Electromagnetic properties of the neutrino

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2012

- the Year of the Higgs Boson
  (... probably ...)

- status of Standard Model

  (... lecture of Igor Boiko ...)

ν is the only known particle Beyond Standard Model

ν is quite

invisible

particle

ν exhibits unexpected properties (puzzles)

W. Pauli, 1930 — E.Fermi, 1933

- neutral 'neutron' $\Rightarrow$ ν
- $m_\nu = 0$ (now $m_\nu \neq 0$ but ? after 80 yrs !)
- 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 … $\Longrightarrow$

Crucial role of neutrino

ν is a "tiny" particle :

- very light $m_{\nu_f} \ll m_f, \quad f = e, \mu, \tau$
- electrically neutral $q_\nu = 0$ $q_\nu < 4 \times 10^{-17} e$
- with very small magnetic moment $\mu_\nu ?$

$\sigma_{\nu_e N} \sim 10^{-39}\ cm^2$ ν-N scattering
$\sigma_{\bar{\nu}_e p} \sim 10^{-40}\ cm^2$ inverse β-decay
$\sigma_{\nu_e e} \sim 10^{-43}\ cm^2$ ν-e scattering

- weak interactions are indeed weak $\bar{\nu} + p \to e^+ + n$

$\sigma \sim 10^{-43}\ cm^2$ $L \sim 10^{15} km$

$E_\nu \sim 3 MeV$ ... free path in water...

at the final stages of development of particular elementary particle physics framework

horizons of new physics

ν manifests itself most vividly under the influence of extreme external conditions:

- strong external electromagnetic fields

and

- dense background matter

Outline

- ν electromagnetic properties (review)

1 Carlo Giunti, Alexander Studenikin :
"Neutrino electromagnetic properties"
Phys.Atom.Nucl. 73, 2089-2125 (2009)
arXiv:0812.3646 v5, Apr 12, 2010

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 neutrinos"
J.Phys.: Conf.Series. 203 (2010) 012100
arXiv:1006.1502 June 8, 2010

4 C.Broggini, C.Giunti, A.Studenikin :
"Electromagnetic properties of neutrinos",
in: "Neutrino Physics"(Adv. in High Ener. Phys.)
arXiv: 1207.3980 July 17, 2012

5 C.Giunti, A.Studenikin : "Theory and phenomenology
of neutrino electromagnetic properties"
Rev.Mod.Phys. (in preparation)

Outline (short list)

- ν electromagnetic properties - theory
- ν magnetic moment - experiment
- constraints on ν electromagnetic properties
- ν electromagnetic interactions
  (ν-γ processes)

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 masses)
   - 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)

- **Neutrino magnetic moments**

  - results of recent experimental searches for upper bound on μ_ν

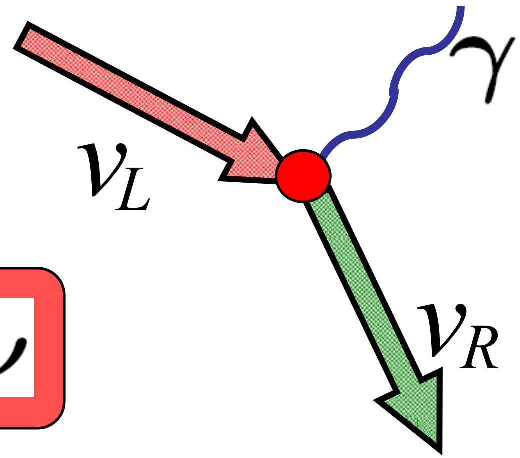
  - our corresponding theoretical studies of ν-e scattering

    ⇒ present best indeed laboratory limit on μ_ν (GEMMA Coll.)

- 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"
  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", **Phys.Rev.D** 83 (2011) 113001
  arXiv: 1101.4878, 25 Jan 2011
- "On neutrino-atom scattering in searches for neutrino magnetic moments" **Nucl.Phys.B** (Proc.Supp.) 2011 (Proc. of Neutrino 2010 Conf.)
  arXiv: 1102.0643, 3 Feb 2011
- "Testing neutrino magnetic moment in ionization of atoms by neutrino impact", **JETP Lett.** 93 (2011) 699
  arXiv: 1105.5543, 27 May 2011
- M.Voloshin,
  "Neutrino scattering on atomic electrons in search for neutrino magnetic moment"
  Phys.Rev.Lett. 105 (2010) 201801, arXiv: 1008.2171

Outline (III)

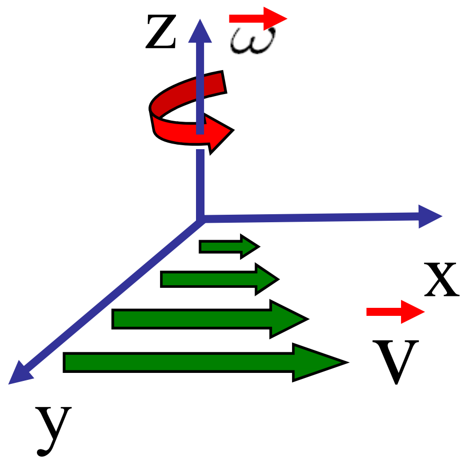
2 problems:



1. Spin Light of ν in matter

$SL\nu$

2. ν energy quantization in rotating matter



ν quantum states in matter
New approach to particles in matter

Method of exact solutions

Modified Dirac equations for ν (and e)

(containing the correspondent effective matter potentials)

+

exact solutions (particles wave functions)

⇓

a basis for investigation of different phenomena which can proceed when neutrinos (and electrons) move in dense media

(astrophysical and cosmological environments).

«method of exact solutions »

Interaction of particles in external electromagnetic fields

(**Furry representation** in quantum electrodynamics)

$$e \xrightarrow{B_\perp} e + \gamma$$

synchrotron radiation

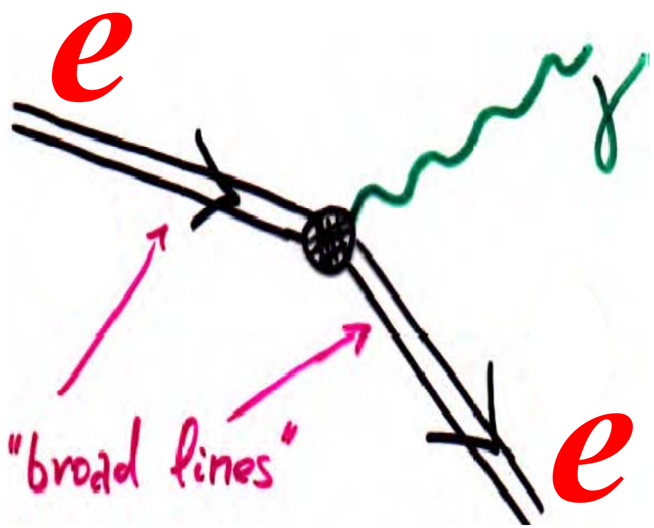
Potential of electromagnetic field

$$A_\mu(x) = A^q_\mu(x) + A^{ext}_\mu(x),$$

quantized part of potential

evolution **operator**

$$U_F(t_1,t_2) = Texp\Big[-i\int_{t_1}^{t_2} j^\mu(x)A^q_\mu(x)dx\Big],$$



charged particles **current**

$$j_\mu(x) = \frac{e}{2}\left[\overline{\Psi}_F\gamma_\mu, \Psi_F\right],$$

Dirac equation in **external classical (non-quantized) field** $A^{ext}_\mu(x)$

$$\Big\{\gamma^\mu\Big(i\partial_\mu - eA^{ext}_\mu(x)\Big) - m_e\Big\}\Psi_F(x) = 0$$

…beyond perturbation series expansion, strong fields and non linear effects…

Outline (IV)

ν and e in matter treated within «method of exact solutions» (of quantum wave equations)

A.Studenikin, A.Ternov, "Neutrino quantum states in matter", Phys.Lett.B 608 (2005) 107;

"Generalized Dirac-Pauli equation and neutrino quantum states in matter" hep-ph/0410296,

A.Grigoriev, A.Studenikin, A.Ternov, Phys.Lett.B 608 622 (2005)19

- ν energy quantization in rotating matter …

A.Studenikin,"Method of wave equations exact solutions in studies of neutrino and electron interactions in dense matter",

- J.Phys.A:Math.Theor. 41 (2008) 16402

Neutrinos and electrons in background matter: a new approach",

- Ann. Fond. de Broglie 31 (2006) 289,
- J.Phys.A: Math.Gen.39 (2006) 6769

- I.Balantsev, Yu.Popov, A.Studenikin, "On a problem of relativistic particles motion in a strong magnetic field and dense matter", J.Phys.A: Math.Theor. 44 (2011) 255301

- A.Studenikin, I.Tokarev, "Millicharged neutrino with anomalous magnetic moment in rotating magnetized matter", arXiv :1209.3245 September 3, 2012

Outline (V)

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 …

- A review on neutrino electromagnetic properties

  (including magnetic moments μ_ν)

…Why

electromagnetic properties of ν

provide a kind of

window / bridge

to

NEW Physics ?

… 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,*

... simple answer ...

$$m_\nu \neq 0$$

Neutrino mass

$$m_\nu \neq 0 \; !$$

Neutrino magnetic moment

$$\mu_\nu \neq 0$$

(*) Lee, Shrock 1977; Shrock, Fujikawa 1980

...Massive neutrino electromagnetic properties...

In the Standard Model : $m_\nu = 0$,
there is no ν_R $\Longrightarrow$
ν magnetic moment $\mu_\nu = 0$.
Thus, $\mu_\nu \neq 0$ ← beyond the SM . !

... a tool for studying physics beyond the 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

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

anomalous magnetic moment of electron

... much greater values are desired for astrophysical or cosmology

visualization of μ_ν

Astrophysical bounds

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

(Red Giant lumin.) etc.

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

…the present status
(preliminary conclusion) …

to have visible $m_\nu \neq 0$

is not an easy task for

theoreticians

and experimentalists

… puzzling

ν electromagnetic properties and μ_ν

something that is tiny but not zero

$m_\nu \neq 0 \Longrightarrow$

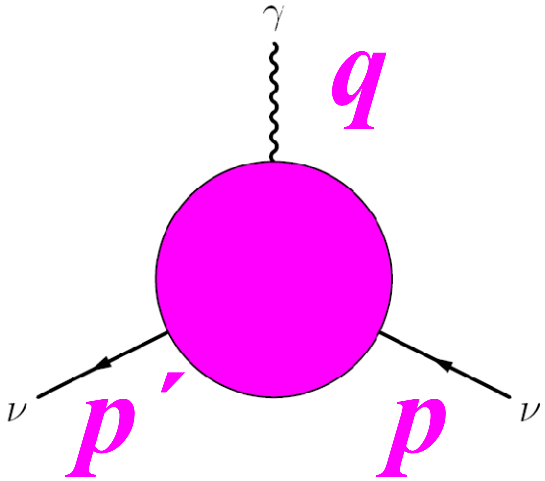
weak
gravitational
and
electromagnetic
interactions

ν electromagnetic

properties

… theoretical introduction…

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

Lorentz covariance (1)

$\Lambda_\mu(q,l)$ *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

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

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

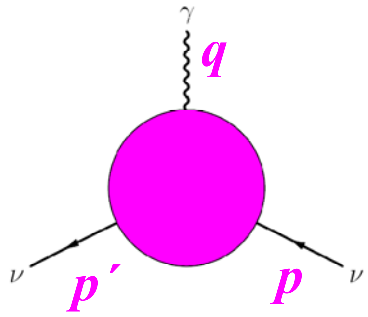
- $\hat{\mathbf{1}} q_\mu, \quad \hat{\mathbf{1}} l_\mu, \quad \gamma_5 q_\mu, \quad \gamma_5 l_\mu$

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

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

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

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



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 $p^2 = p'^2 = m^2, \; l^2 = 4m^2 - q^2$

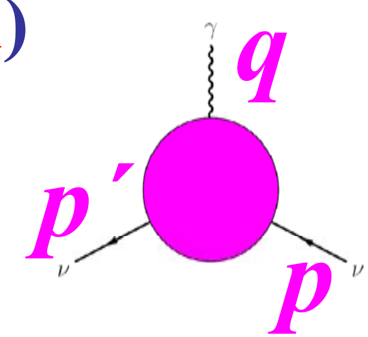
Gordon-like identities

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

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

Electromagnetic gauge invariance (2)

(requirement of current conservation)



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

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

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

ν 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:* $Im f_Q = Im f_M = Im f_A = 0$.

Majoran ν

1) *from CPT invariance (regardless CP or ~~CP~~) .*

$$f_Q = f_M = f_E = 0$$

…as early as 1939, W.Pauli…

EM properties ⟹ a way to distinguish **Dirac** and **Majorana** ν

In general case matrix element of $J_\mu^{\rm EM}$ can be considered between different initial $\psi_i(p)$ and final $\psi_j(p')$ states of different masses $p^2 = m_i^2, \ p'^2 = m_j^2$:

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

… beyond beyond SM…

and

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

! form factors are matrices in ν mass eigenstates space.

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

1) *hermiticity* itself *does not apply restrictions on form factors,*

2) *CP invariance + hermiticity*

$$f_Q(q^2), \ f_M(q^2), \ f_E(q^2), \ f_A(q^2)$$

are relatively real (no relative phases) .

1) *CP invariance + hermiticity*

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

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

… quite different EM properties …

... 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

$\Longrightarrow$

…two remarks ….

1 Difference between electromagnetic vertex function of massive and massless ν

Dirac Form factor (the only one…)

- $m_\nu = 0$: $$\bar{u}(p')\Lambda_\mu(q)u(p) = f_D(q^2)\bar{u}(p')\gamma_\mu(1+\gamma_5)u(p)$$

electric charge $f_Q(q^2)$ *and anapole* $f_A(q^2)$ ***FF*** *are related to* ***DF*** *(and to each other):*

$$f_Q(q^2) = f_D(q^2), \quad f_A(q^2) = f_D(q^2)/q^2$$

- *In case* $m \neq 0$ *there is no such simple relation (because term* $q_\mu \not{q}\gamma_5$ *in anapole* ***FF*** *cannot be neglected).*

2 ν form factors in gauge models

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

- *Form Factors at zero momentum transfer* ($q^2 = 0$) *are elements of scattering matrix* ⇒ *in any consistent theoretical model FF in matrix element* ⇒ *gauge independent and finite.*

  Therefore

  FF at $q^2 = 0$ determine static properties of ν that can be probed (measured) in direct interaction with external em fields .

This is the case for
$f_Q(q^2),\ f_M(q^2),\ f_E(q^2)$
in minimally extended SM
($f_A(q^2)$ is an exceptional case)

- *In non-Abelian gauge models,*

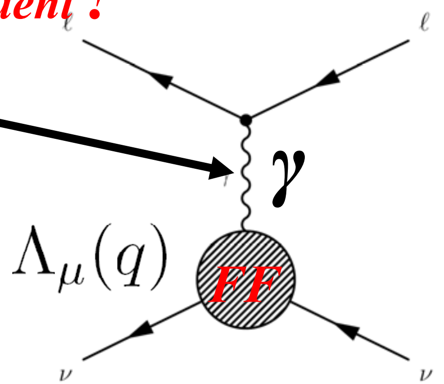
  FF at $q^2 \neq 0$ can be not invariant under gauge transformation

  because (in general) off-shell photon propagator *is gauge dependent !*

  … One-photon approximation is not enough to get physical quantity…

  … FF in matrix element cannot be directly measured in experiment with em field …

  … FF can contribute to higher order processes accessible for experimental observation.



magnetic moment ?

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 ???

