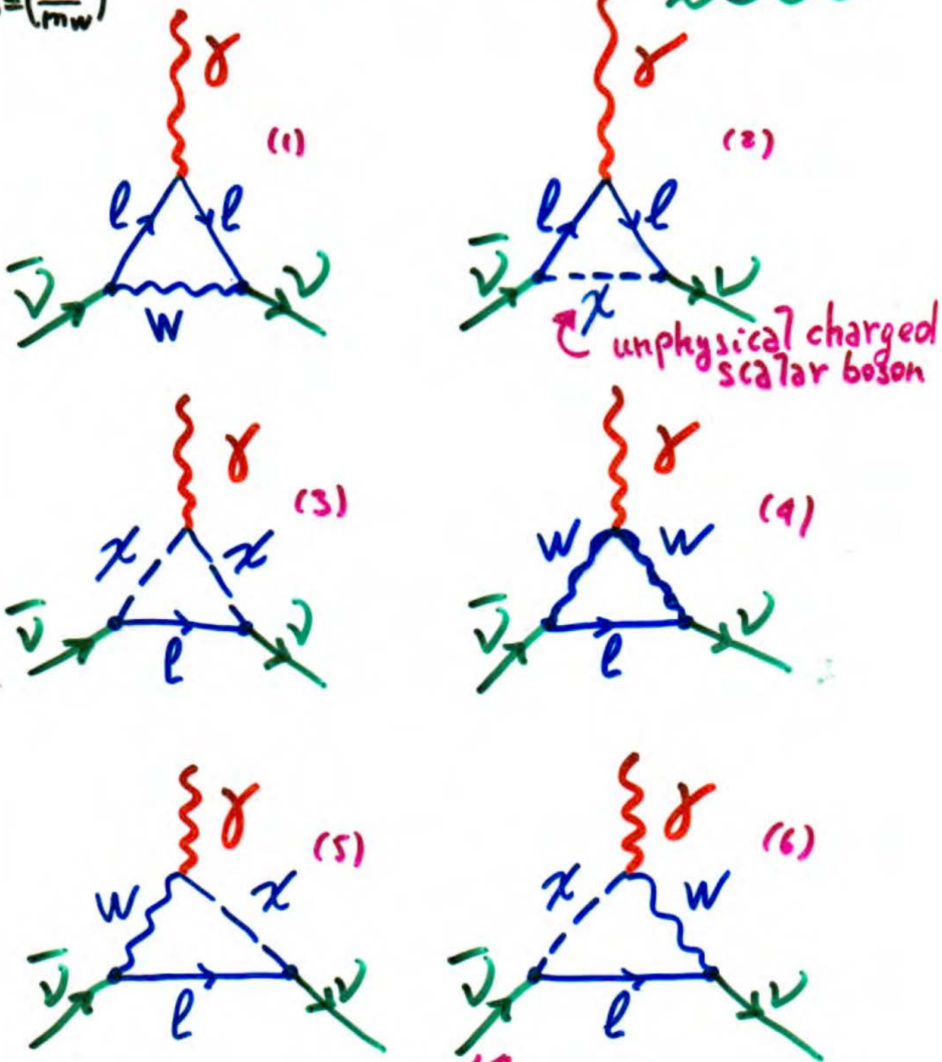
charge — magnetic moment

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

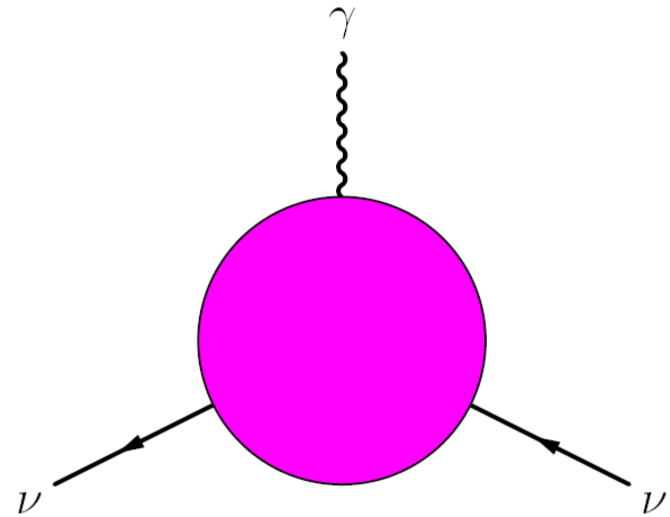
electric moment — anapole moment

$a=\left(\frac{m_\ell}{m_W}\right)^2$, $b=\left(\frac{m_\nu}{m_W}\right)^2$

Proper vertices $\{R_\xi\text{-gauge}\}$



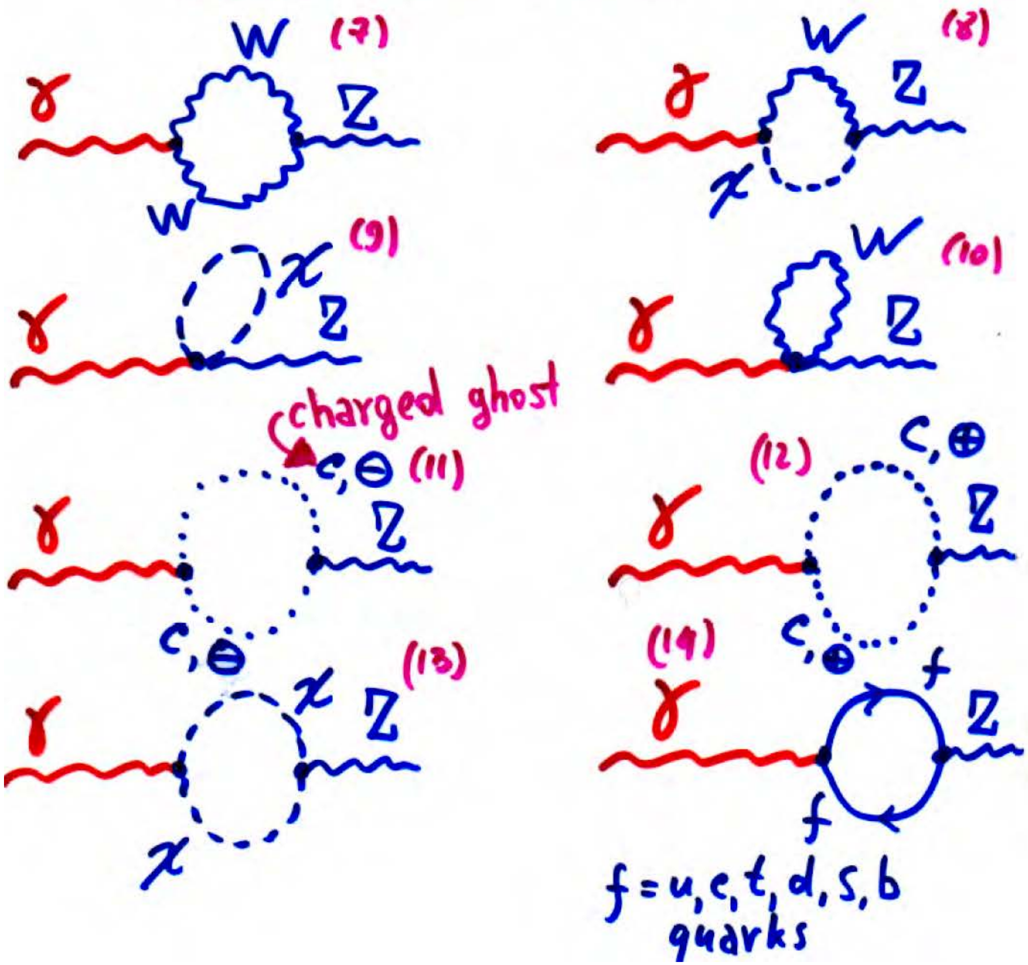
$$\Lambda_\mu(q)=\sum_{i=1}^{14}\Lambda_\mu^i(q)$$

