Научный семинар
по программе Школы молодых ученых
“Физика нейтрино и астрофизика”

NeuAstroSch_2010

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29 сентября 2010 г.
Физический факультет МГУ
ЮФА (начало в 17.00)
Лекцию

«Электромагнитные свойства нейтрино: окно в новую физику»

прочтёт профессор А.И.Студеникин
(кафедра теоретической физики)

Международная школа молодых ученых

“Физика нейтрино и астрофизика”

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«Космологические ограничения на массу нейтрино»

Электромагнитные свойства нейтрино: окно в новую физику

Международная школа для молодёжи по физике нейтрино и астрофизике, 29 сентября 2010

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2004	**Константин Алексеевич Кузаков**	
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2009	**Илья Анатольевич Баланцев**	
2010	**Илья Владимирович Токарев**	

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

… within the agreement on cooperation between Moscow University and Instituto Nazionale di Fisica Nucleare (INFN)

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:1006.3646 June 8, 2010

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

...Why

Electromagnetic properties of ν

provide a kind of window / bridge to

NEW Physics ?

… up to now, in spite of reasonable efforts,

- ***NO** any unambiguous experimental confirmation in favour of nonvanishing ν **em** properties ,*
- *available experimental data in the field does not rule out possibility that ν have **"ZERO" em** properties.*
- *… However, in course of recent development of knowledge on ν mixing and oscillations,*

Recent studies (exp. & theor.) of

flavour conversion of

solar, atmospheric, reactor and accelerator

neutrinos have conclusively established that

! neutrinos have non-zero mass !

and they mix among themselves

that provides the first evidence of new physics

beyond the standard model

В. Грибов, Б. Понтекорво (1969)
С. Биленький, Б. Понтекорво (1976)

Осцилляции ν в вакууме

$\nu^f = \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \not\Leftrightarrow \nu^p = \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$

состояния взаимодействия
$\begin{pmatrix} \pi^+ \to \mu^+ + \nu_\mu \\ n \to p + e + \bar{\nu}_e \end{pmatrix}$

массовые состояния
(m_1, m_2)

$$\nu_e = \nu_1 \cos\theta_v + \nu_2 \sin\theta_v$$

$$\nu_\mu = -\nu_1 \sin\theta_v + \nu_2 \cos\theta_v$$

угол смешивания нейтрино в вакууме

$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$\nu_e = \nu_1 \cos\theta_\nu + \nu_2 \sin\theta_\nu$$

$$\nu_\mu = -\nu_1 \sin\theta_\nu + \nu_2 \cos\theta_\nu$$

угол смешивания нейтрино в вакууме

матрица смешивания

$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

Эволюция пучка ν во времени (пространстве)

$$i\frac{d}{dt}\nu^p(t) = H\,\nu^p(t), \quad H = \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix}, \quad E_i \approx |\vec{p}| + \frac{m_i^2}{2|\vec{p}|}$$

$$P_{\nu_e \to \nu_\mu}(x) = \sin^2 2\theta_\nu \, \sin^2 \frac{\pi x}{L}$$

ν — осцилляции нейтрино

амплитуда осцилляций

путь, пройденный нейтрино

энергия нейтрино

$$L = \frac{4\pi E}{\Delta m^2}, \quad \Delta m^2 = m_2^2 - m_1^2$$

длина осцилляций

$$K = \omega_{23} \cdot \omega_{13} \cdot \omega_{12}$$

PDG

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & e^{i\phi_{23}} s_{23} \\ 0 & -e^{-i\phi_{23}} s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & e^{i\phi_{13}} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\phi_{13}} s_{13} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & e^{i\phi_{12}} s_{12} & 0 \\ -e^{-i\phi_{12}} s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

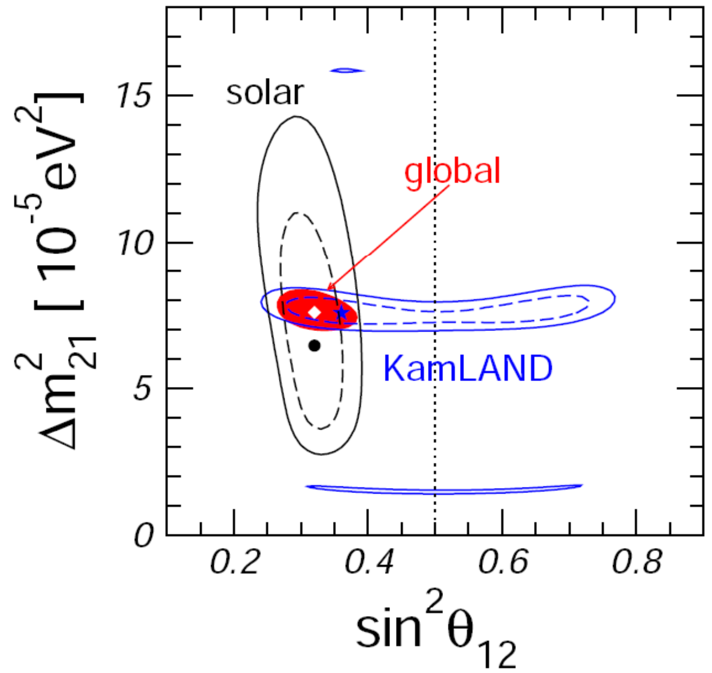
23=atm+acc 13=reactor + .. 12=solar+KL

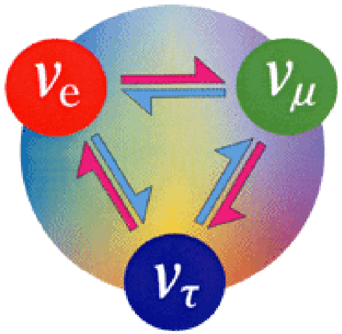
- Even in its simplest unitary form K differs from quark mixing matrix, with two extra (Majorana) phases