1

ν magnetic moment in experiments

Samuel Ting
(wrote on the wall at Department of Theoretical Physics of Moscow State University) :

"Physics is an experimental science"

Studies of ν-e scattering - most sensitive method of 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

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

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

T is the electron recoil energy

$$0 \le T \le \frac{2E_\nu^2}{2E_\nu + m_e},$$

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

for anti-neutrinos $g_A \to -g_A$

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

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

ν-γ coupling … **valid for ν scattering on free e**

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

with change of helicity, contrary to SM

T is the electron recoil energy: $0 \leq T \leq \dfrac{2E_\nu^2}{2E_\nu + m_e}$

If neutrino has electric dipole moment,
or electric or magnetic transition moments,
these quantities would also contribute to scattering cross section

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

*i refers to initial neutrino **flavour***

Possibility of ***distractive interference*** between **magnetic** and **electric** transition moments of **Dirac** neutrino
(**Majorana** neutrino has only magnetic or electric transition moment, but not both if CP is conserved)

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

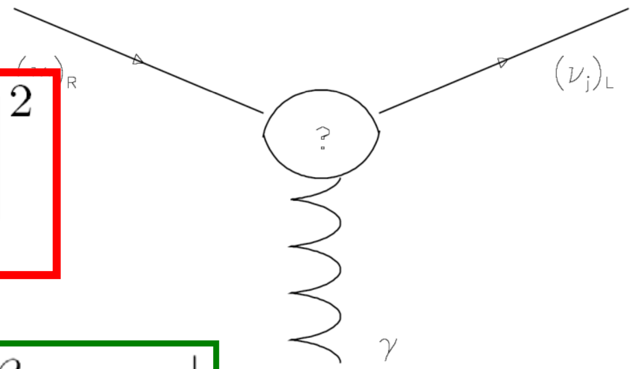
$$\sigma \sim \mu_e^2 = \sum_j \left| \sum_i U_{ei} e^{-iE_i L} \mu_{ji} \right|^2$$

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.

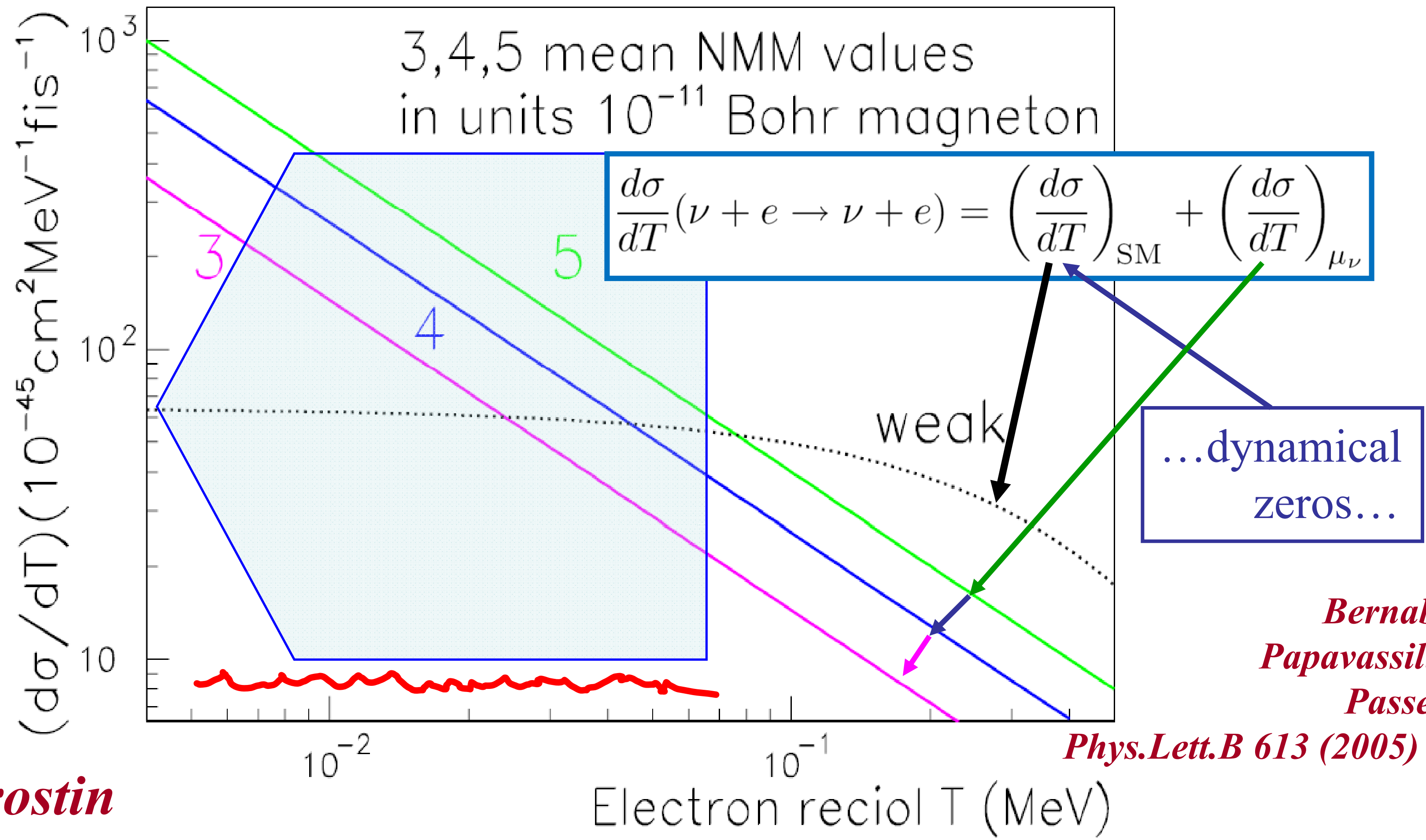
- Implications of μ_ν limits from different experiments (reactor , solar ^{8}B and ^{7}Be) are different.

Magnetic moment contribution is dominated at low electron recoil energies

and $\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} > \left(\frac{d\sigma}{dT}\right)_{SM}$ when $\frac{T}{m_e} < \frac{\pi^2 \alpha_{em}}{G_F^2 m_e^4} \mu_\nu^2$

… the **lower** the smallest measurable electron recoil energy is,

the **smaller** values of μ_ν^2 can be probed in scattering experiments **…**



from A.Starostin

Bernabeu, Papavassiliou, Passera, Phys.Lett.B 613 (2005) 162

First and future ν-e scattering experiments

- $$\mu_\nu \leq 2 \div 4 \times 10^{-10} \mu_B$$

  Savannah River (1976), ***first observation of ν - e***

  Vogel, Engel, 1989

  Kurchatov, Krasnoyarsk (1992), Rovno (1993) reactors

- $$\mu_\nu \leq 1.1 \times 10^{-10} \mu_B$$

  SuperKamiokande (2004)

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

  …in the future…

  Beta-beams

  McLaughlin, Volpe, 2004

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…

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

Montanino, Picariello, Pulido, PRD 2008

based on first release of BOREXINO data

GEMMA (2005-2008)

Germanium Experiment on measurement of Magnetic Moment of Antineutrino

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

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

...till 13 January 2010 and again since 23 August 2010

best limit on ν magnetic moment

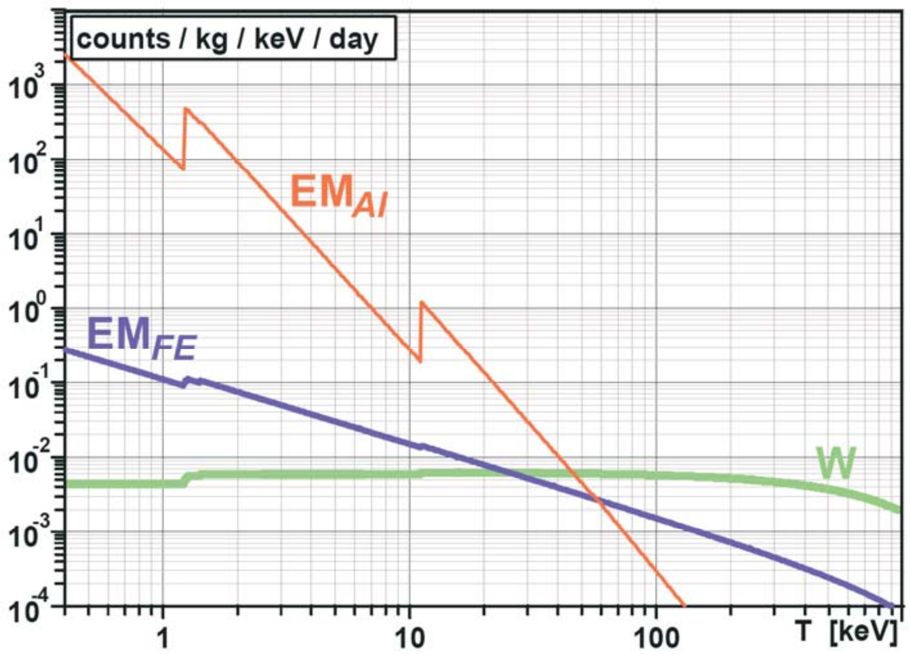
A.Beda et al, Phys.Part.Nucl.Lett. 7 (2010) 406

result known since 2009:

A.Beda, E.Demidova, A.Starostin et al,
arXiv:09.06.1926 , June 10, 2009,
A.Beda, V.Brudanin, E.Demidova et al,
in: "Particle Physics on the Eve of LHC",
ed. A.Studenikin, World Scientific (Singapore),
p.112, 2009 (13th Lomonosov Conference) www.icas.ru

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

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

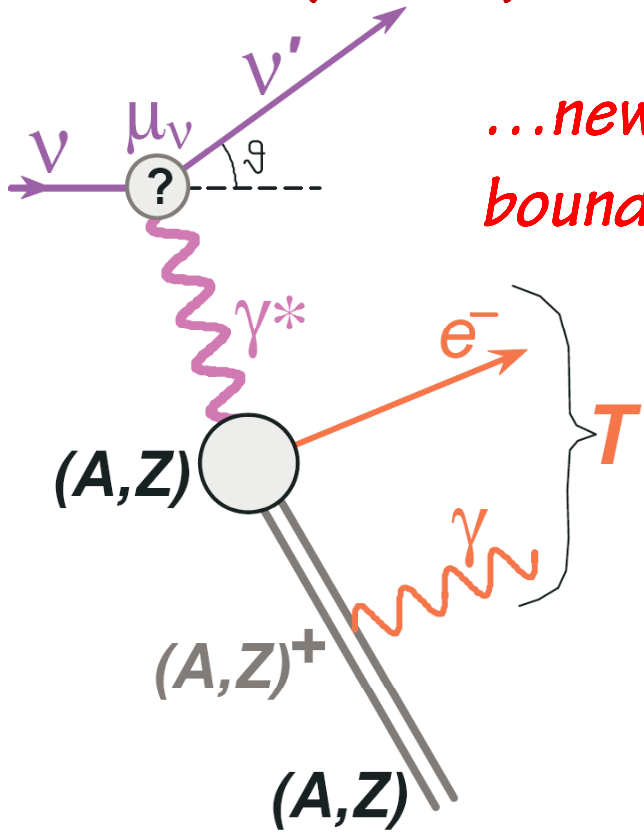


?

H.Wong et al. (TEXONO Coll.), arXiv: 1001.2074, 13 Jan 2010, reported at

Neutrino 2010 Conference (Athens, June 2010),

PRL 105 (2010) 061801



...new ⟹ bounds ...

…much better limits on ν effective magnetic moment …

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

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

… atomic ionization effect accounted for …

Neutrino 2010 Conference, Athens

… ***however*** …

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

… atomic ionization effect accounted for …

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

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

… ν-e scattering on free electrons …

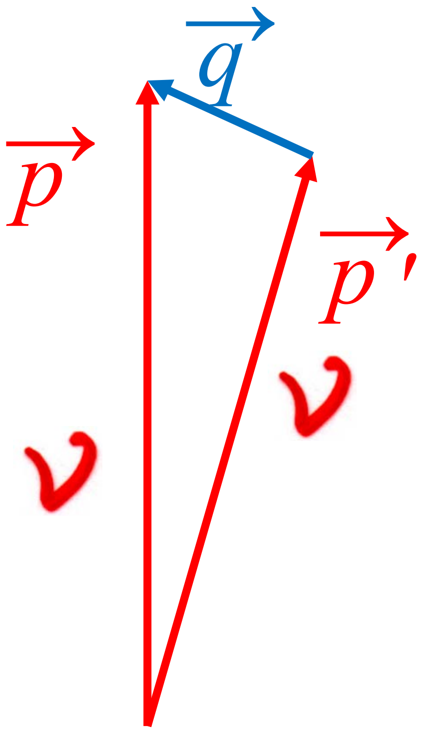
(without atomic ionization)

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

• Neutrino-impact ionization of atoms in search for μ_ν



scattering on atoms (Ge) at low energy transfer

$T \sim$ few keV and lower so that $\frac{T}{E_\nu} \ll 1$ for most of reactor ν

Ge atom recoil energy $< \frac{2E_\nu^2}{M_{Ge}} \ll T$ $\quad M_{Ge} \to \infty$

ν interaction with nucleus is neglected ●

ν scattering on atomic e is important ●

Four momentum transfer $q = p - p'$

$$q_\mu = (T, \vec{q}), \quad q^2 = \vec{q}^{\,2}$$

energy and spatial momentum transfer from neutrinos to atomic electrons

Kouzakov, Studenikin, Voloshin, 2010; 2011

At small T *electrons can be treated nonrelativistically*

so that $\nu i i$ *process is scattering of* μ_ν *on EMF of electrons*

$$A = (A_0, \vec{A}) \qquad A_0(\vec{q}) = \sqrt{4\pi\alpha}\,\rho(\vec{q})/\vec{q}^2 \qquad \vec{A}(\vec{q}) = \sqrt{4\pi\alpha}\,\vec{j}(\vec{q})/\vec{q}^2$$

where

$$\rho(\vec{q}) = \sum_{a=1}^{Z} \exp(i\vec{q}\cdot\vec{r}_a) \qquad \vec{j}(\vec{q}) = -\frac{i}{2m}\sum_{a=1}^{Z}\left[\exp(i\vec{q}\cdot\vec{r}_a)\frac{\partial}{\partial\vec{r}_a} + \frac{\partial}{\partial\vec{r}_a}\exp(i\vec{q}\cdot\vec{r}_a)\right]$$

are Fourier transforms of e *number and current density operators,*
Summation is performed over positions $\vec{r}_a$ *of all Z electrons in atom*

Vertex function

$$\Lambda^i = \frac{\mu_\nu}{2m_e}\sigma^{ik}q_k$$

Double differential ν-e cross section

$$\frac{d^2\sigma_{(\mu)}}{dT\,dq^2} = 4\pi\,\alpha\,\frac{\mu_\nu^2}{q^2}\left[\left(1-\frac{T^2}{q^2}\right)S(T,q^2)+\left(1-\frac{q^2}{4E_\nu^2}\right)R(T,q^2)\right]$$

Kouzakov, Studenikin, Voloshin, 2010; 2011

$$\frac{d^2\sigma_{(\mu)}}{dT dq^2} = \left(\frac{d^2\sigma_{(\mu)}}{dT dq^2}\right)_{\parallel} + \left(\frac{d^2\sigma_{(\mu)}}{dT dq^2}\right)_{\perp}$$

where dynamical structure factor (Van Hove, 1954)

$$S(T,q^2) = \sum_n \delta(T-E_n+E_0)\;|\langle n|\rho(\vec{q})|0\rangle|^2$$

and $(\vec{j}_\perp \cdot \vec{q}) = 0$

$$R(T,q^2) = \sum_n \delta(T-E_n+E_0)\;|\langle n|j_\perp(\vec{q})|0\rangle|^2$$

sum is over all states $|n\rangle$ of electron system, $|0\rangle$ initial state

... dynamical structure factor $(\vec{j}_\perp \cdot \vec{q}) = 0$

$$S(T,q^2) = \sum_n \delta(T - E_n + E_0)\ |\langle n|\rho(\vec{q})|0\rangle|^2$$

and

$$R(T,q^2) = \sum_n \delta(T - E_n + E_0)\ |\langle n|j_\perp(\vec{q})|0\rangle|^2$$

are related

$$S(T,q^2) = \frac{1}{\pi}\,\mathrm{Im}F(T,q^2)\ , \qquad R(T,q^2) = \frac{1}{\pi}\,\mathrm{Im}L(T,q^2)$$

to ρ-ρ and j-j Green's functions

$$F(T,q^2) = \sum_n \frac{|\langle n|\rho(\vec{q})|0\rangle|^2}{T - E_n + E_0 - i\,\epsilon} = \left\langle 0 \left| \rho(-\vec{q})\, \frac{1}{T - H + E_0 - i\,\epsilon}\, \rho(\vec{q}) \right| 0 \right\rangle\ ,$$

$$L(T,q^2) = \sum_n \frac{|\langle n|j_\perp(\vec{q})|0\rangle|^2}{T - E_n + E_0 - i\,\epsilon} = \left\langle 0 \left| j_\perp(-\vec{q})\, \frac{1}{T - H + E_0 - i\,\epsilon}\, j_\perp(\vec{q}) \right| 0 \right\rangle$$