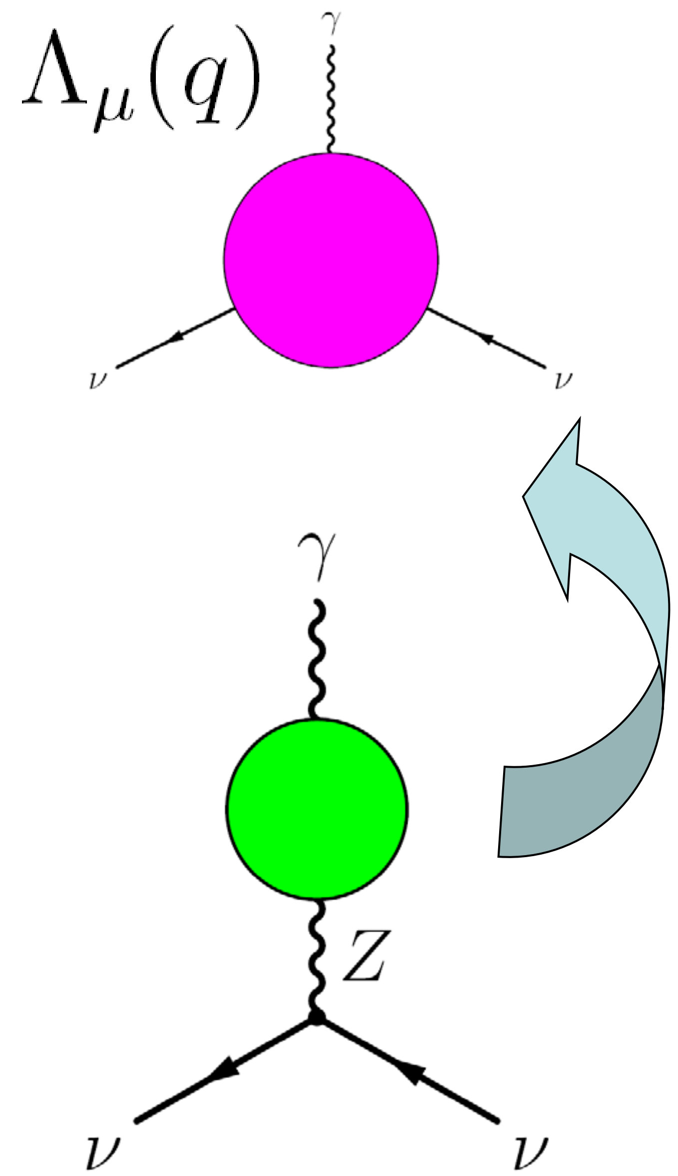


$$\Lambda_\mu(q)$$

$$\Lambda^{j}_{\mu}(q) = \frac{g}{2\cos\theta_W}\,\Pi^{(j)}_{\mu\nu}(q)\,\frac{1}{q^2-M_Z^2} \times \left\{ g^{\nu\alpha} - (1-\alpha_Z)\frac{q^\nu q^\alpha}{q^2-\alpha_Z M_Z^2} \right\} \gamma^4_\alpha ,\quad j=7,\dots,14$$

γ-Z self-energy diagrams





$\gamma - Z$ self-energy diagrams

Magnetic moment dependence

$$\mu_\nu = \mu_\nu(m_\nu)$$

on neutrino mass

ν magnetic moment

(for arbitrary neutrino mass, heavy neutrino…)

- LEP data ⇨

only 3 light νs coupled to Z^0,

for any additional neutrino

$$m_\nu \gtrsim 45 \text{ GeV}$$

● $m_\nu \ll m_e \ll M_W$ **light** ν

$$\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e}$$

$$\mu_\nu = \frac{eG_F}{4\pi^2\sqrt{2}} m_\nu \frac{3}{4(1-a)^3}\left(2 - 7a + 6a^2 - 2a^2 \ln a - a^3\right), \quad a = \left(\frac{m_e}{M_W}\right)^2$$

Dvornikov, Studenikin, Phys.Rev.D 69 (2004) 073001; JETP 99 (2004) 254

Gabral-Rosetti, Bernabeu, Vidal, Zepeda, Eur.Phys.J C 12 (2000) 633

● $m_e \ll m_\nu \ll M_W$ **intermediate** ν

$$\mu_\nu = \frac{3eG_F}{8\pi^2\sqrt{2}} m_\nu \left\{1 + \frac{5}{18} b\right\}, \quad b = \left(\frac{m_\nu}{M_W}\right)^2$$

● $m_e \ll M_W \ll m_\nu$ **heavy** ν

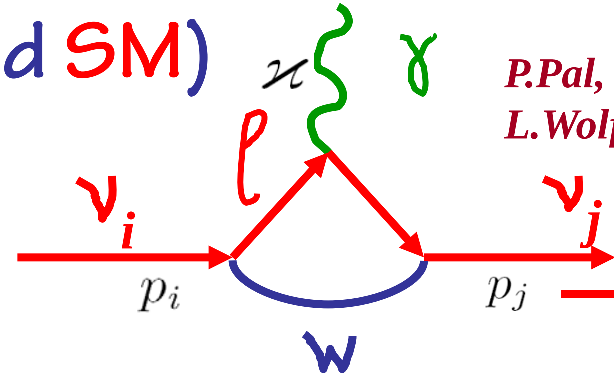
$$\mu_\nu = \frac{eG_F}{8\pi^2\sqrt{2}} m_\nu$$