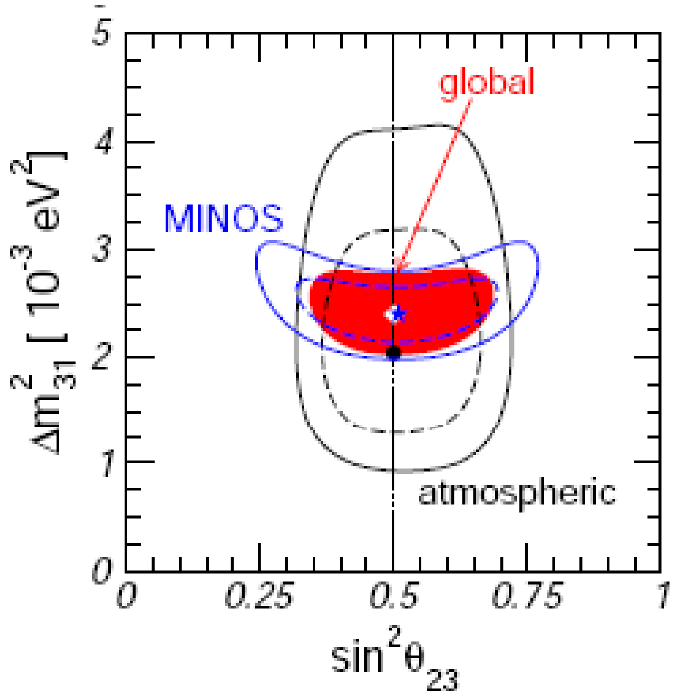
- In seesaw-schemes K is **not** unitary => extra an& phases => NSI, new propagation effects & LFV among charged leptons

- We assume K real unitary in description of oscillations

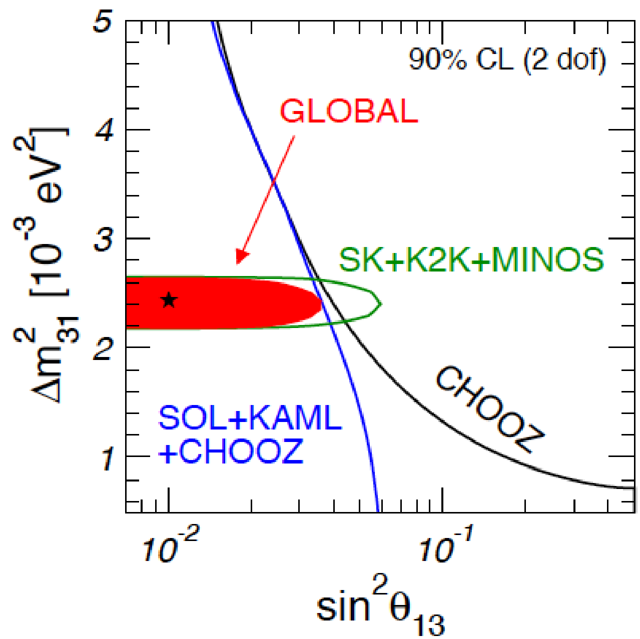
Schwetz et al, NJP 10 (2008) 113011







Homestake, SAGE
GALLEX/GNO,
Super-K,
Borexino
KamLAND (180 Km)



… Super-K

K2K (250 Km)
MINOS
(735 Km)

Table I: Best fit values from global data (solar, atmospheric, reactor (KamLand and CHOOZE) and K2K experiments)

parameter	best fit	2σ	3σ
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	$7.59^{+0.23}_{-0.18}$	7.22–8.03	7.03–8.27
$\lvert\Delta m^2_{31}\rvert\ [10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	0.29–0.36	0.27–0.38
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	≤ 0.039	≤ 0.053

Neutrino20010
Athens 19/06/10

Schwetz, Tartola, Valle, 0808.2016v3, Feb 2010

Neutrino mass

⇓

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

Neutrino magnetic moment

$$\mu_\nu \neq 0$$

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

...Massive neutrino electromagnetic properties...

ν ⊙

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, Shrock, 1980

In the Standard Model: $m_\nu = 0$,

there is no ν_R =>

ν magnetic moment $\mu_\nu = 0$.

Thus, $\mu_\nu \neq 0$ ← beyond the SM.

… *puzzling*

ν **electromagnetic properties**

something that is tiny or probably even does not exist at all…

ν exhibits unexpected properties (puzzles)

W. Pauli, 1930

Pauli himself wrote to Baade:
"Today I did something a physicist should never do. I predicted something which will never be observed experimentally...".

- neutron — now we know that it is *neutrino* *E.Fermi, 1933*
- neutral — now we know that $q_\nu \neq 0$ in plasma and beyond SM (?)
- and probably $\mu_\nu \neq 0$?!
- massless particle — now we know that $m_\nu \neq 0$
- ν very important player (astrophysics, cosmology etc. . .)