For single-differential inclusive cross section measured in experiment

$$\frac{d\sigma_{(\mu)}}{dT} = 4\pi\,\alpha\,\mu_\nu^2 \int_{T^2}^{4E_\nu^2} S(T,q^2)\,\frac{dq^2}{q^2}$$

$$R(T,q^2) = \frac{T^2}{q^2} S(T,q^2)$$

transversal contribution practically for most q^2 is negligible

SM electroweak contribution to cross section

$$\frac{d\sigma_{EW}}{dT} = \frac{G_F^2}{4\pi}\left(1 + 4\,\sin^2\theta_W + 8\,\sin^4\theta_W\right)\int_{T^2}^{4E_\nu^2} S(T,q^2)\,dq^2$$

nonrelativistic limit $\int_{T^2}^{4E_\nu^2} \Rightarrow \int_0^\infty$

For free electron $S_{(FE)}(T,q^2) = \delta(T - q^2/2m)$

$$\int_0^\infty S_{(FE)}(T,q^2)\,\frac{dq^2}{q^2} = \frac{1}{T}, \quad \int_0^\infty S_{(FE)}(T,q^2)\,dq^2 = 2\,m$$

$$\frac{d\sigma_{(\mu)}}{dT} = 4\pi\,\alpha\,\mu_\nu^2\left(\frac{1}{T} - \frac{1}{E_\nu}\right) = \pi\,\frac{\alpha^2}{m^2}\left(\frac{\mu_\nu}{\mu_B}\right)^2\left(\frac{1}{T} - \frac{1}{E_\nu}\right)$$

- … for electron bound in atom …

$$S(T,q^2) = \frac{m}{2\,p\,q}\left[\theta\left(T - \frac{q^2}{2m} + \frac{p\,q}{m}\right) - \theta\left(T - \frac{q^2}{2m} + \frac{p\,q}{m}\right)\right]$$

(ν-e scattering on free electrons)

free electron approximation is valid

! No important effect of Atomic Ionization on cross section in μ_ν experiments

(once all possible final electronic states accounted for)

M.Voloshin, 23 Aug 2010;

K.Kouzakov, A.Studenikin, 26 Nov 2010;

- H.Wong et al, arXiv: 1001.2074 V3, 28 Nov 2010

GEMMA (2005-2008)

Germanium Experiment on measurement of Magnetic Moment of Antineutrino

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in: "Particle Physics on the Eve of LHC",
ed. A.Studenikin, World Scientific (Singapore),
p.112, 2009 (13th Lomonosov Conference) www.icas.ru

GEMMA (2005-2012)

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

Best world experimental limit 2012

!

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

A.Beda et al, Special issue on "Neutrino Physics" of Advances in High Energy Physics 2012, ID 350150

... further quite realistic prospects of the near future (V.Brudanin) :

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

3

… a bit of ν electromagnetic properties theory

3.1 ν vertex function

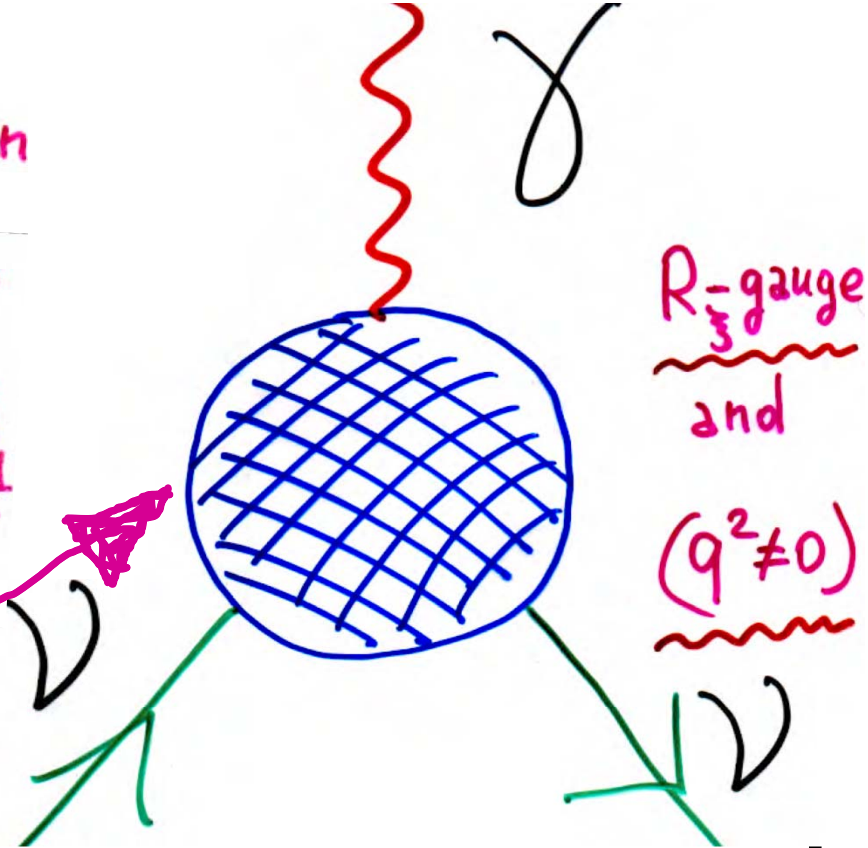
The most general study of the **massive neutrino** vertex function (including electric and magnetic form factors) in arbitrary R_ξ gauge in the context of the SM + SU(2)-singlet ν_R accounting for masses of particles in polarization loops

!

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

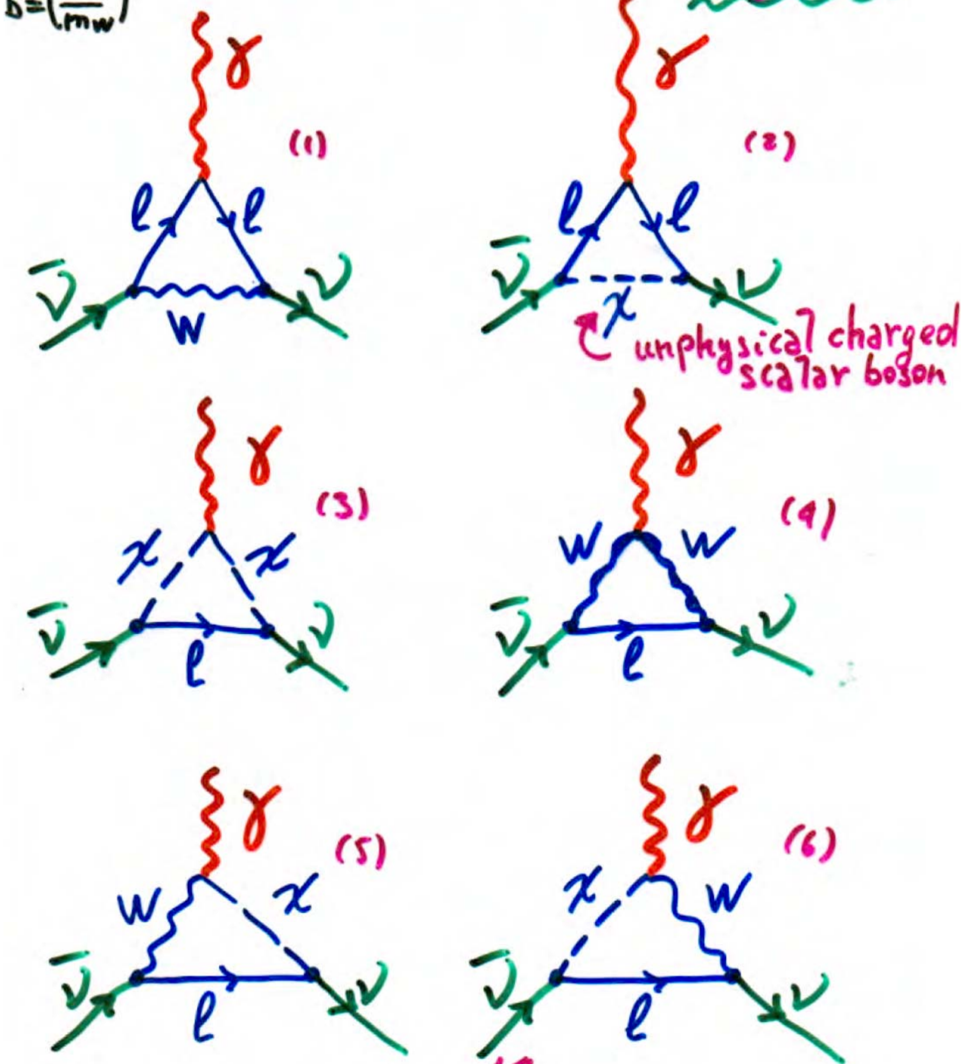
$$\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2)\, i\sigma_{\mu\nu} q^\nu - f_E(q^2)\, i\sigma_{\mu\nu} q^\nu \gamma_5 - f_A(q^2)\left(q^2\gamma_\mu - q_\mu \not{q}\right)\gamma_5$$

electric moment — anapole moment

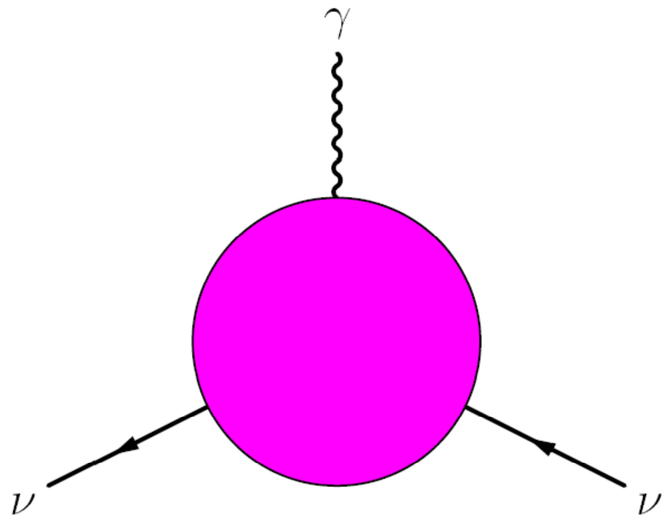
$a = \left(\frac{m_\ell}{m_W}\right)^2$, $b = \left(\frac{m_\nu}{m_W}\right)^2$

Proper vertices

R_ξ-gauge



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



$$\Lambda_\mu(q)$$

Contributions of proper vertices diagrams

(dimensional-regularization scheme)

- $$\Lambda_\mu^{(1)} = i\frac{eg^2}{2}\int\frac{d^Nk}{(2\pi)^N}\left[g^{\kappa\lambda}-(1-\alpha)\frac{k^\kappa k^\lambda}{k^2-\alpha M_W^2}\right]\times\frac{\gamma_\kappa^L(\not{p}\,'-\not{k}+m_\ell)\gamma_\mu(\not{p}-\not{k}+m_\ell)\gamma_\lambda^L}{[(p'-k)^2-m_\ell^2][(p-k)^2-m_\ell^2][k^2-M_W^2]},$$

- $$\Lambda_\mu^{(2)} = i\frac{eg^2}{2M_W^2}\int\frac{d^Nk}{(2\pi)^N}\frac{(m_\nu P_L-m_\ell P_R)(\not{p}\,'-\not{k}+m_\ell)\gamma_\mu(\not{p}-\not{k}+m_\ell)(m_\ell P_L-m_\nu P_R)}{[(p'-k)^2-m_\ell^2][(p-k)^2-m_\ell^2][k^2-\alpha M_W^2]},$$

- $$\Lambda_\mu^{(3)} = i\frac{eg^2}{2M_W^2}\int\frac{d^Nk}{(2\pi)^N}(2k-p-p')_\mu\frac{(m_\nu P_L-m_\ell P_R)(\not{k}+m_\ell)(m_\ell P_L-m_\nu P_R)}{[(p'-k)^2-\alpha M_W^2][(p-k)^2-\alpha M_W^2][k^2-m_\ell^2]},$$

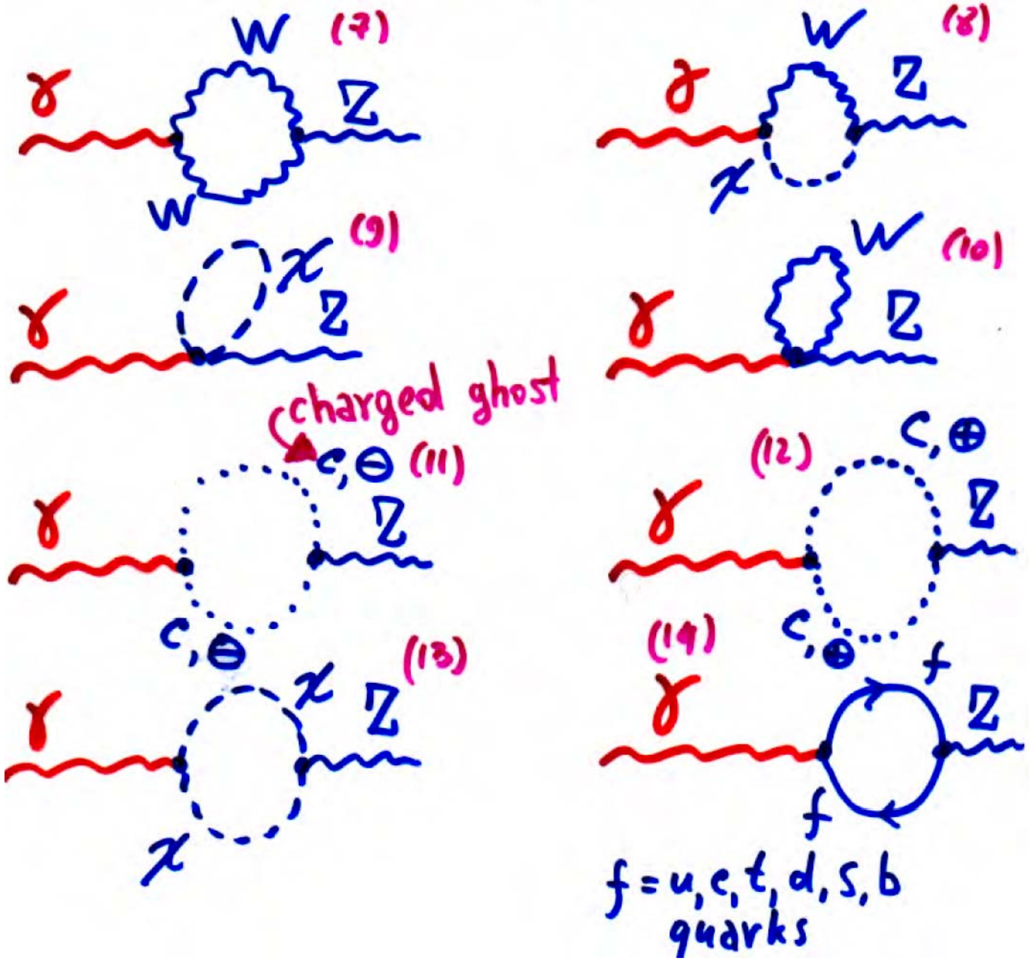
- $$\Lambda_\mu^{(4)} = i\frac{eg^2}{2}\int\frac{d^Nk}{(2\pi)^N}\gamma_\kappa^L(\not{k}+m_\ell)\gamma_\lambda^L\left[\delta_\beta^\kappa-(1-\alpha)\frac{(p'-k)^\kappa(p'-k)_\beta}{(p'-k)^2-\alpha M_W^2}\right]\left[\delta_\gamma^\lambda-(1-\alpha)\frac{(p-k)^\lambda(p-k)_\gamma}{(p-k)^2-\alpha M_W^2}\right]$$
$$\times\frac{\delta_\mu^\beta(2p'-p-k)^\gamma+g^{\beta\gamma}(2k-p-p')_\mu+\delta_\mu^\gamma(2p-p'-k)^\beta}{[(p'-k)^2-M_W^2][(p-k)^2-M_W^2][k^2-m_\ell^2]},$$