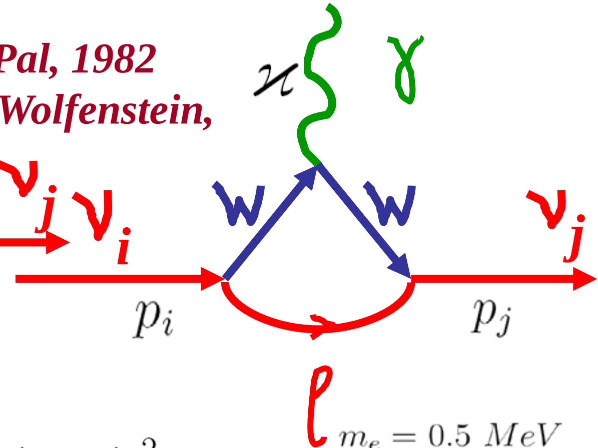
$$\sim 10^{-19} \mu_B \left(\frac{m_{\nu_e}}{1\,\mathrm{eV}}\right)$$

. . . μ_ν *in case of mixing . . .*

3.5 # 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** $i \neq j$

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

or

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

… depending on relative ***CP*** phase of ν_i and ν_j

The first nonzero contribution from neutrino transition moments

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

GIM cancellation

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

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

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

… **neutrino radiative decay is very slow**

- **Dirac** ν **diagonal** ***(i=j)*** **magnetic moment**

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

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

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

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

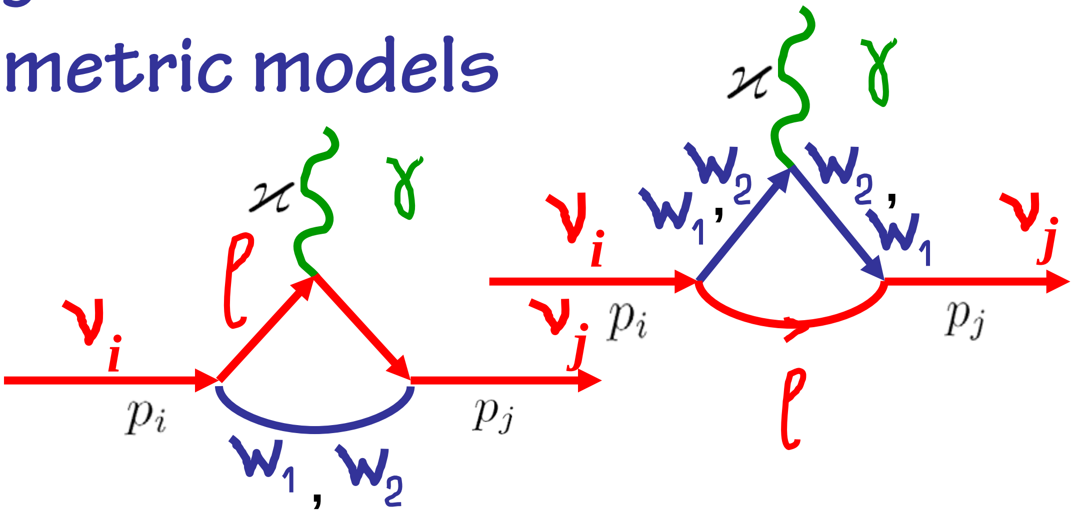
Lee, Shrock, Fujikawa, 1977

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

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

3.6 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 …*

...the present status...

to have visible $m_\nu \neq 0$

is not an easy task for

theoreticians

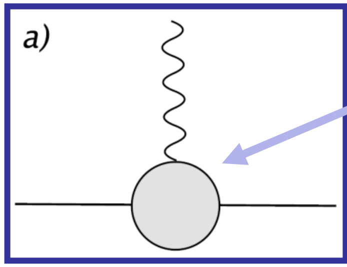
and experimentalists

3.3 Naïve relationship between m_ν and μ_ν

… problem to get large μ_ν and still acceptable m_ν

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

P.Vogel e.a., 2006

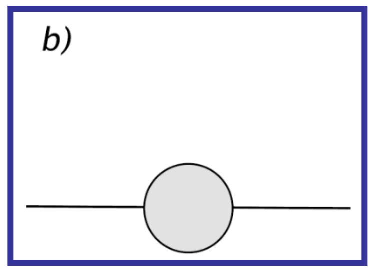


then

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

…combination of constants and loop factors…

contribution to m_ν given by



, then

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

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

Voloshin, 1988;
Barr, Freire, Zee, 1990

Large magnetic moment

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

Kim, 1976

Beg, Marciano, Ruderman, 1978

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

- *Voloshin, 1988*

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

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

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

considerable enhancement of μ_ν to experimentally relevant range

- **model-independent constraint μ_ν**

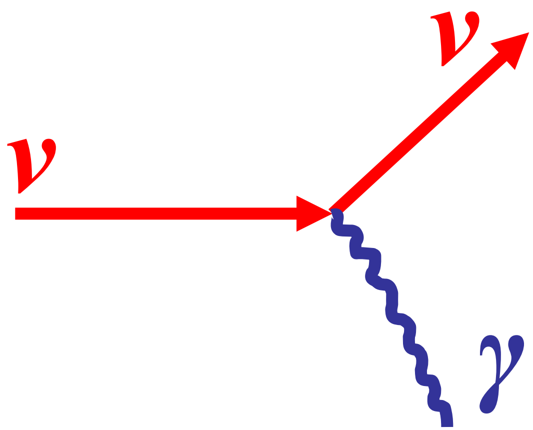
$\mu_\nu^D \leq 10^{-15} \mu_B$

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

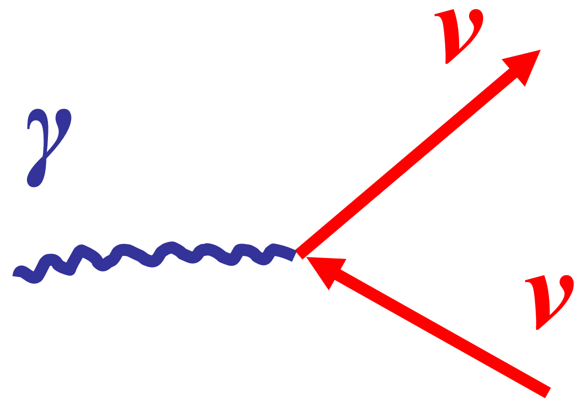
for BSM ($\Lambda \sim 1$ TeV) without fine tuning and under the assumption that $\delta m_\nu \leq 1$ eV