… we very much hope that

ν electromagnetic properties

will not follow the presentiment of Pauli

Outline (short list)

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

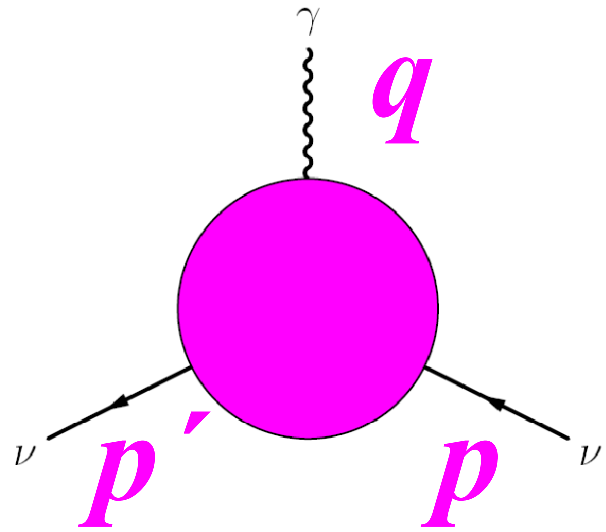
Outline

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

Giunti, Studenikin : *"Neutrino electromagnetic properties"* arXiv:0812.3646, Phys.Atom.Nucl. 73 (2009)

Studenikin : *"Neutrino magnetic moment: a window to new physics"* arXiv:0812.4716, Nucl.Phys.B (Proc.Supl.) 188, 220 (2009)

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:

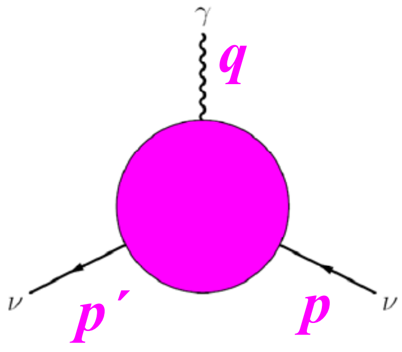
- $\hat{\mathbf{1}} q_\mu, \quad \hat{\mathbf{1}} l_\mu, \quad \gamma_5 q_\mu, \quad \gamma_5 l_\mu$

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

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

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

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



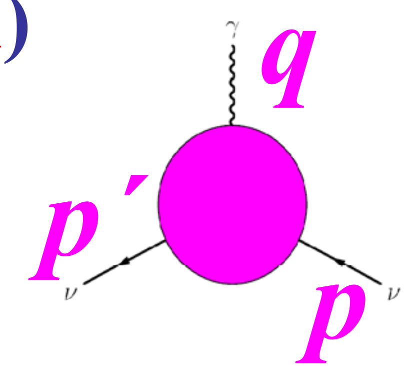
ν vertex function (using Gordon-like identities)

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

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

Electromagnetic gauge invariance (2)

(requirement of current conservation)



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

$$f_1(q^2)q^2 + f_2(q^2)q^2\gamma_5 + 2m f_4(q^2)\gamma_5 = 0,$$

$$f_1(q^2) = 0, \qquad f_2(q^2)q^2 + 2m f_4(q^2) = 0$$

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 *2. magnetic* *dipole* *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_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 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 …

ν 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

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

T is the electron recoil energy and

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

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

,

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

for anti-neutrinos $g_A \to -g_A$

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

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

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: $0 \le T \le \dfrac{2E_\nu^2}{2E_\nu + m_e}$

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

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

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 ? μ_e^2

Two steps:

1) consider ν_e as superposition of mass eigenstates ($i=1,2,3$) at some distance L, 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

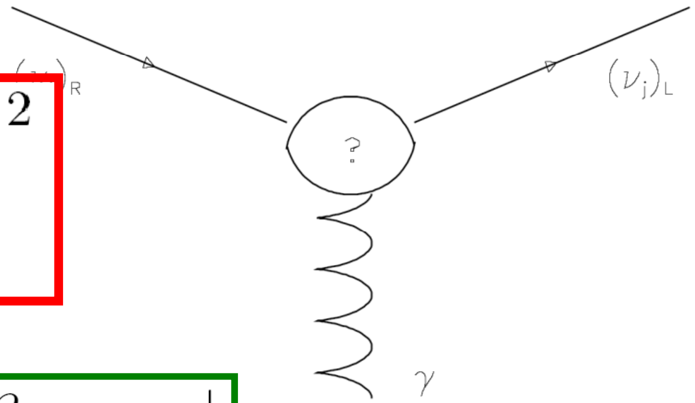
$$\sigma \sim \mu_e^2 = \sum_j \left| \sum_i U_{ei} e^{-iE_i L} \mu_{ji} \right|^2$$

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.