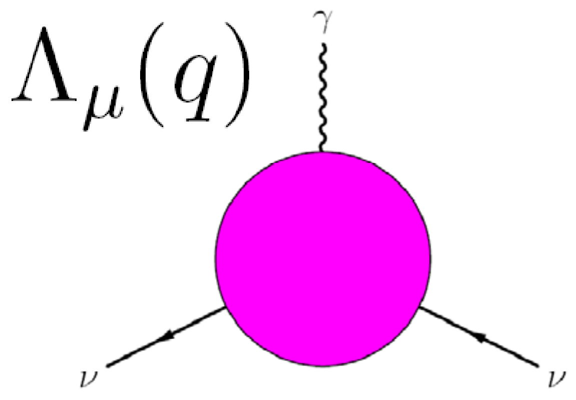
- $$\Lambda_\mu^{(5)+(6)} = i\frac{eg^2}{2}\int\frac{d^Nk}{(2\pi)^N}$$
$$\times\left\{\frac{\gamma_\beta^L(\not{k}-m_\ell)(m_\ell P_L-m_\nu P_R)}{[(p'-k)^2-M_W^2][(p-k)^2-\alpha M_W^2][k^2m_\ell^2]}\left[\delta_\mu^\beta-(1-\alpha)\frac{(p'-k)^\beta(p'-k)_\mu}{(p'-k)^2-\alpha M_W^2}\right]\right.$$
$$\left.-\frac{(m_\nu P_L-m_\ell P_R)(\not{k}-m_\ell)\gamma_\beta^L}{[(p'-k)^2-\alpha M_W^2][(p-k)^2-M_W^2][k^2-m_\ell^2]}\left[\delta_\mu^\beta-(1-\alpha)\frac{(p-k)^\beta(p-k)_\mu}{(p-k)^2-\alpha M_W^2}\right]\right\}$$

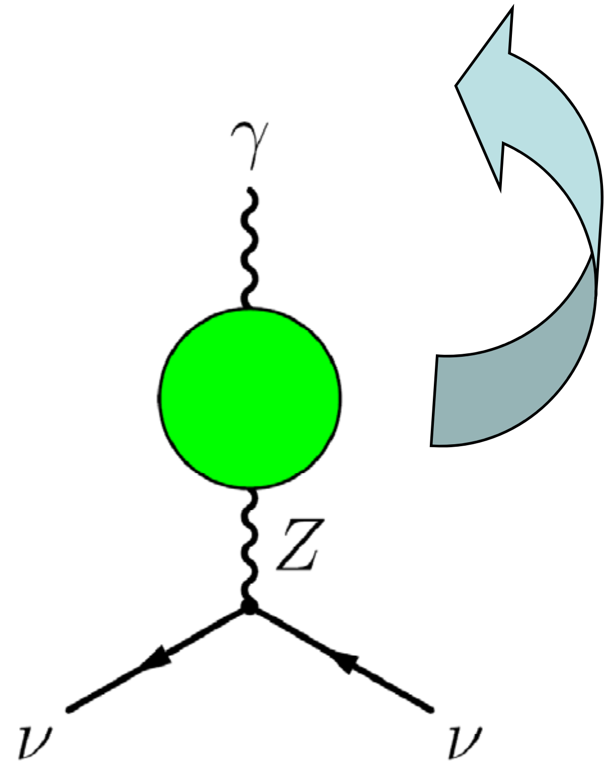
$$\Lambda^{j}_{\mu}(q) = \frac{g}{2\cos\theta_W}\,\Pi^{(j)}_{\mu\nu}(q)\,\frac{1}{q^2-M_Z^2}$$

$$\times\left\{ g^{\nu\alpha} - (1-\alpha_Z)\frac{q^\nu q^\alpha}{q^2-\alpha_Z M_Z^2}\right\}\gamma^L_\alpha,\ j=7,\dots,14$$

γ-Z self-energy diagrams







$\gamma - Z$ self-energy diagrams

Direct calculations of complete set of one-loop contributions to ν vertex function in minimally extended Standard Model

for a massive Dirac neutrino:

M.Dvornikov, A.Studenikin, PRD, 2004

… in case CP conservation

- $\Lambda_\mu(q) \Rightarrow f_Q(q^2),\ f_M(q^2),\ f_E(q^2),\ f_A(q^2)$
- Electric charge $f_Q(0) = \mathbf{0}$ and is gauge-independent
- Magnetic moment $f_M(0)$ is finite and gauge-independent
- Gauge and $\boldsymbol{q}\text{x}\boldsymbol{q}$ dependence … ⇒

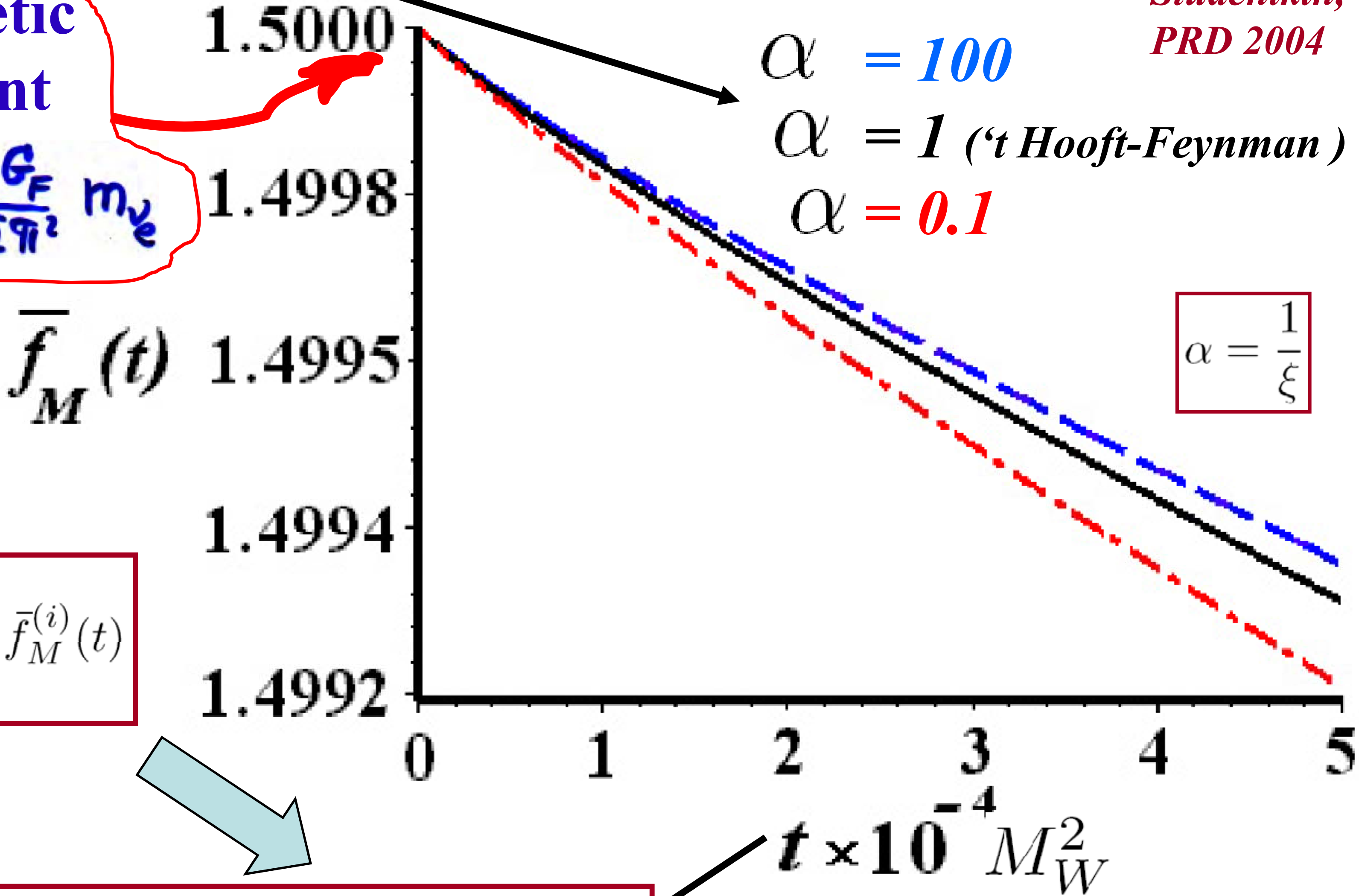
ν

Gauge and q x q dependence …

Dvornikov, Studenikin, PRD 2004

ν **magnetic moment**

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



$$\bar{f}_M(t) = \sum_{i=1}^{6} \bar{f}_M^{(i)}(t)$$

$$f_M(q^2) = \frac{eG_F}{4\pi^2\sqrt{2}} m_\nu \sum_{i=1}^{6} \bar{f}_M^{(i)}(q^2)$$

ν **dipole magnetic form factor**

Magnetic moment dependence

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

on neutrino mass

3.2

Calculation of ν magnetic moment (massive ν, arbitrary R_ξ - gauge)

Dvornikov, Studenikin, PRD 2004

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

magnetic moment

$$\mu(a,b,\alpha) = f_M(q^2=0)$$

two mass parameters

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

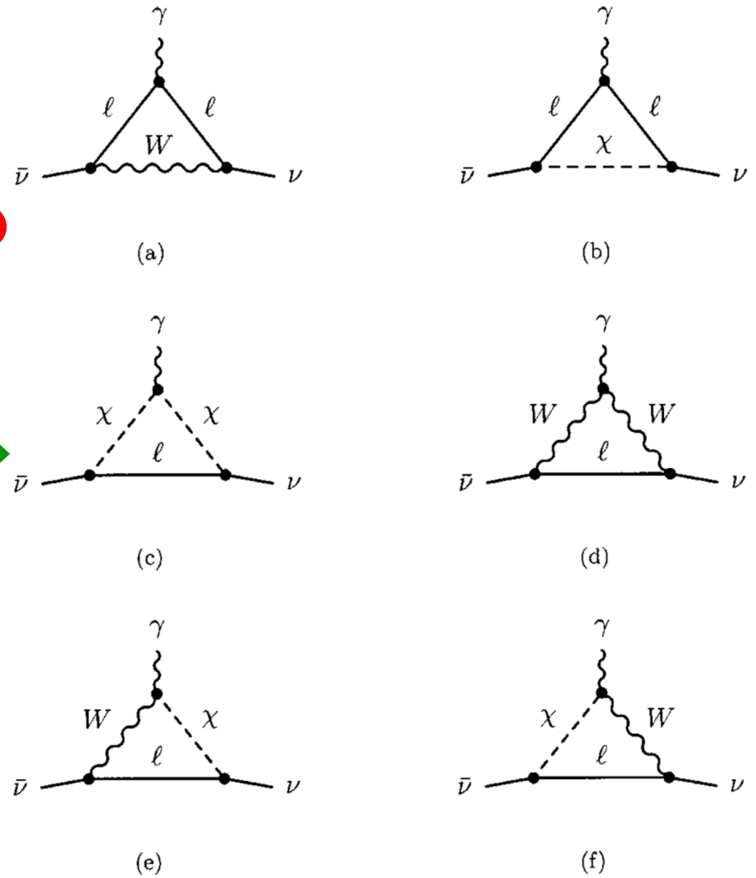
$$\mu(a,b,\alpha) = \sum_{i=1}^{6} \mu^{(i)}(a,b,\alpha)$$

and gauge-fixing parameter

$$\alpha = \frac{1}{\xi}$$

$\xi = 0$ - unitary gauge, $\xi = 1$ - 't Hooft-Feynman gauge

Proper vertices



ν magnetic moment

(for arbitrary neutrino mass, heavy neutrino…)

- LEP data ⇒

only 3 light νs coupled to Z°,

for any additional neutrino

$$m_{\nu} \geq 45 \ Gev$$

$m_\nu \ll m_e \ll M_W$ **light** ν

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

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

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

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

$m_e \ll m_\nu \ll M_W$ **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

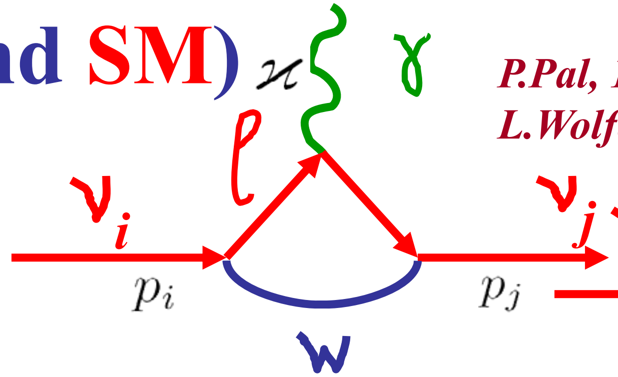
$$\mu_\nu = \frac{eG_F}{8\pi^2\sqrt{2}} m_\nu$$

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

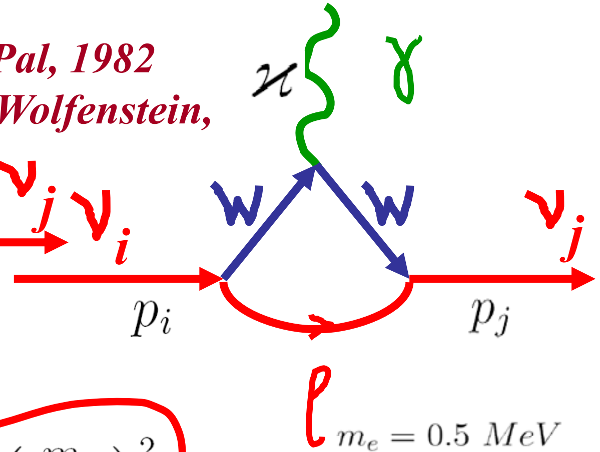
. . . μ_ν *in case of mixing . . .*

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

- **Majorana neutrino** **only for** $i \neq j$

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

or

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

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

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

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

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

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

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

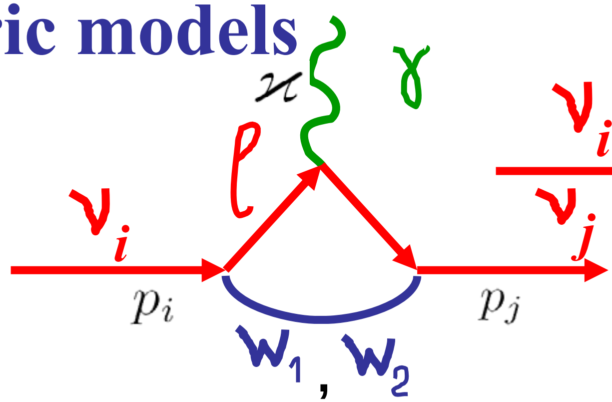
Lee, Shrock, Fujikawa, 1977

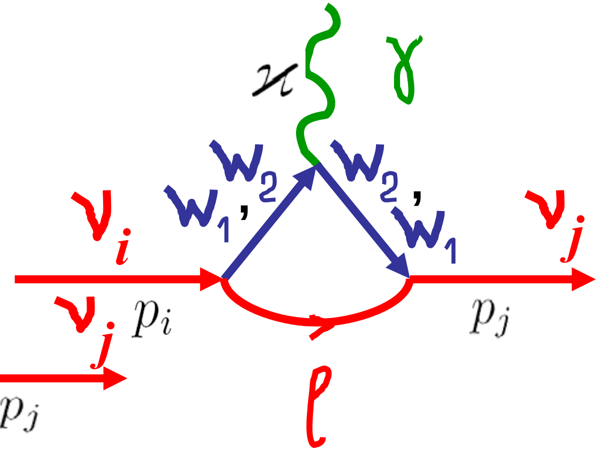
- *no GIM cancellation*
- μ_{ii}^D - to leading order - independent on U_{li} and $m_{l=e,\mu,\tau}$
- $\mu_e^2 = \sum_{i=1,2,3} \mid U_{ie}\mid^2 \mu_{ii}^2$ …possibility to measure fundamental μ_{ii}^D