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

ν electromagnetic interactions

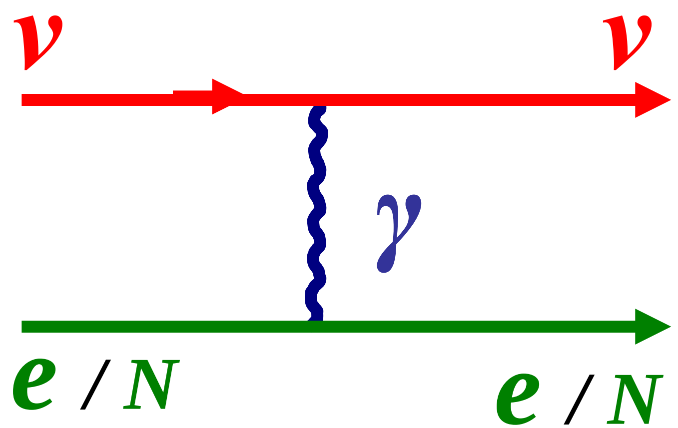


ν decay, Cherenkov radiation

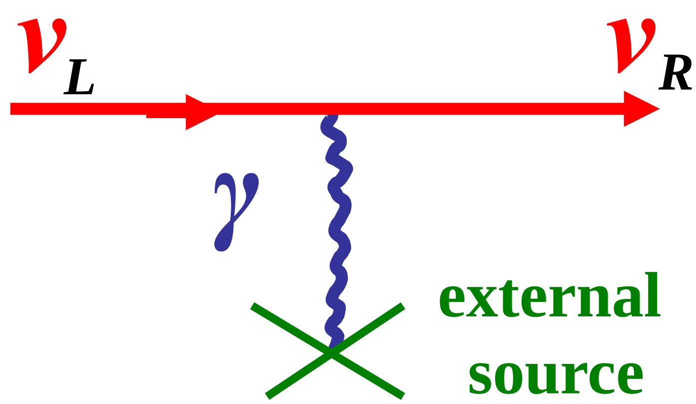


γ decay in plasma

!!!



Scattering

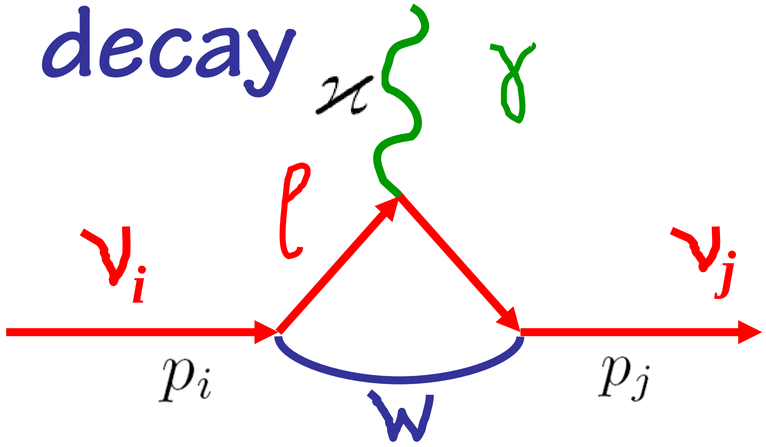


Spin precession

3.7 Neutrino radiative decay

$$\nu_i \longrightarrow \nu_j + \gamma$$

$$m_i > m_j$$



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

Radiative decay rate

Petkov 1977; Zatsepin, Smirnov 1978; Bilenky, Petkov 1987; Pal, Wolfenstein 1982

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

$$\mu_{eff}^2 = |\ \mu_{ij}\ |^2 + |\ \epsilon_{ij}\ |^2$$

- Radiative decay has been constrained from absence of decay photons:

1) reactor $\bar{\nu}_e$ and solar ν_e fluxes,

Raffelt 1999

2) SN 1987A ν burst (all flavours),

Kolb, Turner 1990;

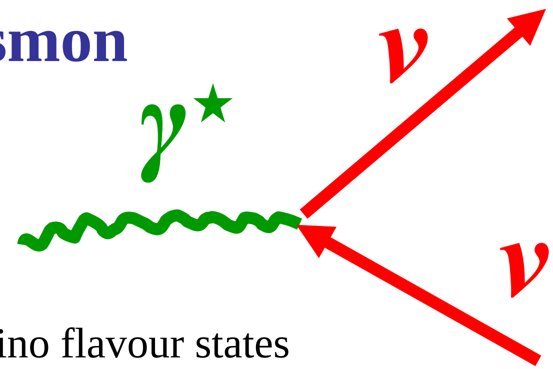
3) spectral distortion of CMBR

Ressell, Turner 1990

3.9 Tightest 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

Matrix element

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

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

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 $\omega^2 - k^2 = \omega^2_{pl}$

Energy-loss rate per unit volume

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

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

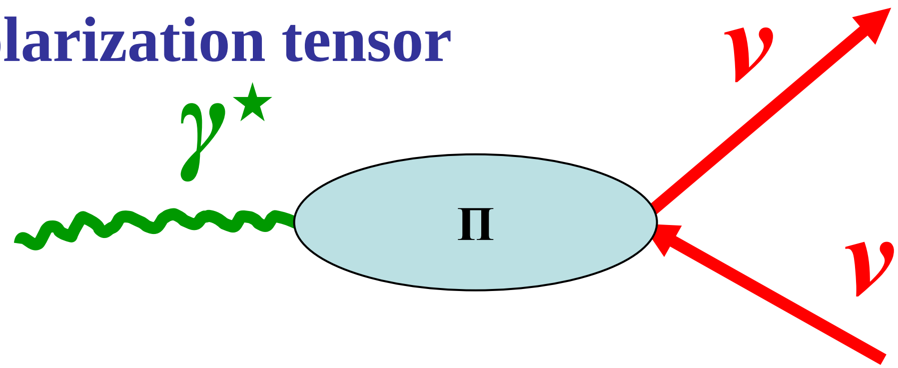
distribution function of plasmons

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 cooling of the star.