H.Wong,
H.-B.Li, 2005

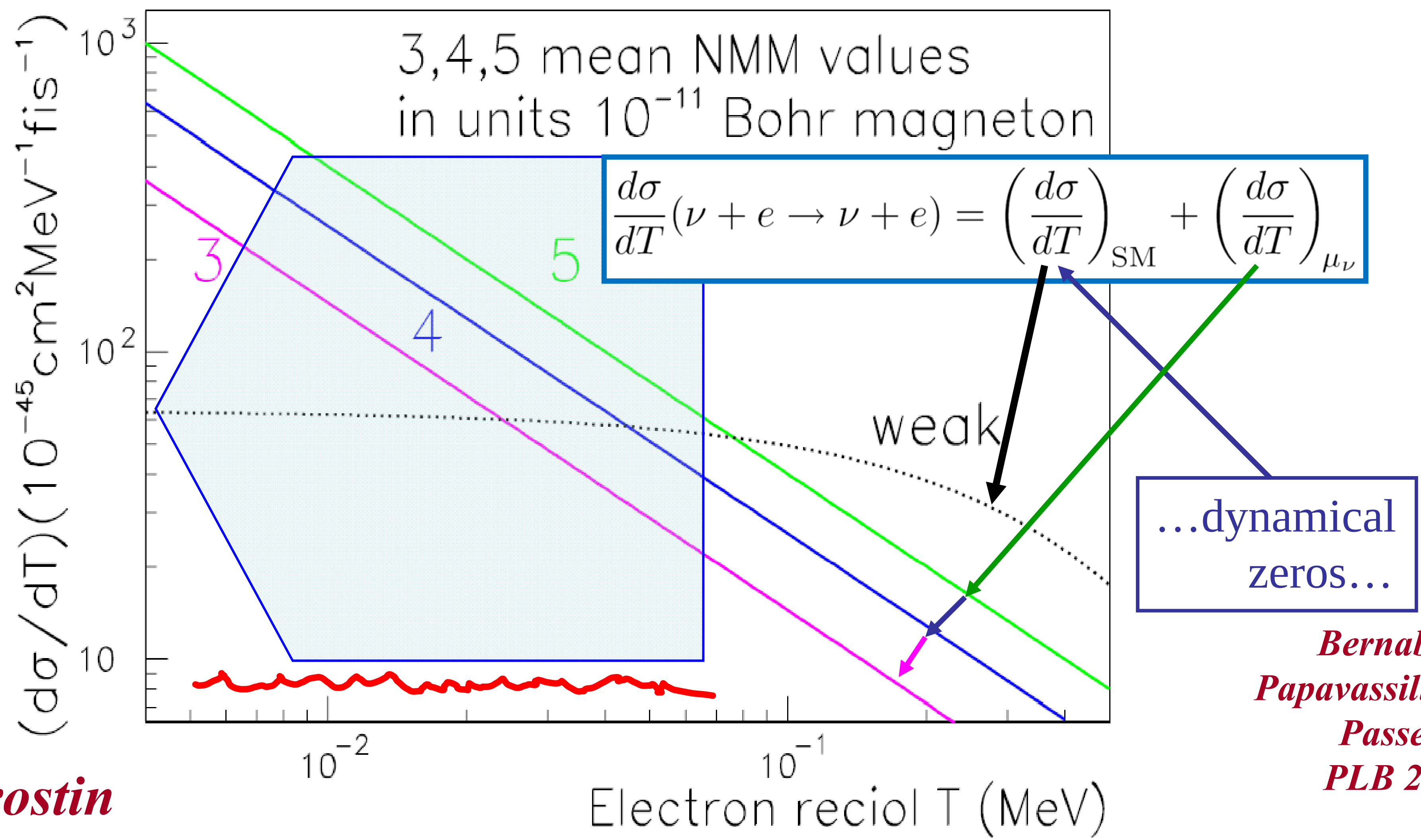
- Implications of μ_ν limits from different experiments (reactor , solar ^{8}B and ^{7}Be) are different.

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, PLB 2005

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

2

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, E.Demidova, A.Starostin, V.Brudanin, V.Egorov, D.Medvedev, M.Shirchenko, A.Starostin, Ts.Vylov,
arXiv:09.06.1926 , June 10, 2009,

A.Beda, V.Brudanin, E.Demidova, V.Egorov, G.Gavrilov, M.Shirchenko, A.Starostin, Ts.Vylov,
in: "Particle Physics on the Eve of LHC",
ed. A.Studenikin, World Scientific (Singapore), p.112, 2009
www.icas.ru (13th Lomonosov Conference)

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

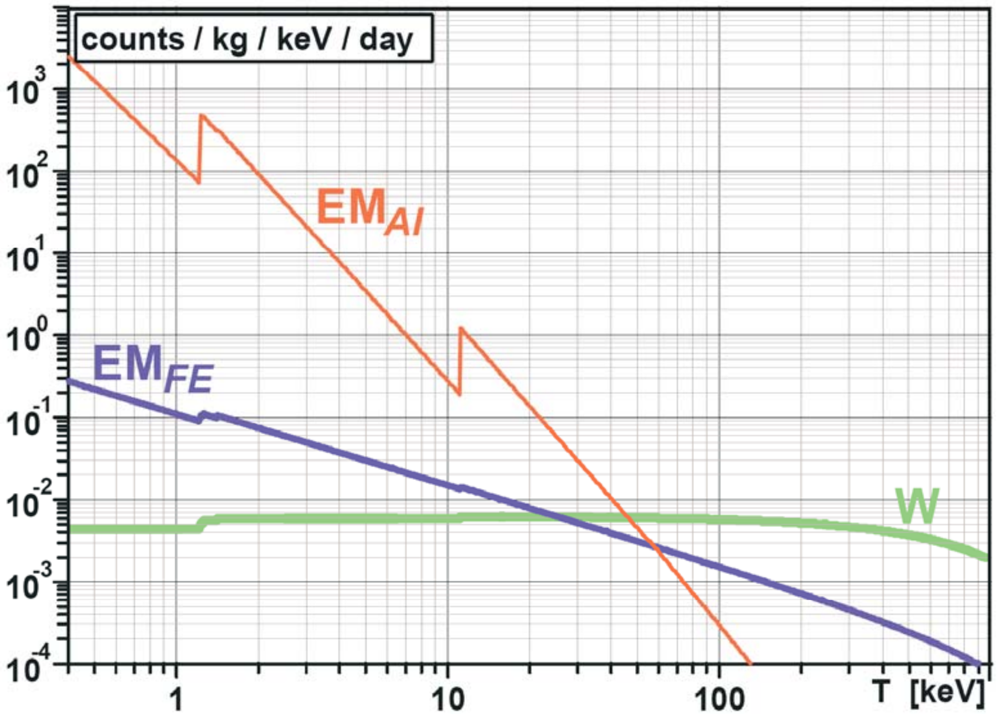
?