$\mu_{ii}^D = 0$ 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

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

… charged lepton mass … *… neutrino mass …*

...the present status...

to have visible $m_\nu \neq 0$

is not an easy task for

theoreticians

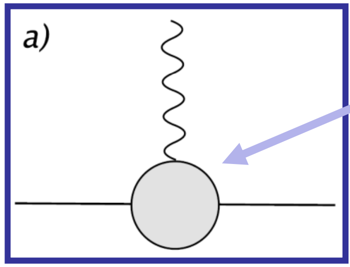
and experimentalists

3.3 Naïve relationship between the size of m_ν and μ_ν

… problem to get large μ_ν and still acceptable m_ν

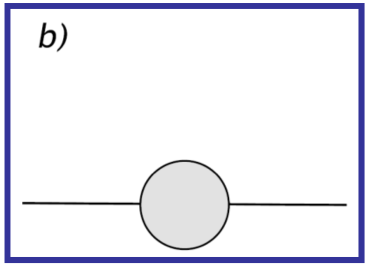
If μ_ν is generated by physics beyond the SM at energy scale Λ,

P.Vogel e.a., 2006



then $\mu_\nu \sim \frac{eG}{\Lambda}$, …combination of constants and loop factors…

contribution to m_ν given by

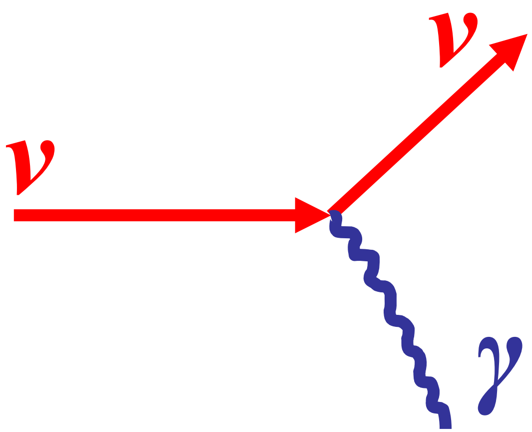


, then $m_\nu \sim G\Lambda$

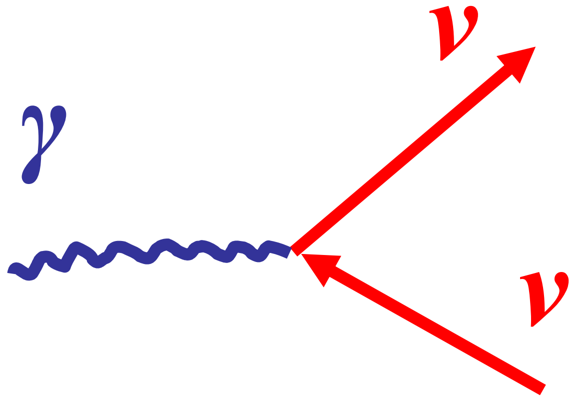
$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \frac{\mu_\nu}{10^{-18}\mu_B}[\Lambda(\mathrm{TeV})]^2 \ \mathrm{eV}$$

Voloshin, 1988; Barr, Freire, Zee, 1990

Neutrino–photon couplings

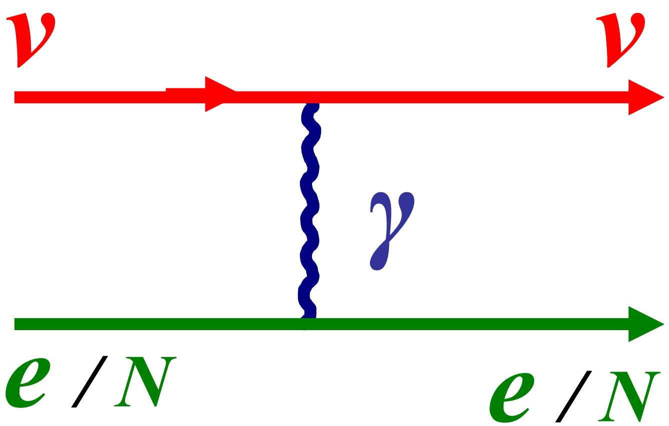


ν decay, Cherenkov radiation

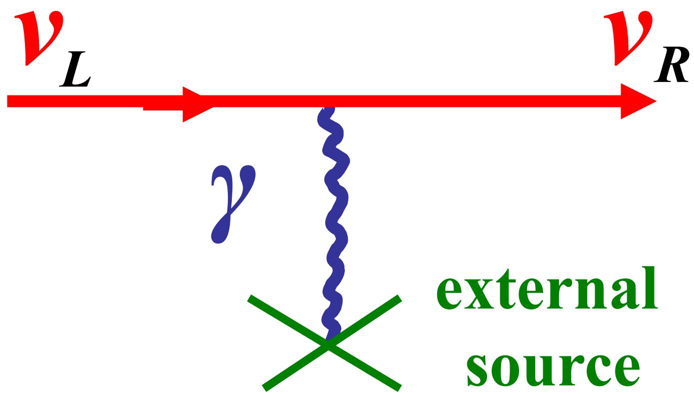


γ decay in plasma

!!!



Scattering



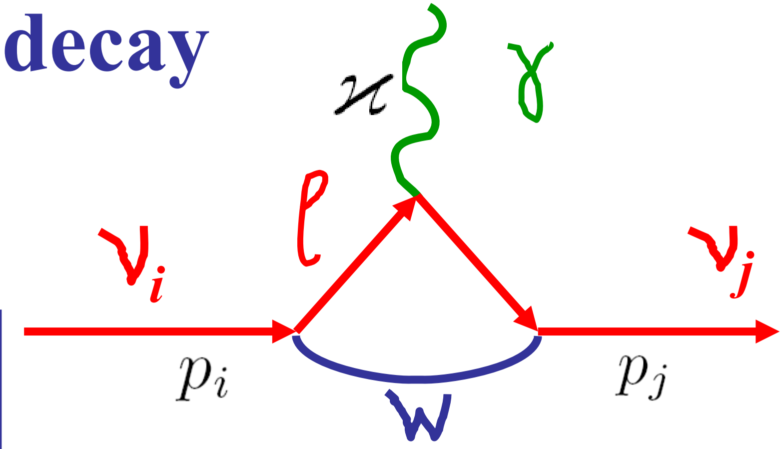
Spin precession

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,
  2) SN 1987A ν burst (all flavours),
  3) spectral distortion of CMBR

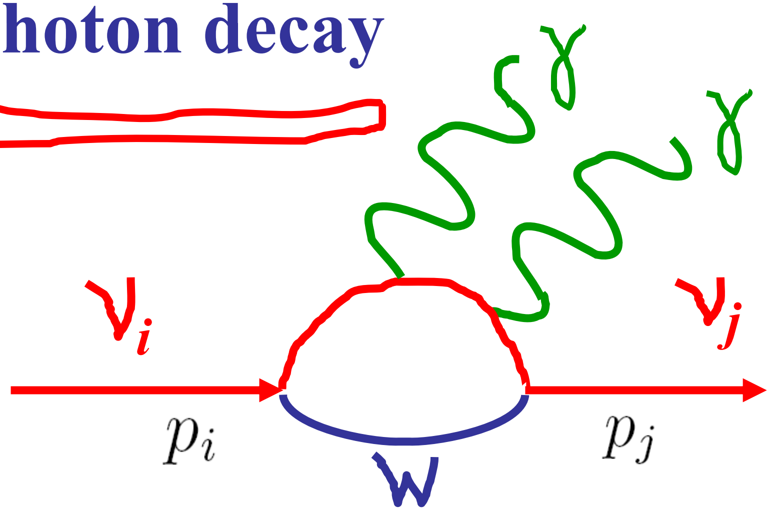
Raffelt 1999
Kolb, Turner 1990;
Ressell, Turner 1990

3.8

Neutrino radiative two-photon decay

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

$m_i > m_j$



fine structure constant $\ll 1$

$$\Gamma_{\nu_i \to \nu_j + \gamma + \gamma} \sim \frac{\alpha_{QED}}{4\pi} \Gamma_{\nu_i \to \nu_j + \gamma}$$

$$f(r_l) \approx \frac{3}{2}\left(1 - \frac{1}{2}\left(\frac{m_l}{m_W}\right)^2\right) \to (m_i/m_l)^2$$

… there is no GIM cancellation…

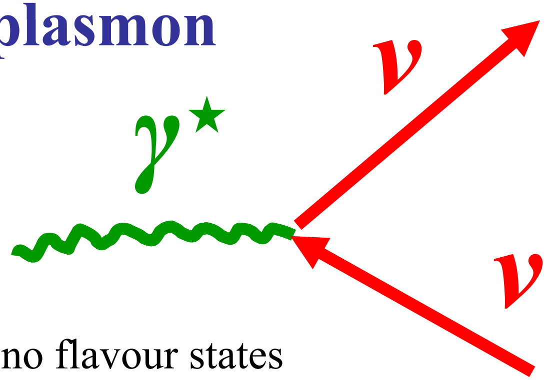
Nieves, 1983; Ghosh, 1984

… can be of interest for certain range of ν masses…

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

Energy-loss rate per unit volume

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

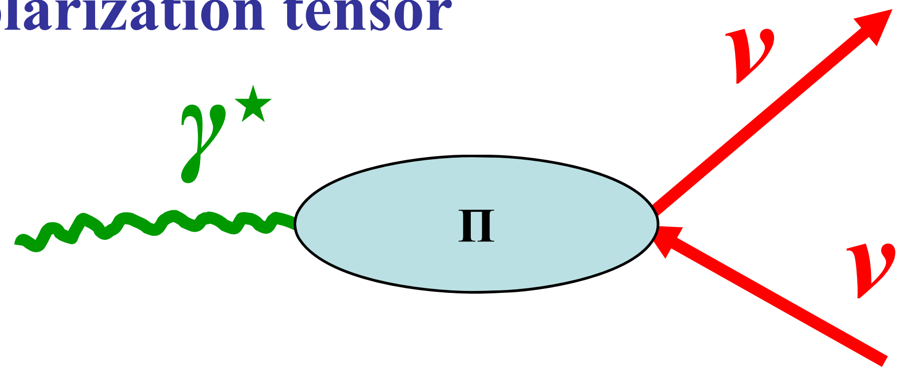
$$\mu^2 \to \sum_{a,b}\left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2\right)$$

distribution function of plasmons

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

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 (≤5% in Q)

! *… best astrophysical limit on ν magnetic moment…*

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

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

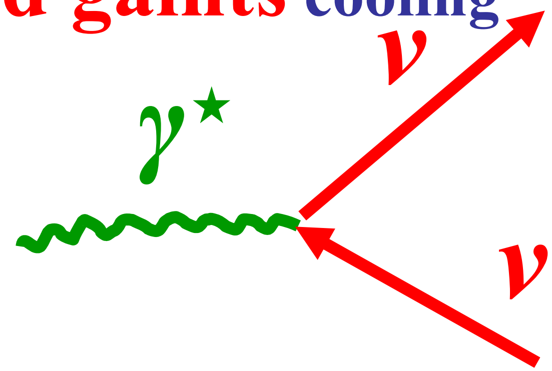
G.Raffelt, PRL 1990

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

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

Direct and Indirect influence of electromagnetic fields on ν

Direct

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

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

Indirect

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 …

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

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

Twisting magnetic field $B = |\mathbf{B}_\perp| e^{i\phi(t)}$ ⟸ **for solar** ν **etc …**

ν **evolution equation**

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

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

!

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

… Flavour oscillations ⟺ Spin oscillations…

$$P_{\nu_e\nu_\mu} = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} z \quad \Longleftrightarrow \quad P_{\nu_L\nu_R} = \sin^2\beta \, \sin^2\Omega z$$

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

$$\sin^2 2\theta \quad \Longleftrightarrow \quad \frac{(\mu_{e\mu}B)^2}{(\mu_{e\mu}B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2} = \sin^2\beta$$

$$\frac{\Delta m^2}{4E} \quad \Longleftrightarrow \quad \sqrt{(\mu_{e\mu}B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2}$$

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

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

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

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

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

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

Resonance amplification of oscillations in matter:

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

Akhmedov, 1988
Lim, Marciano

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

- ⊛ $\nu_\odot$ problem — $\nu_L \overset{B}{\leftrightarrow} \nu_R$

  Cisneros, 1971

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

  ⊙ twisting B { Smirnov, 1991; Akhmedov, Petcov, Smirnov, 1993

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

  …subdominant contribution to LMA – MSW solution… $\nu_\odot$

- ⊛ Supernova $\nu_L \overset{B}{\leftrightarrow} \nu_R$

  Dar, 1987

  Fujikawa, Shrock, 1988

  Voloshin, 1988

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

Criteria of significant importance of ν spin oscillations in $B_\perp$: $\nu_L \overset{B_\perp}{\Longleftrightarrow} \nu_R$

1) amplitude of oscillations must be far from zero

$$B \geq B_{cr} = \frac{1}{2\tilde{\mu}} \left| \frac{\Delta m_\nu^2}{2E_\nu} - \sqrt{2} G_F n_{eff} + \dot{\phi} \right|$$