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

… best astrophysical limit on ν magnetic moment…

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

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

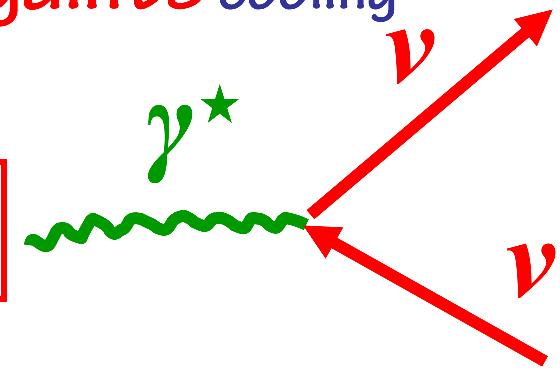
G.Raffelt, PRL 1990

3.10

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

- Constraints on neutrino millicharge from red gaints cooling

$\gamma^\star \rightarrow \nu\nu$



Interaction Lagrangian

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

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…** $q_\nu \leq 3 \times 10^{-21} e$

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 the neutrino properties.**

Generic assumption:

- **absence of other nonstandard interactions except for μ_ν.**

Global treatment would be desirable, incorporating oscillation and matter effects as well as complications due to interference and competitions among various channels

Direct and Indirect influence of electromagnetic fields on ν

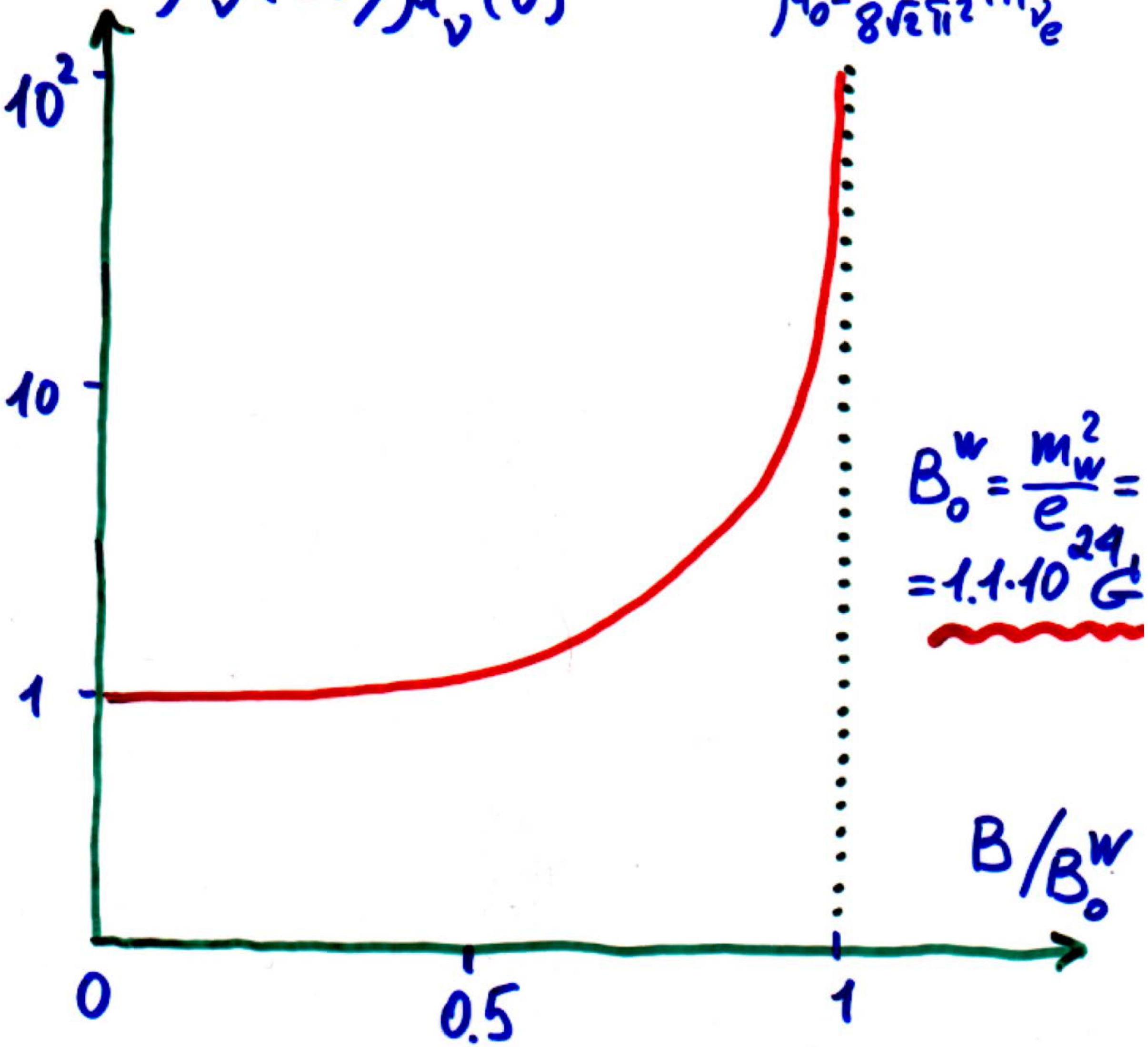
through non-trivial neutrino electromagnetic properties (magnetic moment):

- ★ neutrino spin
- ★ spin-flavour oscillations…
- ★ different $\nu\gamma$ processes

due to e.m. field influence on charged particles coupled to neutrinos

- ★ neutron beta-decay in B
- ★ change of ν oscillation pattern due to matter polarization under influence of external e.m. fields …

Neutrino magnetic moment



$\mu_0 = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e}$

$B_0^w = \frac{m_w^2}{e} = 1.1 \cdot 10^{24}\,G$

Borisov, Zhukovs'ky, Kurilin, Ternov, 1985;

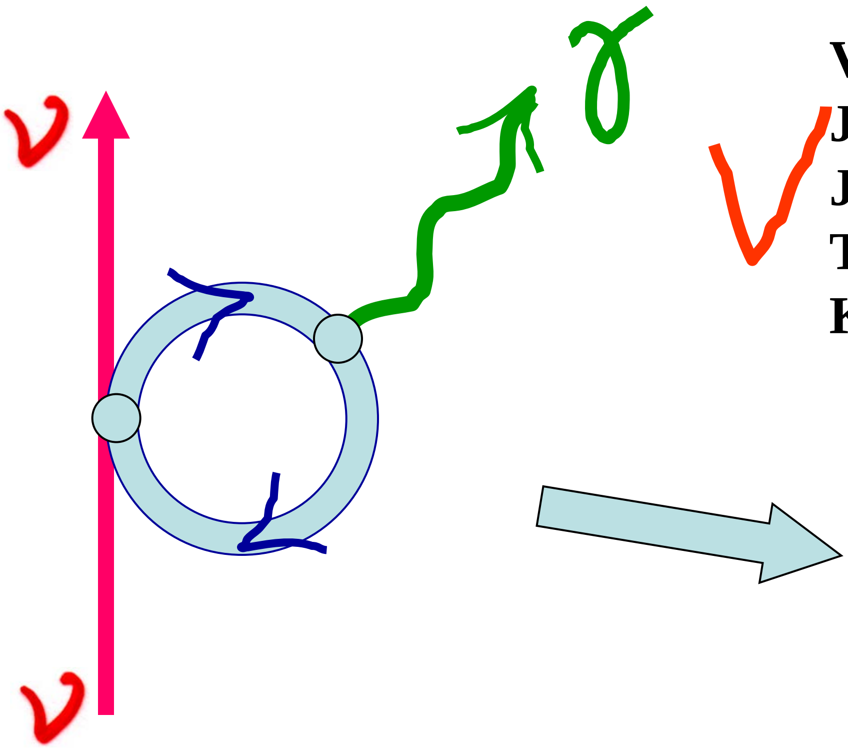
Masood, Perez Rojas, Gaitan, Rodrigues-Romo, 1999