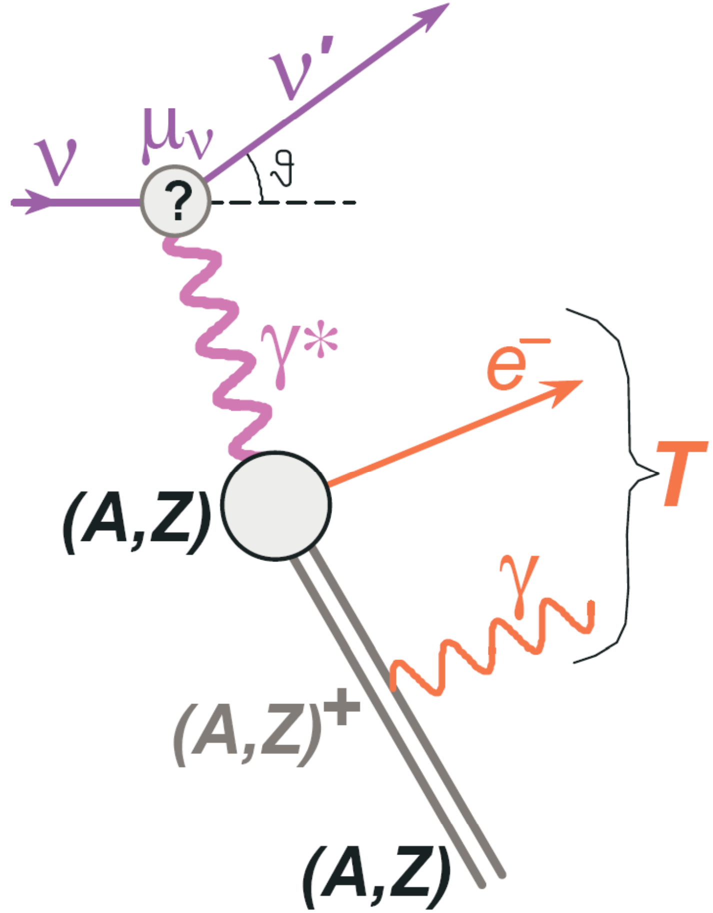
H.Wong et al., arXiv: 1001.2074, 13 Jan 2010, reported at the

Neutrino 2010 Conference (Athens, June 2010),

PRL 105 (2010) 061801

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





…much better limits on ν effective magnetic moment :

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

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

Neutrino 2010 Conference, Athens

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

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

(*Atomic Ionization* effect "accounted for")

… however…

- *M.Voloshin, arXiv: 1008.2171, 23 Aug 2010: no important effect of Atomic Ionization on ν cross section once all possible final electronic states accounted for*

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

(ν-e scattering on free electrons)

3

… a bit of ν electromagnetic properties theory

3.1 ν vertex function

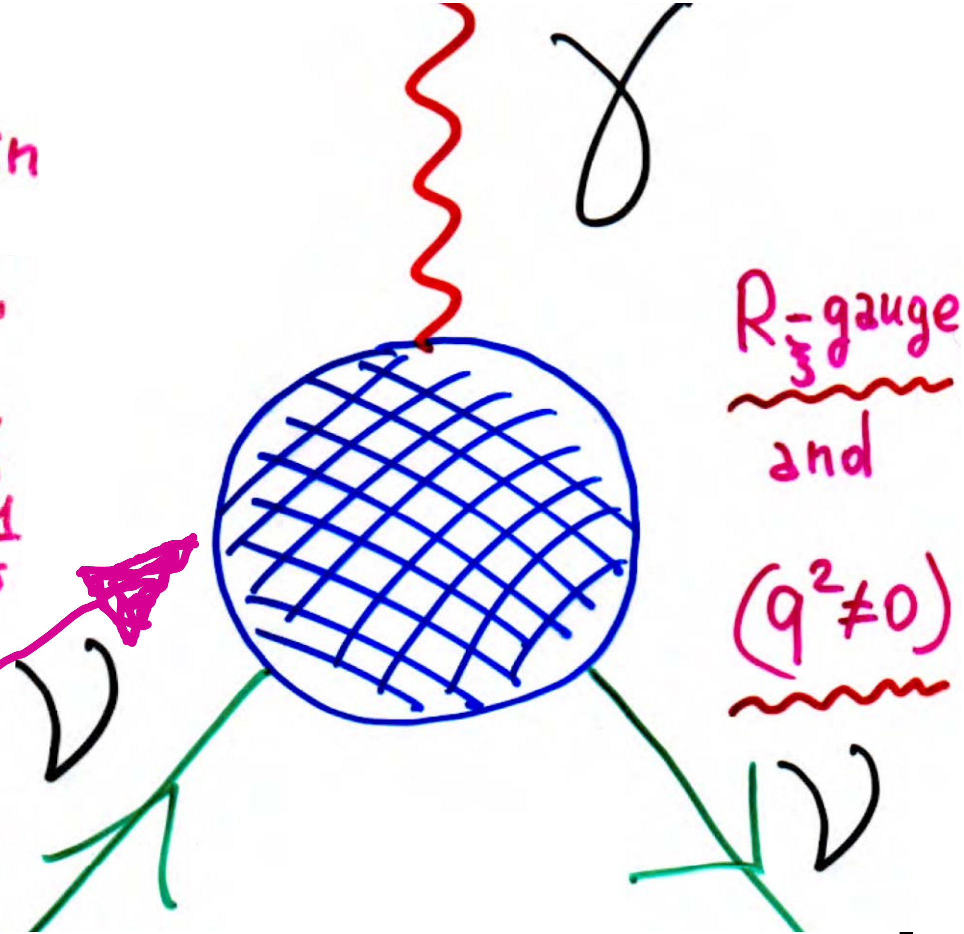
The most general study of the **massive neutrino** vertex function (including electric and magnetic form factors) in arbitrary R_ξ gauge in the context of the SM + SU(2)-singlet ν_R accounting for masses of particles in polarization loops

!