2) ν path length in medium must be large

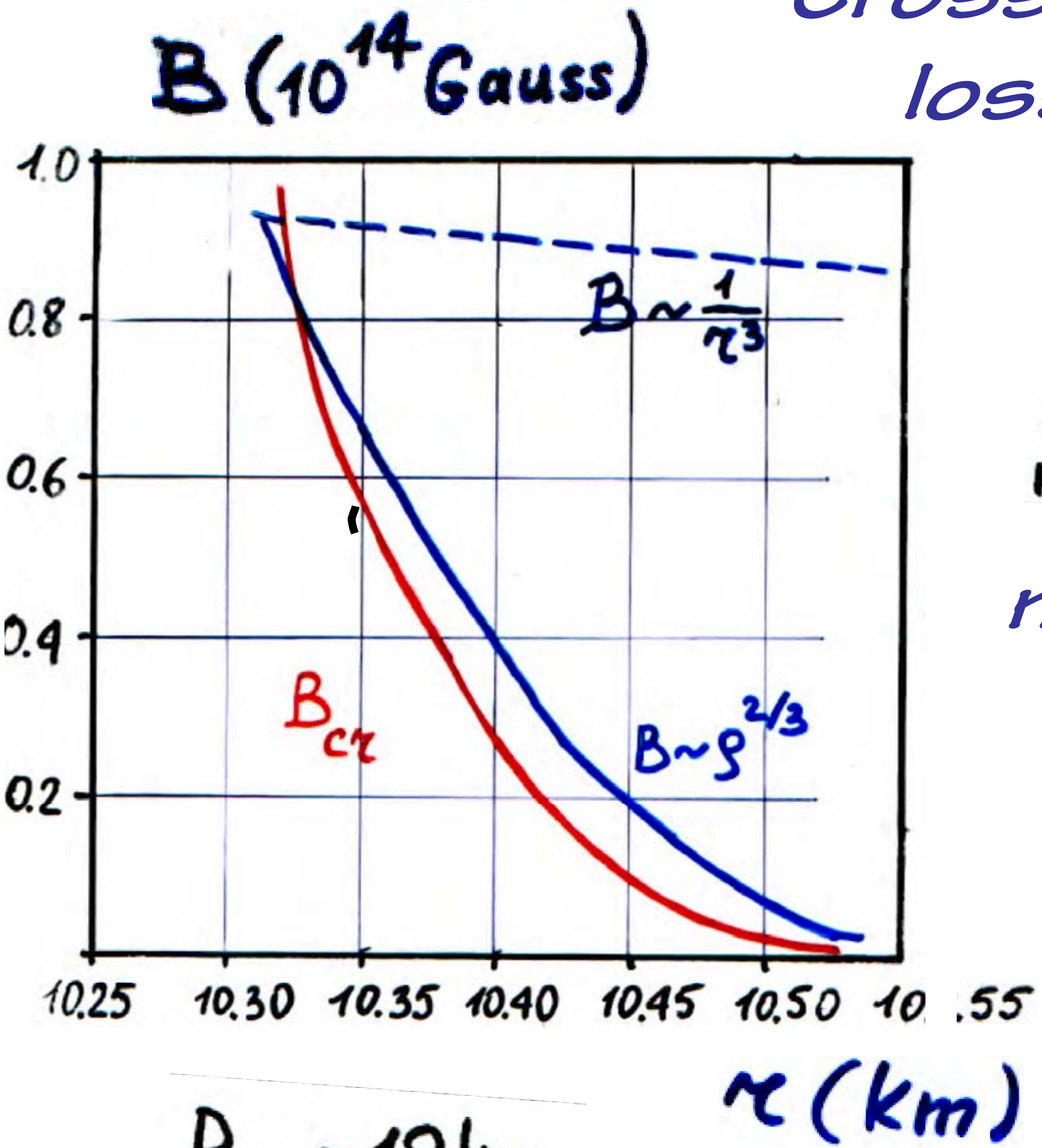
$$x \geq L_{\rm eff}/2$$

G.Likhachev, A.S., JETP 81 (1995) 419

A.S., Phys.Atom.Nucl. 67 (2004) 993

$$L_{\rm eff} = 2\pi \left[\left(\frac{\Delta m_\nu^2}{2E} A - \sqrt{2} G_{\rm F} n_{\rm eff} + \dot{\phi} \right)^2 + (2\tilde{\mu} B)^2 \right]^{-1/2}$$

"Cross-boundary effect": losses of 50% of ν



$R_{NS} \sim 10$ km

$\nu_L \rightarrow \nu_R$

active neutrino

sterile neutrino

near NS surface

A. Egorov, G. Likhachev, A. Studenikin, 1995, 1997

JETP 81 (1995) 419;

A. Studenikin, Phys.Atom.Nucl. 67 (2004) 993

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 …

β-decay of neutron in magnetic field

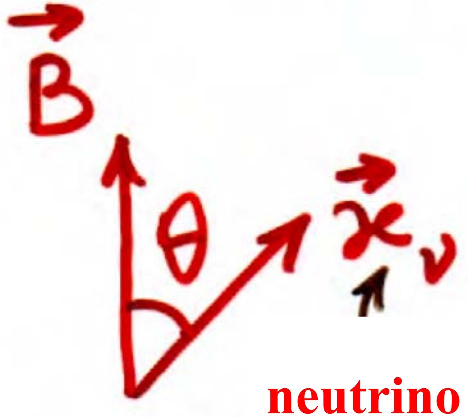
{Birth of ν astrophysics in B}

$n \xrightarrow{B} p + e + \tilde{\nu}_e$

- * L. Korovina, "β-decay of polarized neutron in magnetic field", **Sov.Phys.J., # 6 (1964) 86**
- * I. Ternov, B. Lysov, L. Korovina, **Mosc.Univ.Bull.,Phys.,Astron., #5 (1965) 58** "On the theory of neutron β-decay in external magnetic field",
- * J. Matese, R. O'Connell, "Neutron beta decay in a uniform magnetic field", **Phys.Rev.180 (1969) 1289**
- * L. Fassio-Canuto, "Neutron beta decay in a strong magnetic field" **Phys.Rev.187 (1969) 2141**
- * G. Greenstein, **Nature 223 (1969) 938**

(*) Asymmetry in $\tilde{\nu}$ emission

$$\frac{W(B)}{W_0} = \frac{1}{2}\int \sin\theta_\nu \, d\theta_\nu \left\{ 1 + \frac{2(\alpha^2+\alpha)}{1+3\alpha^2} S_n \cos\theta_\nu - 4.9\,\frac{eB}{\Delta^2}\left(\frac{\alpha^2-1}{1+3\alpha^2}\cos\theta_\nu + \frac{2(\alpha^2-\alpha)}{1+3\alpha^2} S_n \right) \right\}$$



neutrino momentum

⇒ astrophysical applications

K.Kouzakov, A.Studenikin
Phys.Rev.C 72 (2005) 015502

$n \xrightarrow{B} pe + \tilde{\nu}_e$

“Bound-state beta-decay of neutron in strong magnetic field”

$$\text{Usual (continuum-state) } \beta \text{ decay} \qquad n \to p + e^- + \bar{\nu}_e$$

$$\text{"Rare" (bound-state) } \beta \text{ decay} \qquad n \to (pe^-) + \bar{\nu}_e$$

R. Daudel, M. Jean, and M. Lecoin, J. Phys. Radium **8**, 238 (1947)

$$\frac{w_b}{w_c} \cong 4.2 \times 10^{-6}$$

$$\tau_c \sim 15 \text{ min}$$

$$\tau_b \sim 7 \text{ years}$$

J.N. Bahcall, Phys. Rev. **124**, 495 (1961) [Dirac equation]

L.L. Nemenov, Sov. J. Nucl. Phys. **15**, 582 (1972) [Schrödinger equation]

X. Song, J. Phys. G: Nucl. Phys. **13**, 1023 (1987) [Bethe-Salpeter equation]

K.A. Kouzakov and A.I. Studenikin, Phys. Rev. C **72**, 015502 (2005)

http://arxiv.org/hep-ph/0412134

Summary

First analysis of bound-state β decay in a strong magnetic field ($B \sim 10^{13}$-10^{18} G)

✓ $w_b/w_c \sim 0.1$-0.4 in contrast to the field-free case, where $w_b/w_c \sim 10^{-6}$

✓ A logarithmiclike behavior

$$w_b/w_c \propto \log_{10}(B/B_e) + b \quad (b>0)$$

Outlook: Astrophysical applications?

3.12

ν e.m. form factors are affected by matter and B

- magnetic moment $\mu_\nu = \mu_\nu(B)$

Egorov, Studenikin 1999

Borisov, Zhukovsky, Kurilin, Ternov, 1985

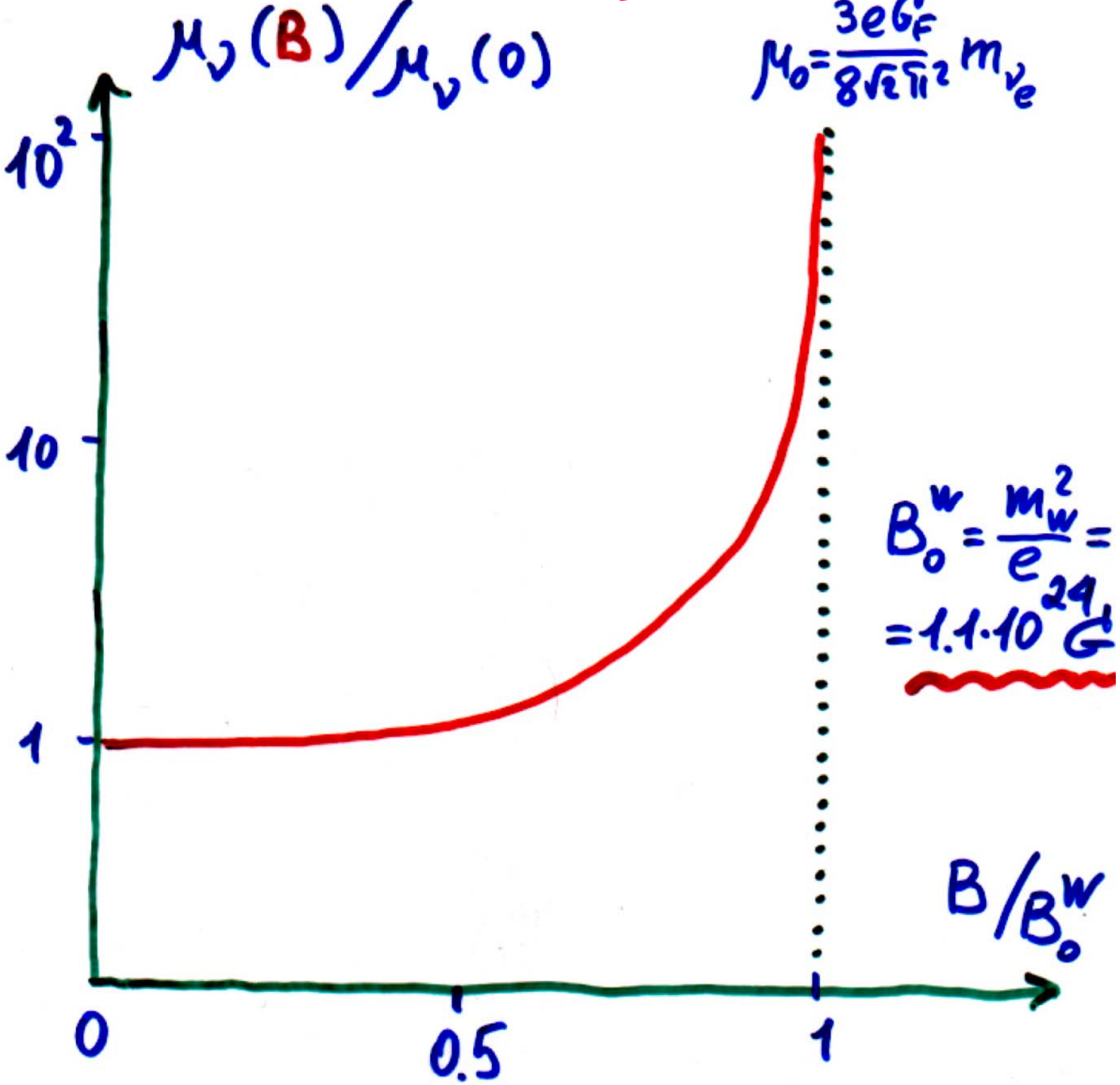
- induced electric charge of ν in magnetized matter

Oraevsky, Semikoz, Smorodinsky, 1986

Bhattacharaya, Ganguly, Konar, 2002

Nieves, 2003

Neutrino magnetic moment



Borisov, Zhukovsky, Kurilin, Ternov, 1985;

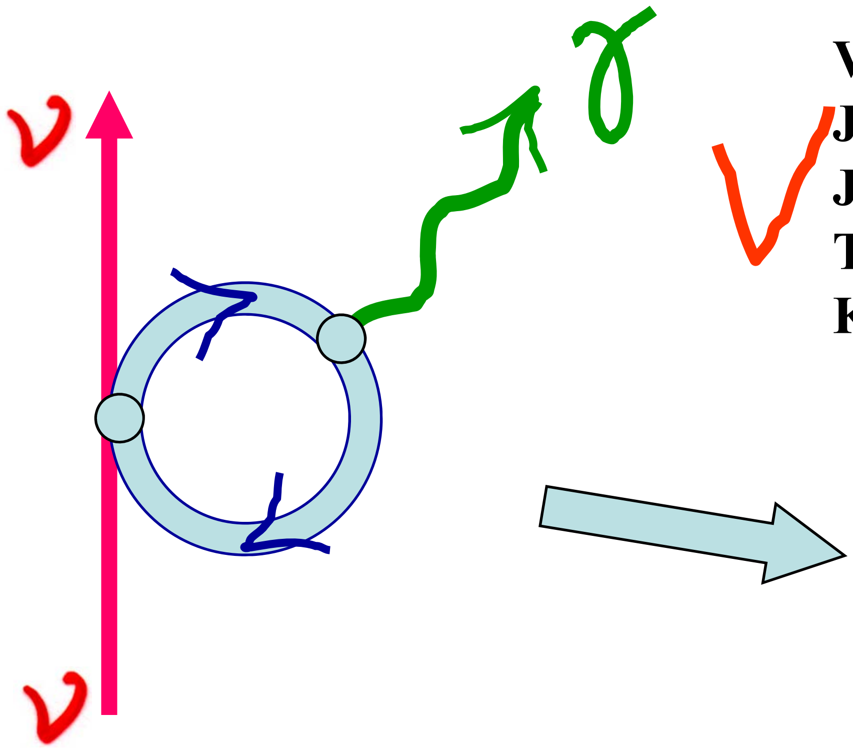
Masood, Perez Rojas, Gaitan, Rodrigues-Romo, 1999

ν "effective electric charge" in magnetized plasma

- νs do not couple with γs 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

New mechanism of electromagnetic radiation

Spin light of neutrino in matter

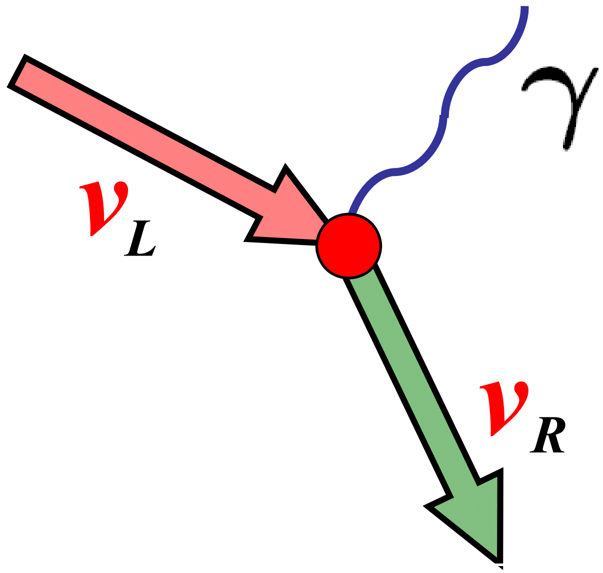
$SL\nu$

"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***

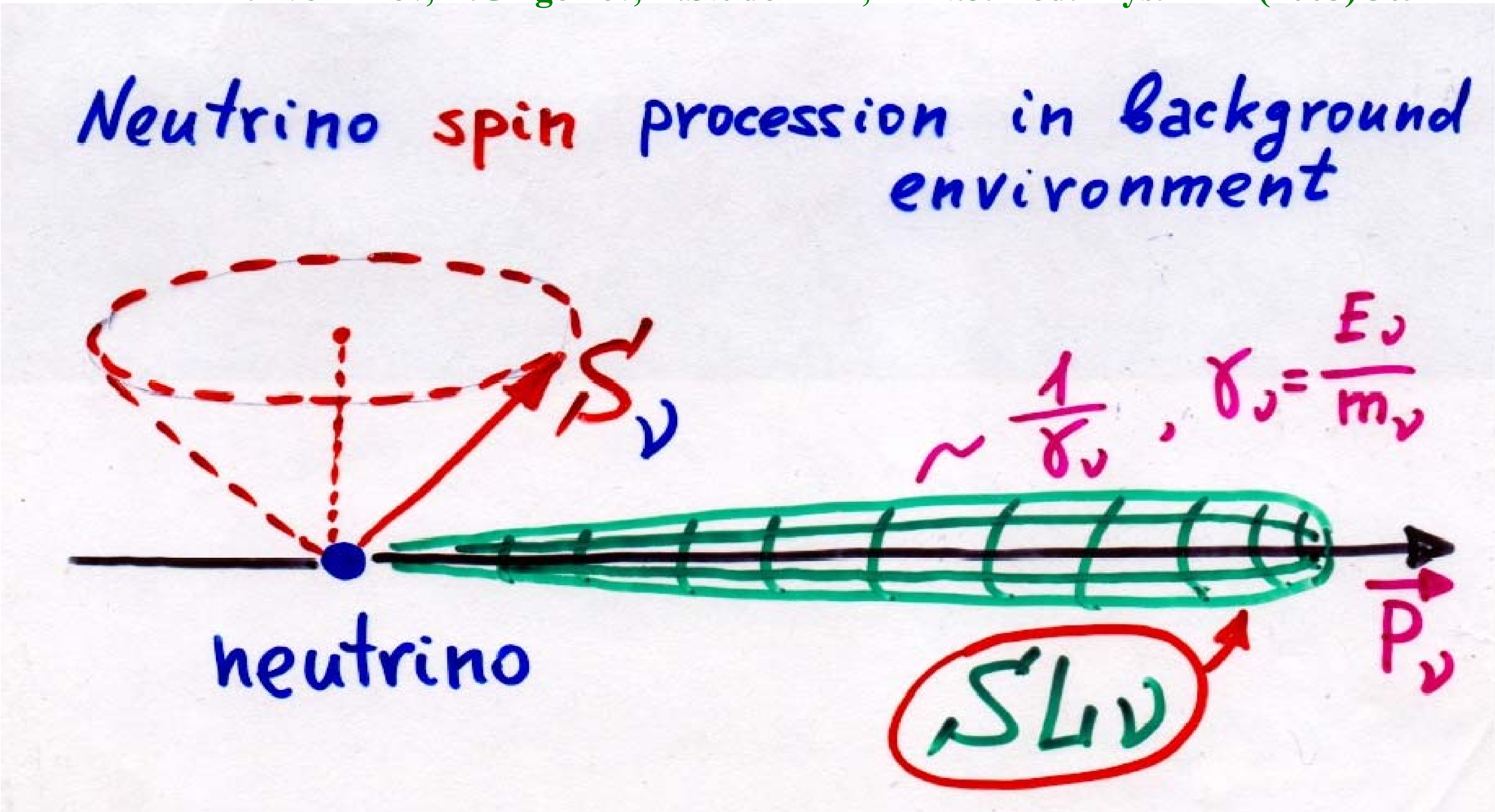
- **new mechanism** of the electromagnetic process stimulated by the presence of matter, in which neutrino with **non-zero magnetic moment** emits light