ν "effective electric charge" in magnetized plasma

- ν s do not couple with γ s in vacuum,

  . . . however, when

- ν in thermal medium (e^- and e^+)



V.Oraevsky, V.Semikoz, Ya.Smorodinsky, JETP Lett. 43 (1986) 709;
J.Nieves, P.Pal, Phys.Rev.D 49 (1994) 1398;
T.Altherr, P.Salati, Nucl.Phys.B421 (1994) 662;
K.Bhattacharya, A.Ganguly, 2002

…different νγ interactions in astrophysical and cosmological media

... more about

Indirect influence of external $F_{\mu\nu}$

- $\nu\gamma$ interactions

$$\nu \to \nu + \gamma$$
$$\gamma \to \nu + \nu$$
$$\gamma\gamma \to \nu\bar{\nu} \ldots$$

DeRaad, Milton, Hari Dass
Galtsov, Nikitina, Skobelev
Chistakov, Gvozdev, Mikheev, Vasilevskaya
Ionnisian, Raffelt
Dicus, Repko, Shaisultanov
Borisov, Zhukovsky, A.Ternov, Eminov
Radomski, Grimus, Sakuda
Mohanty, Samal
Nieves, Pal . . .

- νe interactions

$$e \to e\nu\nu$$
$$\nu e \to \nu e \ldots$$

Landstreet, Baier, Katkov, Strakhovenko
Ritus, Nikishov
Loskutov, Zakhartsov
I.Ternov, Rodionov, Studenikin
Borisov, Kurilin
Narynskaya . . .

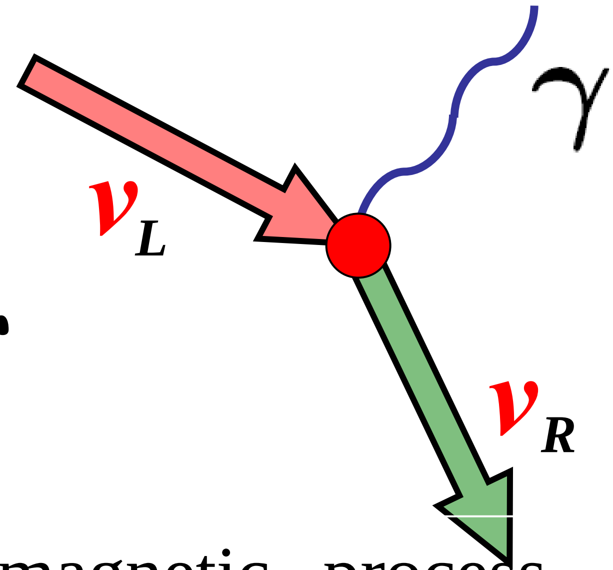
... astrophysical applications ...

"Spin light of neutrino" in matter and electromagnetic fields

$SL\nu$

$$\nu \xrightarrow{F_{\mu\nu},\ G_{\mu\nu}} \nu + \gamma$$

$SL\nu$ Spin light of neutrino in matter



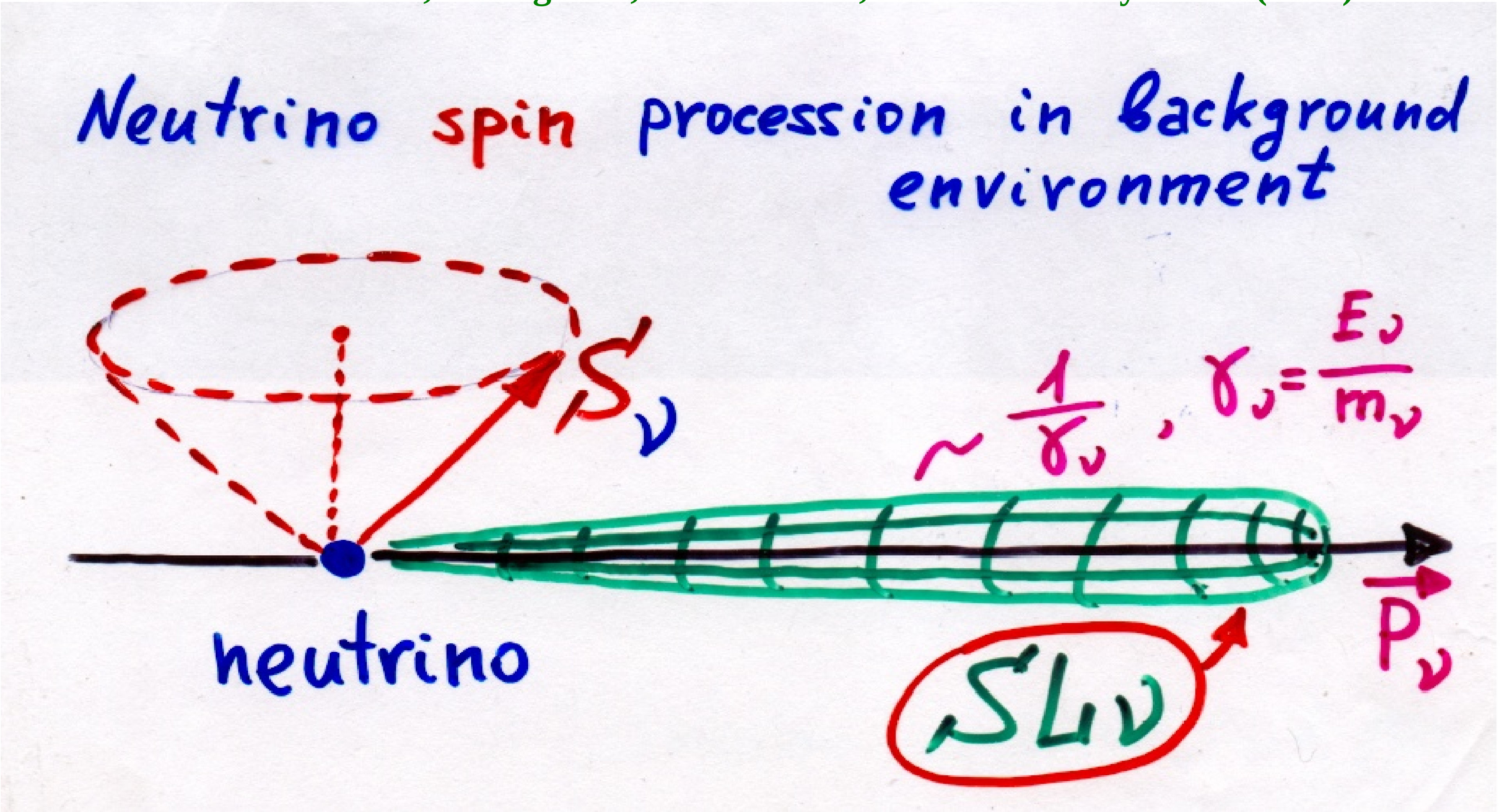
- **new mechanism** of the electromagnetic process stimulated by the presence of matter, in which neutrino with **non-zero magnetic moment** emits light