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."



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

Magnetic moment dependence

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

on neutrino mass

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

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

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

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

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

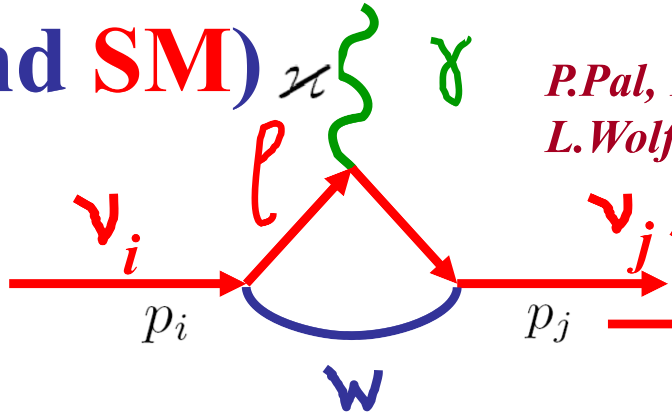
. . . μ_ν *in case of mixing . . .*

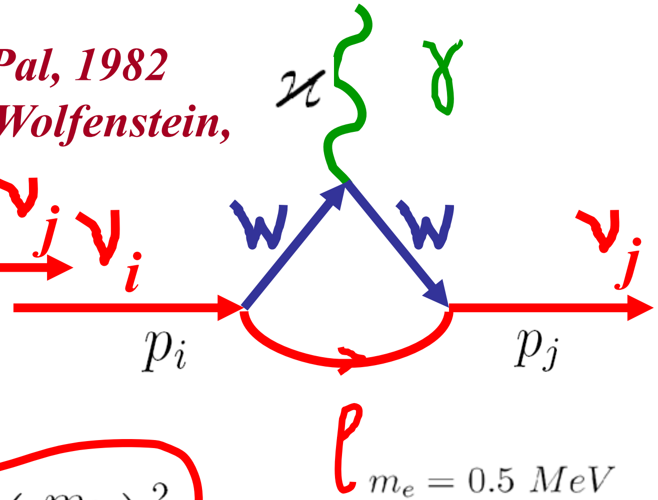
3.5

Neutrino (beyond SM) dipole moments

(+ transition moments)

P.Pal, 1982
L.Wolfenstein,





- **Dirac neutrino**

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

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

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

- $m_i, m_j \ll m_l, m_W$

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

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** $i \neq j$

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

or

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

… 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

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

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

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

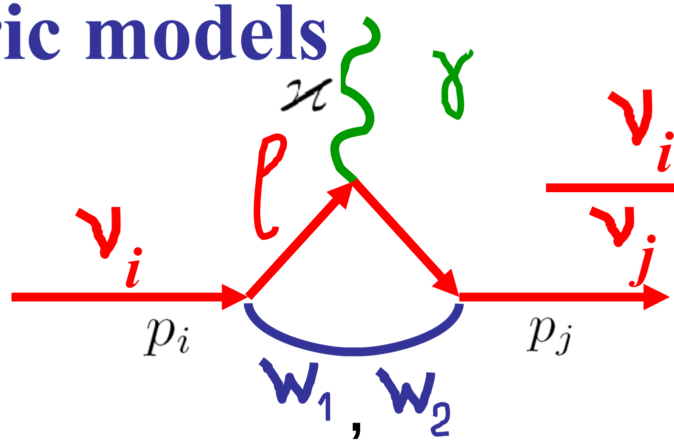
Lee, Shrock, Fujikawa, 1977

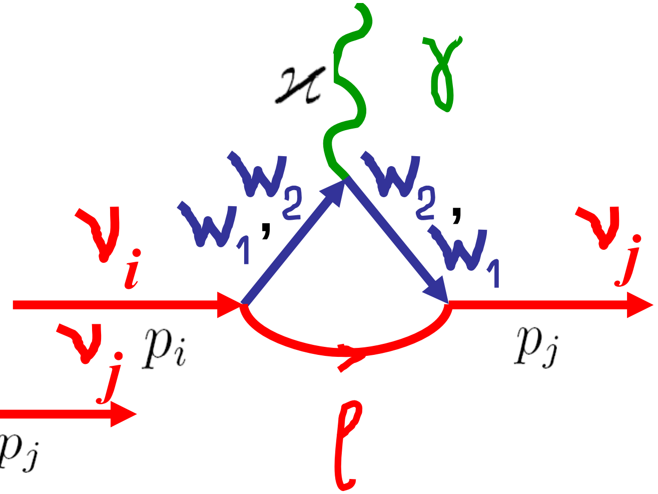
- *no GIM cancellation*
- μ_{ii}^D - to leading order - independent on U_{li} and $m_{l=e,\mu,\tau}$
- $\mu_e^2 = \sum_{i=1,2,3} \mid U_{ie}\mid^2 \mu_{ii}^2$ …possibility to measure fundamental μ_{ii}^D

$\mu_{ii}^D = 0$ 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

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

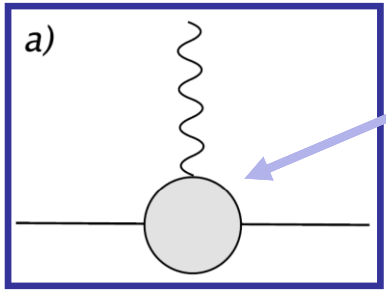
… charged lepton mass … ***… neutrino mass …***