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.Gen. 39 (2006) 6769
A.S., J.Phys.A: Math.Theor. 41 (2008) 16402

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:

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

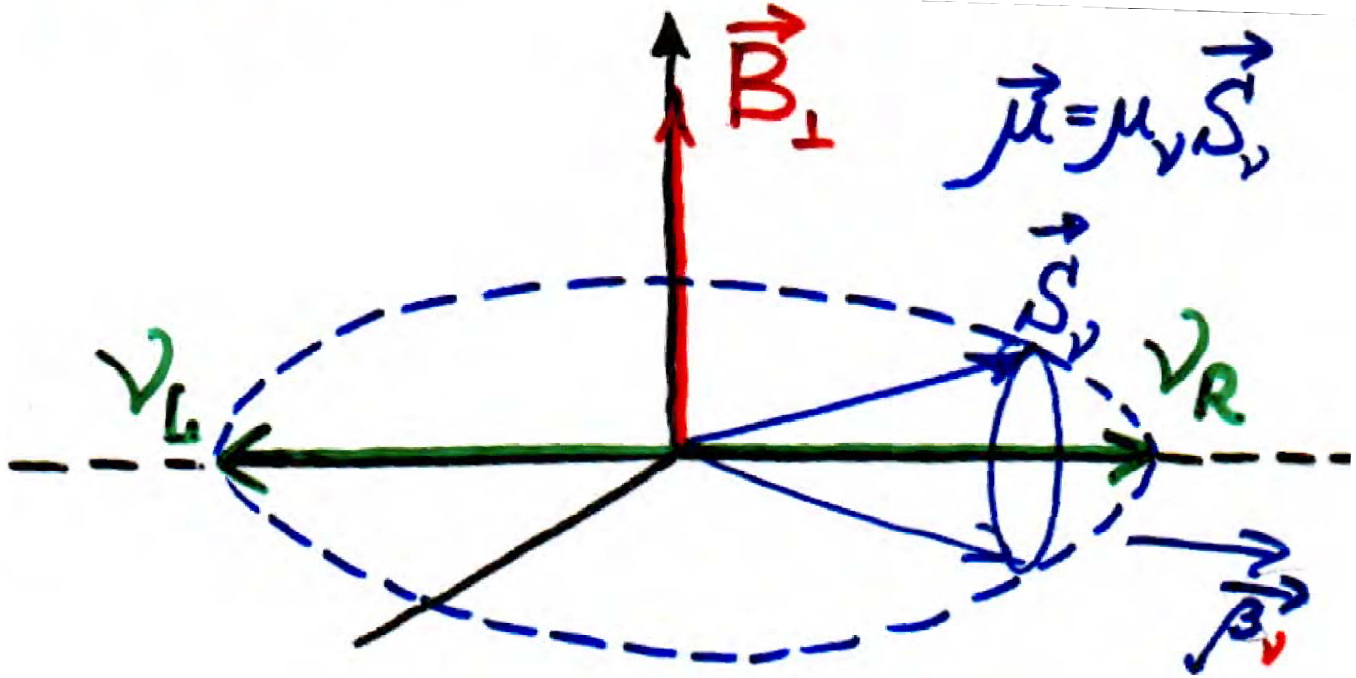
- *Neither **s** nor **π** nor **V** contributes to spin evolution*

- **Electromagnetic interaction**

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

- **SM weak interaction**

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



$$\frac{d\vec{S}_\nu}{dt} = 2\mu_\nu [\vec{S}_\nu \times \vec{B}] + 2\mu_\nu [\vec{S}_\nu \times \vec{G}]$$

electromagnetic interacton with e.m. field

weak interaction with matter

New mechanism of electromagnetic radiation

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

Analogies with:

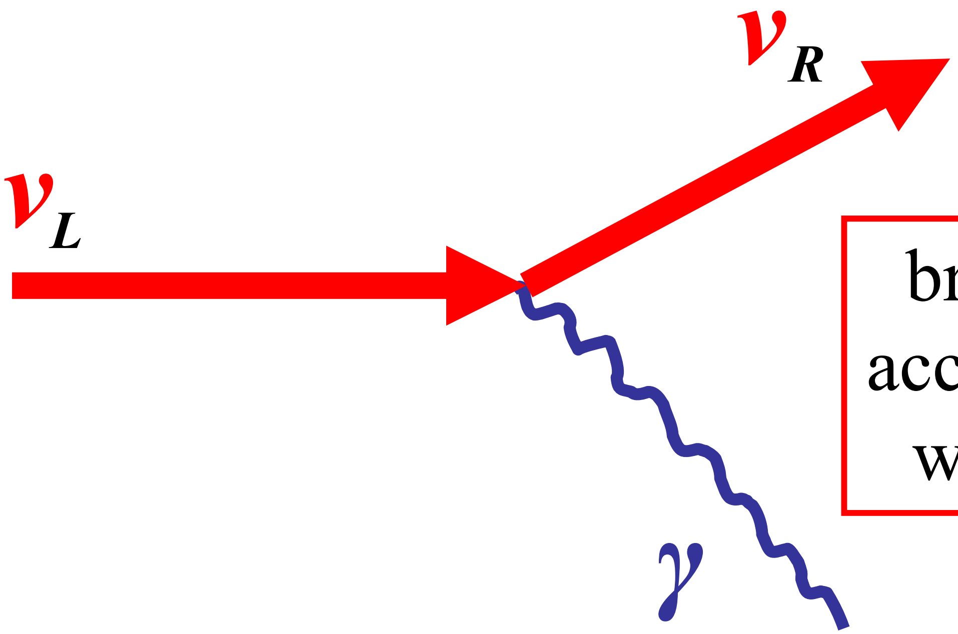
* classical electrodynamics

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 (II)



broad neutrino lines account for interaction with environment

"Spin light of neutrino in matter"

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

ν and e in matter being treated within «method of exact solutions» of quantum wave equations

A.Studenikin, A.Ternov,
Phys.Lett.B 608 (2005) 107;
hep-ph/0410297,
"Neutrino quantum states in matter";
hep-ph/0410296,
"Generalized Dirac-Pauli equation and neutrino quantum states in matter"

A.Grigoriev, A.Studenikin, A.Ternov,
Phys.Lett.B 608 622 (2005) 199

A.Studenikin, J.Phys.A: Math.Theor. 41 (2008) 16402,"Method of wave equations exact solutions in studies of neutrino and electron interactions in dense matter";

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

J.Phys.A: Math.Gen.39 (2006) 6769

I.Balantsev, Yu.Popov, A.Studenikin,
J.Phys.A: Math.Theor. 44 (2011) 255301,
"On a problem of relativistic particles motion in a strong magnetic field and dense matter"

- ν *energy quantization in rotating matter …*

Method of exact solutions

Modified **Dirac equations** for ν (and e)
(containing the correspondent effective matter potentials)

+

exact solutions (particles wave functions)

⇓

a basis for investigation of different phenomena which can proceed when **neutrinos** and **electrons** move in dense media
(**astrophysical** and **cosmological** **environments**).

«method of exact solutions »

Interaction of particles in external electromagnetic fields

(**Furry representation** in quantum electrodynamics)

$$e \xrightarrow{\mathrm{B}_\perp} e + \gamma$$

synchrotron radiation

Potential of electromagnetic field

$$A_\mu(x) = A_\mu^q(x) + A_\mu^{ext}(x),$$

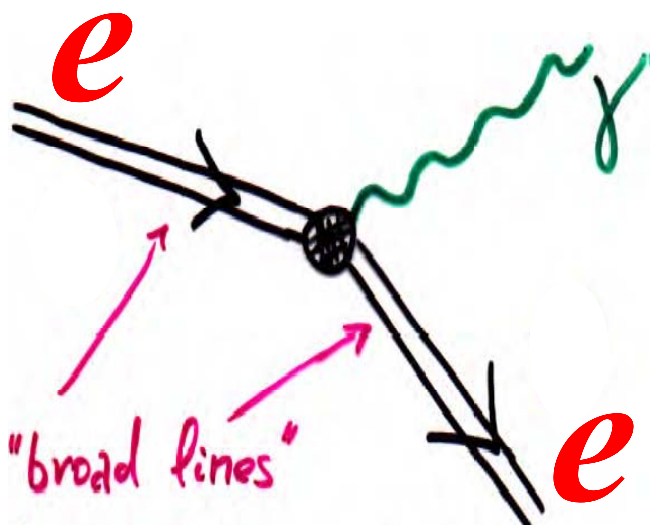
quantized part of potential

evolution **operator**

$$U_F(t_1, t_2) = Texp\left[- i \int_{t_1}^{t_2} j^\mu(x) A_\mu^q(x) dx \right],$$

charged particles **current**

$$j_\mu(x) = \frac{e}{2}\left[\bar{\Psi}_F \gamma_\mu, \Psi_F\right],$$



Dirac equation in **external classical (non-quantized) field** $A_\mu^{ext}(x)$

$$\left\{ \gamma^\mu \Big(i\partial_\mu - eA_\mu^{ext}(x) \Big) - m_e \right\} \Psi_F(x) = 0$$

…beyond perturbation series expansion,
strong fields and non linear effects…

Modified Dirac equation for neutrino in matter

Addition to the vacuum neutrino Lagrangian

$$\Delta L_{eff} = \Delta L_{eff}^{CC} + \Delta L_{eff}^{NC} = -f^{\mu}\Big(\bar{\nu}\gamma_{\mu}\frac{1+\gamma^5}{2}\nu\Big)$$

matter current

where $$f^{\mu} = \frac{G_F}{\sqrt{2}}\Big((1+4\sin^2\theta_W)j^{\mu} - \lambda^{\mu}\Big)$$

matter polarization

$$\Big\{i\gamma_{\mu}\partial^{\mu} - \frac{1}{2}\gamma_{\mu}(1+\gamma_5)f^{\mu} - m\Big\}\Psi(x) = 0$$

A.Studenikin, A.Ternov, hep-ph/0410297; ***Phys.Lett.B* 608 (2005) 107**

It is supposed that there is a macroscopic amount of electrons in the scale of a neutrino de Broglie wave length. Therefore, **the interaction of a neutrino with the matter (electrons) is coherent.**

L.Chang, R.Zia,'88; J.Panteleone,'91; K.Kiers, N.Weiss, M.Tytgat,'97-'98; P.Manheim,'88; D.Nötzold, G.Raffelt,'88; J.Nieves,'89; V.Oraevsky, V.Semikoz, Ya.Smorodinsky,89; W.Naxton, W-M.Zhang'91; M.Kachelriess,'98; A.Kusenko, M.Postma,'02.

This is the most general equation of motion of a neutrino in which the effective potential accounts for both the **charged** and **neutral-current** interactions with the background matter and also for the possible effects of the matter **motion** and **polarization**.

Neutrino wave function in matter (II)

$$\Psi_{\varepsilon,\mathbf{p},s}(\mathbf{r},t)=\frac{e^{-i(E_\varepsilon t-\mathbf{pr})}}{2L^{\frac{3}{2}}}\begin{pmatrix}\sqrt{1+\frac{m}{E_\varepsilon-\alpha m}}\sqrt{1+s\frac{p_3}{p}}\\ s\sqrt{1+\frac{m}{E_\varepsilon-\alpha m}}\sqrt{1-s\frac{p_3}{p}}\;\;e^{i\delta}\\ s\varepsilon\eta\sqrt{1-\frac{m}{E_\varepsilon-\alpha m}}\sqrt{1+s\frac{p_3}{p}}\\ \varepsilon\eta\sqrt{1-\frac{m}{E_\varepsilon-\alpha m}}\sqrt{1-s\frac{p_3}{p}}\;\;e^{i\delta}\end{pmatrix}$$

A.Studenikin, A.Ternov, hep-ph/0410297;
***Phys.Lett.B* 608 (2005) 107;**

$$\eta=\text{sign}\left(1-s\alpha\frac{m}{p}\right),\ \delta=\arctan\left(p_2/p_1\right)$$

A.Grigoriev, A.Studenikin, A.Ternov,
***Phys.Lett.B* 622 (2005) 199**

$$E_\varepsilon-\alpha m=\varepsilon\sqrt{\mathbf{p}^2\left(1-s\alpha\frac{m}{p}\right)^2+m^2}$$

The quantity $\varepsilon=\pm 1$ splits the solutions into the two branches that in the limit of vanishing matter density, $\alpha\to 0,$ reproduce the positive and negative-frequency solutions, respectively.