A.Lobanov, A.Studenikin, Phys.Lett. B 564 (2003) 27,
Phys.Lett. B 601 (2004) 171
A.S., A.Ternov, Phys.Lett. B 608 (2005) 107
A.Grigoriev, A.S., A.Ternov, Phys.Lett. B 622 (2005) 199
A.S., J.Phys.A: Math.Theor. 41 (2008) 16402
A.S., J.Phys.A: Math.Gen. 39 (2006) 6769
A.Grigoriev, A.Lokhov, A.Ternov, A.Studenikin,
Phys.Lett. B 718 (2012) 512

Quasi-classical theory of spin light of neutrino in matter and gravitational field

$SL\nu$

A.Lobanov, A.Studenikin, Phys.Lett. B 564 (2003) 27,
Phys.Lett. B 601 (2004) 171;
M.Dvornikov, A.Grigoriev, A.Studenikin, Int.J.Mod.Phys. D 14 (2005) 309



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**

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

New mechanism of electromagnetic radiation

? **Why** **Spin Light** **of neutrino** $SL\nu$ **of electron** SLe **in matter.**

Analogies with:

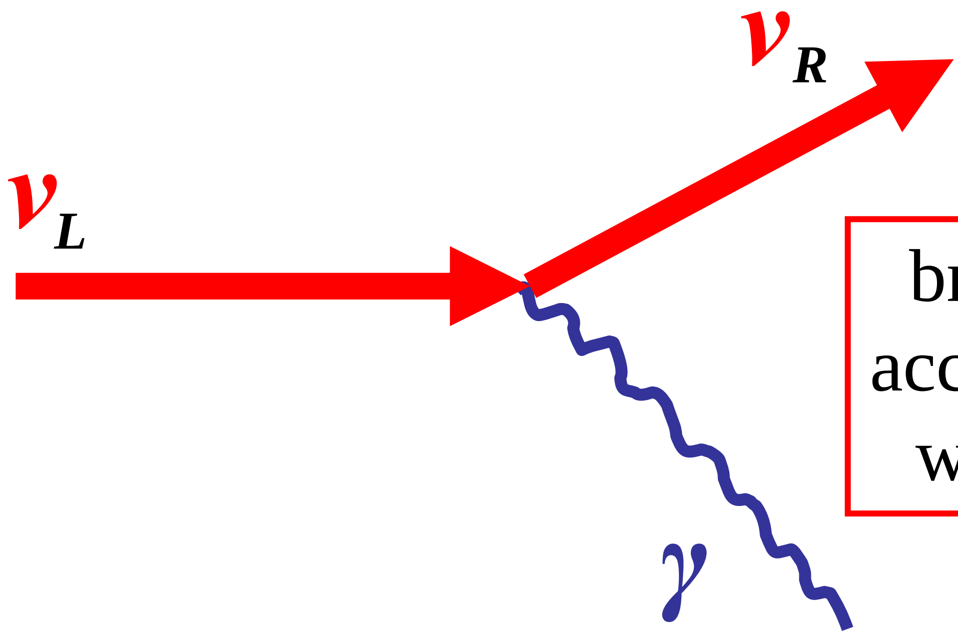
* classical electrodynamics

an object with charge $Q=0$ and magnetic moment $\vec{m} = \frac{1}{2}\sum_i e_i [\vec{r}_i \times \vec{v}_i] \neq 0$

$$I^{cl.el.} = \frac{2}{3}\ddot{\vec{m}}^2$$

← magnetic dipole radiation power

Neutrino – photon couplings



broad neutrino lines account for interaction with environment

“Spin light of neutrino in matter”

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

... evaluation of the method

(ν under extreme external conditions - dense matter and strong external fields)

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»

Method of exact solutions

Modified Dirac equations for ν (and e)

(with corresponding effective matter potentials)

+

exact solutions (particles wave functions)

↓

basis for investigation of different phenomena which can proceed when neutrinos move in dense media

(astrophysical and cosmological environments)

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) 512-515

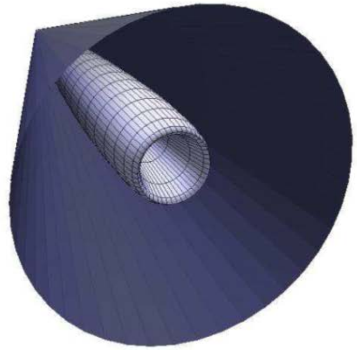


Figure 1: 3D representation of the radiation power distribution.

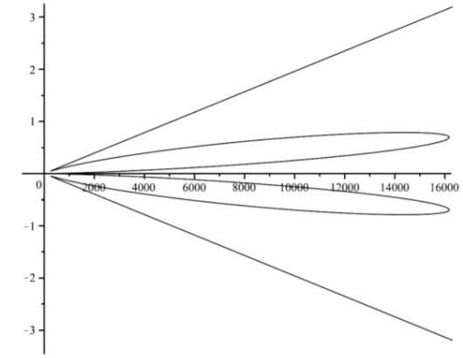


Figure 2: The two-dimensional cut along the symmetry axis. Relative units are used.

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].