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

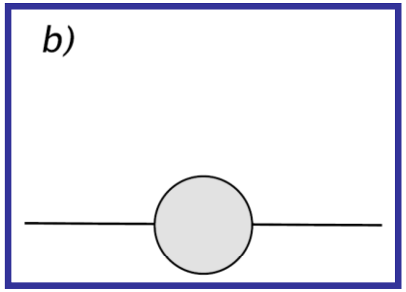


then

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

…combination of constants and loop factors…

contribution to m_ν given by



, then

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

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

Voloshin, 1988; Barr, Freire, Zee, 1990

from quadratic divergence appearing in renormalization of dimension four neutrino mass operator

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

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

Kim, 1976
Beg, Marciano, Ruderman, 1978

- *Voloshin, 1988*

"On compatibility of small m_ν with large μ_ν 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
- model-independent constraint μ_ν

considerable enhancement of μ_ν to experimentally relevant range

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

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

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

… A remark on electric charge of ν …

ν neutrality ***Q=0*** is attributed to

gauge invariance + anomally cancellation constraints

imposed in SM of electroweak interactions

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

Foot, Joshi, Lew, Volkas, 1990;
Foot, Lew, Volkas, 1993;
Babu, Mohapatra, 1989, 1990

- *…General proof:*
- *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*

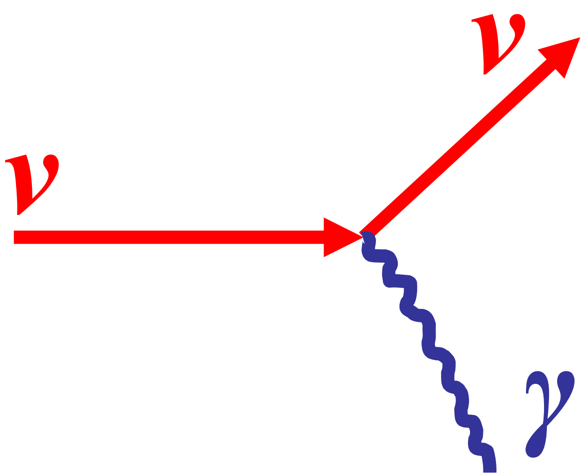
Q=0

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

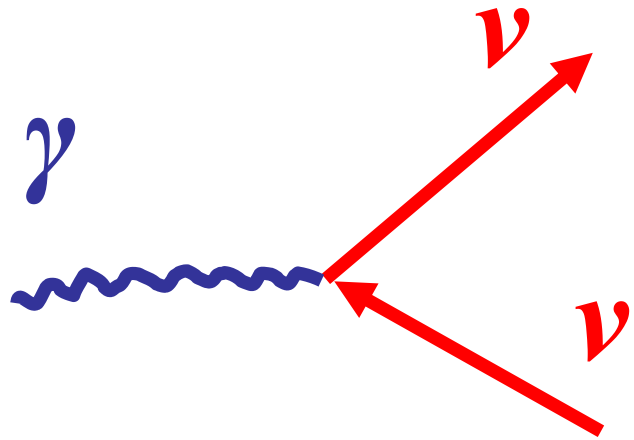
Bardeen, Gastmans, Lautrup, 1972;
Cabral-Rosetti, Bernabeu, Vidal, Zepeda, 2000;
Beg, Marciano, Ruderman, 1978;
Marciano, Sirlin, 1980; Sakakibara, 1981;
- *M.Dvornikov, A.S., 2004 (for extended SM in one-loop calculations)*

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

Neutrino–photon couplings

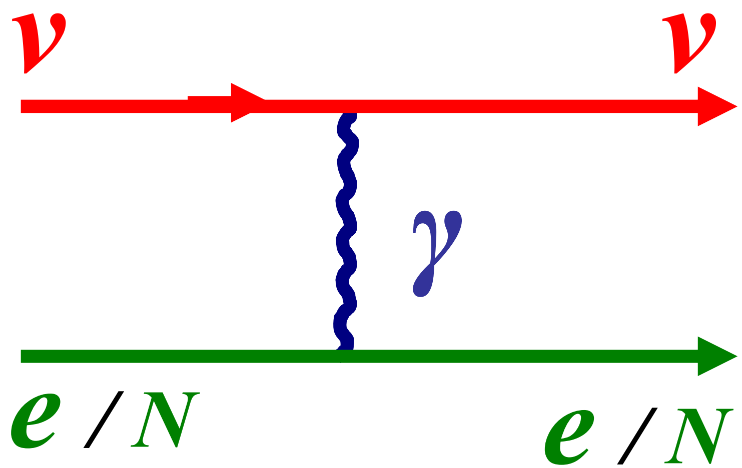


ν decay, Cherenkov radiation

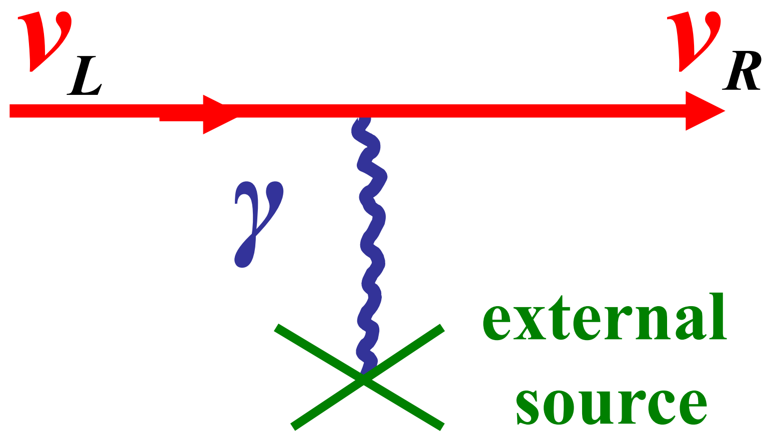


γ decay in plasma

!!!