Quantum theory of spin light of neutrino (I)

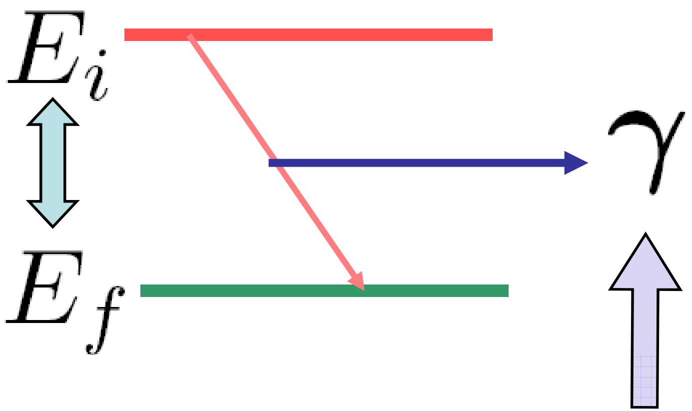
Quantum treatment of *spin light of neutrino* in matter
shows that this process originates from the **two subdivided phenomena:**

$SL\nu$

the **shift** of the neutrino **energy levels** in the presence of the background matter, which is different for the two opposite **neutrino helicity states**,

$$E = \sqrt{\mathbf{p}^2\left(1 - s\alpha\frac{m}{p}\right)^2 + m^2} + \alpha m$$

$$s = \pm 1$$



the radiation of the photon in the process of the neutrino transition from the **"excited" helicity state** to the **low-lying helicity state** in matter

A.Studenikin, A.Ternov, Phys.Lett.B 608 (2005) 107;
A.Grigoriev, A.Studenikin, A.Ternov, Phys.Lett.B 622 (2005) 199;
Grav. & Cosm. 14 (2005) 132;

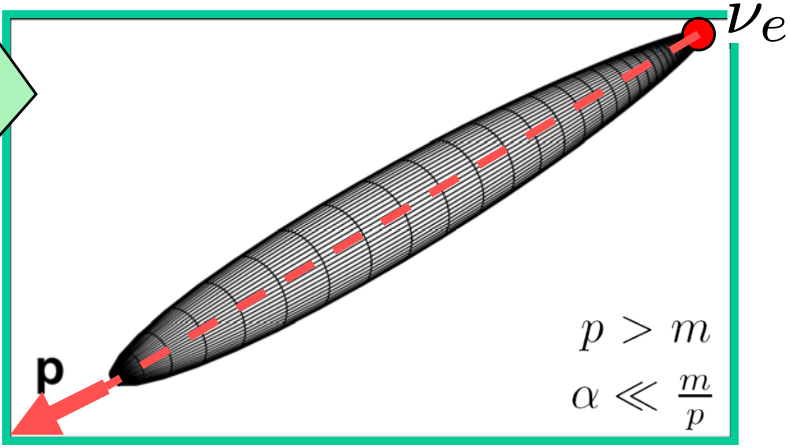
neutrino-spin self-polarization effect in the matter

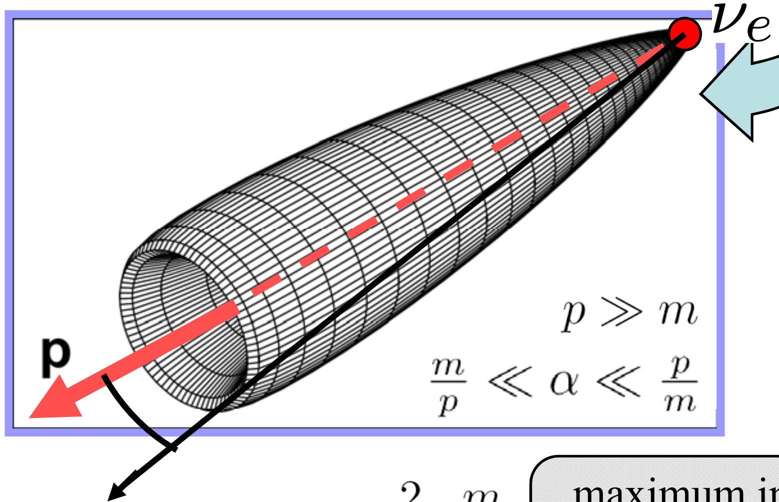
A.Lobanov, A.Studenikin, Phys.Lett.B 564 (2003) 27;
Phys.Lett.B 601 (2004) 171

Spatial distribution of radiation power

From the angular distribution of $SL\nu$

$$I = \mu^2 \int_0^{\pi} \omega^4 \left[(\tilde{\beta}\tilde{\beta}' + 1)(1 - y\cos\theta) - (\tilde{\beta} + \tilde{\beta}')(\cos\theta - y) \right] \frac{\sin\theta}{1 + \tilde{\beta}' y} d\theta$$





for $p/m = 5$ and $\alpha = 0.01$

$n \approx 10^{35} cm^{-3}$

neutrino momentum

mass

matter density

$$\cos\theta_{max} \simeq 1 - \frac{2}{3}\alpha\frac{m}{p}$$

maximum in radiation power distribution

for $p/m = 10^3$ and $\alpha = 100$

$n \approx 10^{39} cm^{-3}$

increase of matter density

projector-like distribution → cap-like distribution

It is possible to have $\tau = \frac{1}{\Gamma_{SL\nu}} << $ **age of the Universe ?**

For ultra-relativistic ν

with momentum $p \sim 10^{20} eV$

and magnetic moment $\mu \sim 10^{-10} \mu_B$

in very dense matter $n \sim 10^{40} cm^{-3}$

from $\Gamma_{SL\nu} = 4\mu^2 \alpha^2 m_\nu^2 p$

$p \gg m_{plasmon}$

recently also discussed by A.Kuznetsov, N.Mikheev, 2006

A.Lobanov, A.S., PLB 2003; PLB 2004
A.Grigoriev, A.S., PLB 2005
A.Grigoriev, A.S., A.Ternov, PLB 2005

$$\alpha m_\nu = \frac{1}{2\sqrt{2}} G_F n (1 + sin^2\theta_W)$$

it follows that

$$\tau = \frac{1}{\Gamma_{SL\nu}} = 1.5 \times 10^{-8} s$$

Kinematics

$$\nu_i \to \nu_j + \gamma$$

SLν

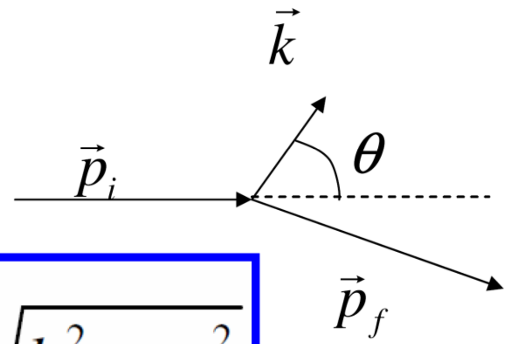
Initial and final neutrino energies:

$$E_{i,f} = \sqrt{\left(p_{i,f} - s_{i,f}\tilde{n}\right)^2 + m^2} + \tilde{n}$$

$$\tilde{n} = \alpha m$$

Energy and momentum conservation laws:

$$E_i = E_f + \omega \qquad \vec{p}_i = \vec{p}_f + \vec{k}$$



$$\sqrt{\left(p_i - s_i\tilde{n}\right)^2 + m^2} = \sqrt{\left(p_f - s_f\tilde{n}\right)^2 + m^2} + \sqrt{k^2 + m_\gamma^2}$$

$$s_i = -1 \qquad s_f = +1$$

$$m_\gamma = \sqrt{2\alpha}(3\sqrt{\pi}n)^{1/3}$$

Threshold condition

$$\tilde{n}p_i > \frac{m_\gamma^2}{4}$$

A.Lobanov, A.Studenikin, PLB 2003; PLB 2004
A.Grigoriev, A.Studenikin, PLB 2005
A.Grigoriev, A.Studenikin, A.Ternov, PLB 2005
A.Kuznetsov, N.Mikheev, 2006

Total rate and power of the Spin Light $SL\nu$

- **SLν without plasma influence**

$$\Gamma = 4\mu^2\tilde{n}^2(\tilde{n}+p)$$

$$I = \frac{4}{3}\mu^2\tilde{n}^2(3\tilde{n}^2+4p\tilde{n}+p^2)$$

$$m_\gamma \to 0$$

- **Far from the threshold**

$$\Gamma = 4\mu^2 p\tilde{n}^2(1+6\lambda+4\lambda\ln\lambda)$$

$$I = \frac{4}{3}\mu^2 p^2\tilde{n}^2\left(1-6\lambda-57\lambda\frac{\tilde{n}}{p}-12\lambda\frac{\tilde{n}}{p}\ln\lambda\right)$$

$$\lambda = \frac{m_\gamma^2}{4\tilde{n}p} \qquad \lambda \ll 1$$

- **Approaching the threshold**

$$\Gamma \sim (1-\lambda)$$

$$I \sim (1-\lambda)$$

$$\lambda \to 1$$

The effect of plasmon mass on spin light of neutrino in dense matter

A.Grigoriev[a], A.Lokhov[b], A.Studenikin[b,c 1], A.Ternov[d]

[a] *Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119991 Moscow, Russia*
[b] *Department of Theoretical Physics, Moscow State University, 119991 Moscow, Russia*
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Abstract

We develop the theory of spin light of neutrino in matter ($SL\nu$) and include the effect of plasma influence on the emitted photon. We use the special technique based on exact solutions of particles wave equations in matter to perform all the relevant calculations, and track how the plasmon mass enters the process characteristics including the neutrino energy spectrum, $SL\nu$ rate and power. The new feature it induces is the existence of the process threshold for which we have found the exact expression and the dependence of the rate and power on this threshold condition. The $SL\nu$ spatial distribution accounting for the above effects has been also obtained. These results might be of interest in connection with the recently reported hints of ultra-high energy neutrinos $E = 1 \div 10$ PeV observed by IceCube.

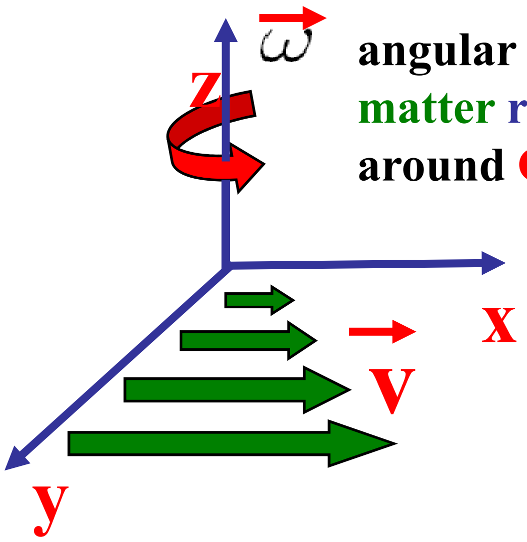
1. Introduction

Neutrino physics in matter and external electromagnetic fields is a rather longstanding research field nevertheless still having advances and providing some interesting predictions for various phenomena. A broad spectrum of issues here are connected with possible electromagnetic properties of neutrino (for more details refer to [1]). The recent studies of neutrino electromagnetic properties revealed a new mechanism of electromagnetic radiation by a neutrino propagating in dense matter that has been proposed in [2]. This type of electromagnetic radiation was called the spin light of neutrino in matter ($SL\nu$). In a quasi-classical treatment this radiation originates due to neutrino electromagnetic moment precession in dense background matter. The quantum theory of this phenomena has been developed in [3, 4].

A new convenient and elegant way of description of neutrino interaction processes in matter has been proposed and developed in a series of papers [3, 5] (see also [4]). The elaborated method is based on the use of the exact solutions of the modified Dirac equation

[1] studenik@srd.sinp.msu.ru

Neutrino energy quantization in matter



$\vec{\omega}$ angular speed of matter rotation around OZ

A.Grigoriev, A.Savochkin,A.Studenikin, Russ.Phys.J. 50 (2007) 845
A.Studenikin, J.Phys.A:Math.Theor. 41 (2008) 164047

Consider ν moving in rotating medium composed of neutrons (generalization s.f.):

ν wave function

$$\left\{ i\gamma_\mu \partial^\mu - \frac{1}{2}\gamma_\mu(1+\gamma_5)f^\mu - m \right\}\Psi(x) = 0$$

A.Ternov, A.Studenikin, Phys.Lett.B 608 (2005) 107; A.Grigoriev, A.S., A.Tetrnov, Phys.Lett.B 622 (2005) 199

where matter potential $f^\mu = -G(n, n\mathbf{v}), \quad \mathbf{v} = (\omega y, 0, 0), \ \rho = Gn\omega \qquad G = \frac{G_F}{\sqrt{2}}$

neutron number density — speed of matter — angular speed of rotation

ν energy spectrum

$$\tilde{p}_0 = \sqrt{p_3^2 + 2\rho N} + Gn, \quad N = 0, 1, 2, \ldots$$

⇒ circular orbits ⇒ trapping inside dense stars

… consistent model of a rotating matter with account for ν mass

I.Balantsev, Yu.Popov, A.Studenikin, Nuov.Cim.B 32 (2009) 53, arXiv: 0906.2391, J.Phys.A: Math.Theor. 44 (2011) 255301

$$\left\{ i\gamma_\mu \partial^\mu - \frac{1}{2}\gamma_\mu (1+\gamma_5) f^\mu - m \right\} \Psi(x) = 0$$

$$f^\mu = -G(n, n\mathbf{v}), \quad \mathbf{v} = (-\omega y, \omega x, 0)$$

Energy spectra

$$p_0 = \sqrt{m^2 + p_3^2 + 4N\rho} - Gn$$ *for* ν

$$\tilde{p}_0 = \sqrt{m^2 + p_3^2 + 4N\rho} + Gn$$ *for* $\tilde{\nu}$

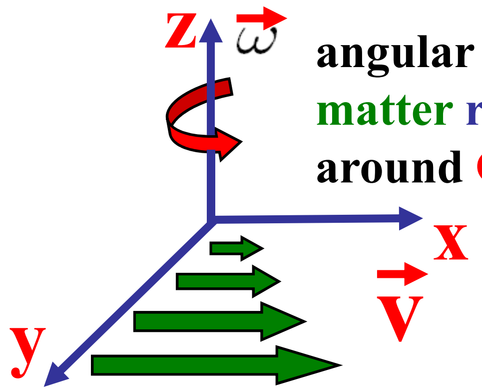
$$N = 0, 1, 2, \ldots \qquad \rho = Gn\omega$$

One example: consider antineutrino $\tilde{\nu}$

in rotating neutron matter,

then energy of transversal motion

$$\tilde{p}_{\perp} = \sqrt{2\rho N} \qquad \rho = Gn\omega$$



angular speed of matter rotation around OZ

Quantum number N also determines **radius** of antineutrino quasi-classical orbit in moving matter:

$$R = \sqrt{\frac{2N}{Gn\omega}}$$

⇨ **binding orbits inside a Neutron Star !?**

NS:

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

radius of trajectory

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

if $N \leq N_{max} = 10^{10}$, $\tilde{\nu}$ **with** $N \leq 10^{10}$ can be bound inside the star

thus, $\tilde{\nu}$ **with energy** $\tilde{p}_0 \sim 1\ eV$ **can be bound inside NS**

$N \gg 1$ and $p_3 = 0$

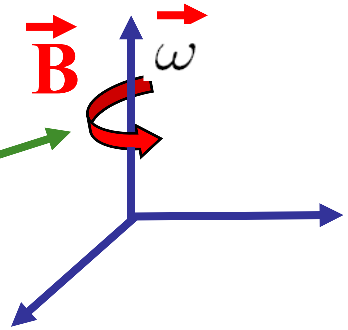
Millicharged magnetic ν in rotating magnetized matter

Ilya Balatsev, Ilya Tokarev, A.S., 2012,
Phys.Atom.Nucl.,
Phys.El.Part.&Atom.Nucl., arXiv:1209.

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



matter potential

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

rotating matter

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

ν energy is quantized in magnetized and rotating matter

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

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

scalar potential of electric field

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

... similar to Landau levels in magnetic field ...

Effective Lorentz force

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

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

matter induced 'charge' $q_m = -G$

matter 'electric' field $\mathbf{E}_m = -\boldsymbol{\nabla} n_n$

matter induced 'magnetic' field

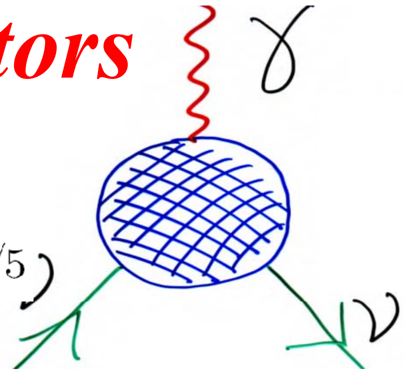
$$\mathbf{B}_m = 2n_n\boldsymbol{\omega}$$

... consequences ...

binding orbits inside a Neutron Star !?

Conclusion

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.)

- *Limits from astrophysics, star cooling (1990):*

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

  G.Raffelt

μ_ν is presently *most probably* "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 physics beyond the Standard Model

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

!

Bruno Pontecorvo
was a staff member
of Faculty of Physics of MSU
and headed
Department of Elementary
Particle Physics