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

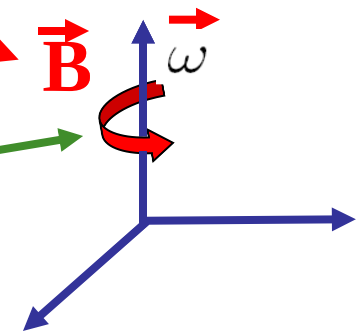
Millicharged ν in rotating magnetized matter

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

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

external magnetic field



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

matter potential

rotating matter

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

rotation angular frequency

✓ wave function (exact solution)

$$\Psi(x) = \Psi_L(x) + \Psi_R(x)$$

$$\psi_1 = \frac{1}{2}\sqrt{\frac{|2Gn_n\omega - \epsilon q_\nu B|}{2\pi L}}\sqrt{1 - \frac{p_3}{p_0^L + Gn_n}}\mathcal{L}_s^{l-1}\left(\frac{|2Gn_n\omega - \epsilon q_\nu B|}{2}r^2\right)e^{i(l-1)\varphi}$$

$$\psi_2 = \frac{i}{2}\sqrt{\frac{|2Gn_n\omega - \epsilon q_\nu B|}{2\pi L}}\sqrt{1 + \frac{p_3}{p_0^L + Gn_n}}\mathcal{L}_s^{l}\left(\frac{|2Gn_n\omega - \epsilon q_\nu B|}{2}r^2\right)e^{il\varphi}.$$

$$\psi_3 = \frac{1}{2}\sqrt{\frac{q_\nu B}{2\pi L}}\sqrt{1 - \frac{p_3}{p_0^R}}\mathcal{L}_s^{l-1}\left(\frac{q_\nu B}{2}r^2\right)e^{i(l-1)\varphi}$$

$$\psi_4 = \frac{i}{2}\sqrt{\frac{q_\nu B}{2\pi L}}\sqrt{1 + \frac{p_3}{p_0^R}}\mathcal{L}_s^{l}\left(\frac{q_\nu B}{2}r^2\right)e^{il\varphi},$$

Laguerre functions
($N = l + s = 0, 1, 2 \ldots$)

✓ energy :

$$p_0^R = \sqrt{p_3^2 + 2Nq_\nu B} \qquad p_0^L = \sqrt{p_3^2 + 2N|2Gn_n\omega - \epsilon q_\nu B|} - Gn_n$$

$$N = 0, 1, 2, \ldots$$

energy quantization in rotating magnetized matter

ν energy is quantized in rotating matter

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

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

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

matter rotation frequency

millicharge of ν

scalar potential of electric field

A.Studenikin, I.Tokarev, Nucl.Phys.B (Proc.Suppl.) (2013)

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**

Studenikin, J.Phys. A (2008)

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

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

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 ?

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

. . . we predict :

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

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

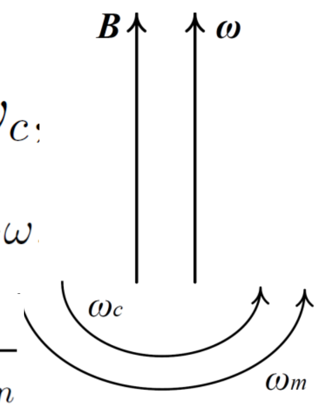
Millicharged ν as star rotation engine

- Single ν generates feedback force with projection on rotation plane

$$\Omega = \omega_m + \omega_c;$$

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

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



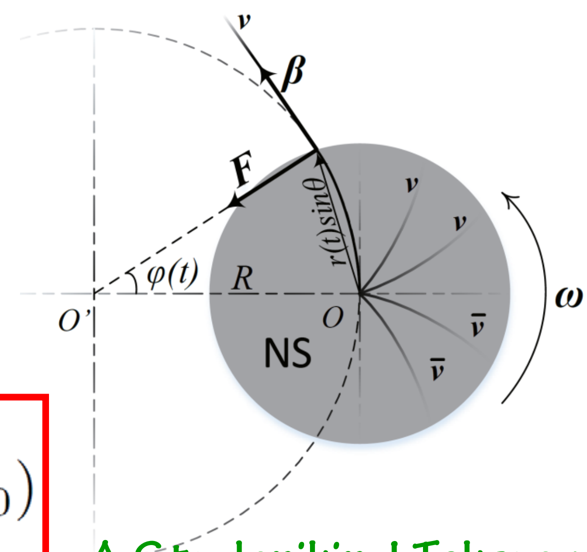
- $F = (q_0 B + 2Gn_n\omega)\sin\theta$

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

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



- Shift of star angular velocity

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

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

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

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

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

- $$q_0 < 1.3 \times 10^{-19} e_0$$ ... best astrophysical bound ...

Spin light of electron in dense neutrino fluxes SLe_{ν}

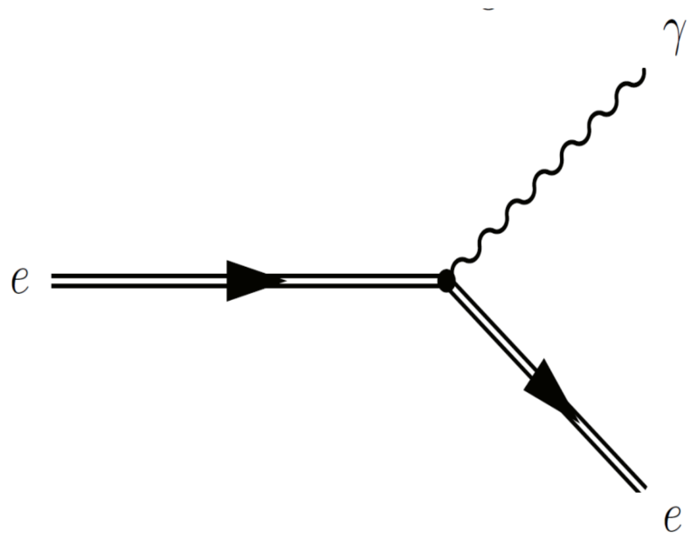
I.Balantsev, A.Studenikin, arXiv: 1405.6598

Dirac eq for e in dense relativistic flux of ν

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

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

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

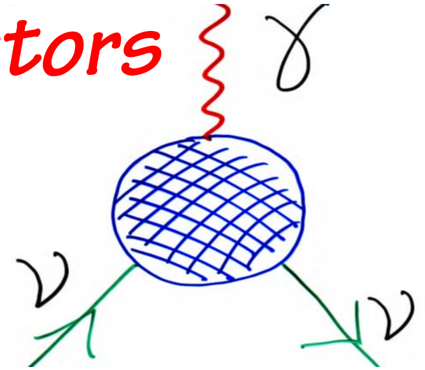


$$f^{\mu} = G(n, 0, 0, n)$$

background matter
(ν flux) potential

Conclusions

ν e.m. vertex function → 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 → a way to distinguish Dirac and Majorana ν**

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

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

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

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

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

- Limits from astrophysics, star cooling (1990):

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

  $$q_\nu < 1.3 \times 10^{-19} e_0$$ ν ST mechanism

μ_ν is "presently known" to be in the range

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

μ_ν provides a tool for exploration possible New Physics

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

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

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

Beyond Extended Standard Model