Scattering



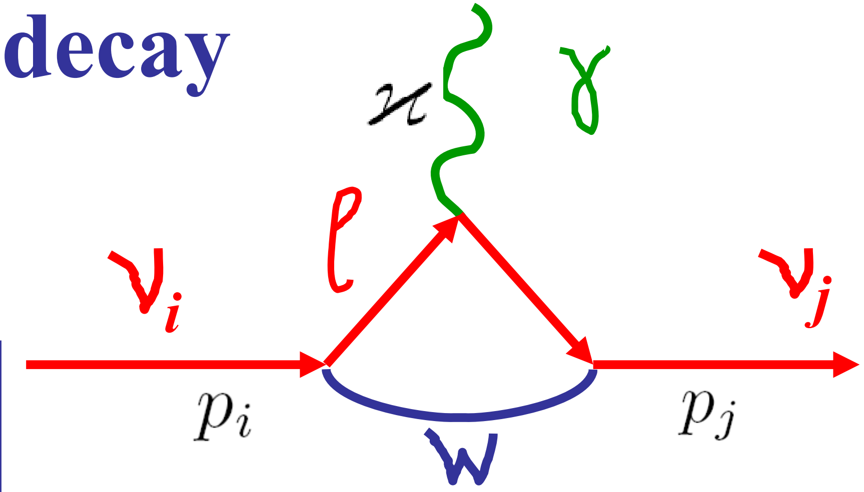
Spin precession

3.7 Neutrino radiative decay

$\nu_i \longrightarrow \nu_j + \gamma$

$m_i > m_j$

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



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

Radiative decay rate

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

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

- 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

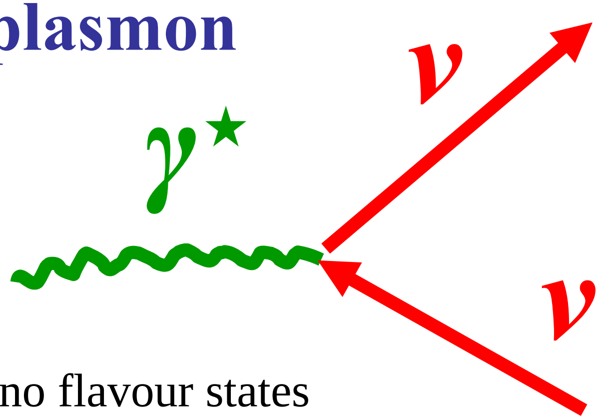
Kolb, Turner 1990;

Ressell, Turner 1990

3.9 The tightest astrophysical bound on μ_ν

G.Raffelt, PRL 1990

comes from cooling of red giant 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

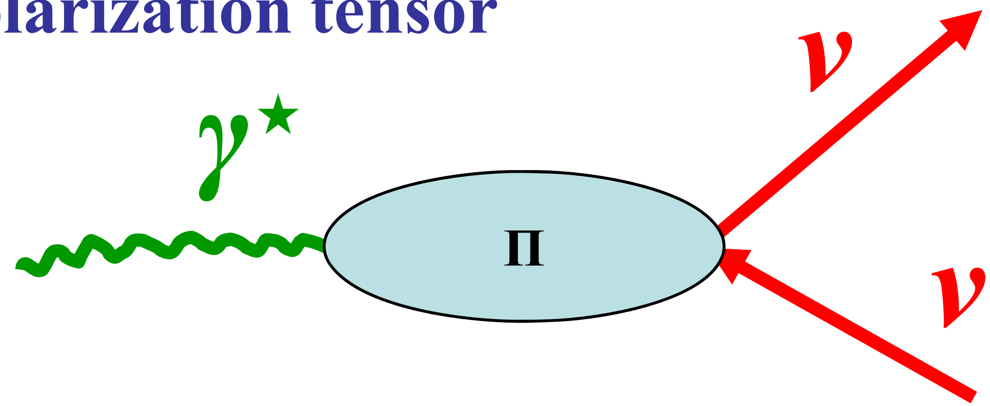
$$Q_\mu = g\int \frac{d^3k}{(2\pi)^3}\omega f_{BE}\Gamma_{\gamma\to\nu\bar{\nu}}$$

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

distribution function of plasmons

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

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...

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

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

G.Raffelt, PRL 1990

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

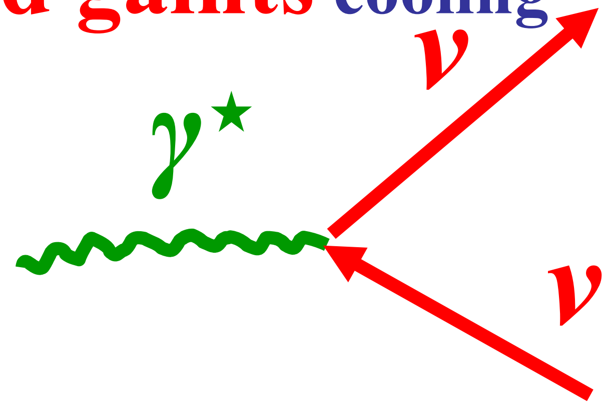
A global treatment would be desirable, incorporating **oscillation** and **matter effects** as well as the complications due to interference and competitions among various channels

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

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

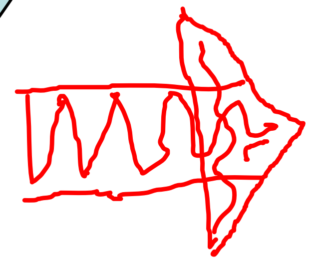
- $q_\nu \leq 2 \times 10^{-14} e$ …to avoid helium ignition in low-mass **red gaints**

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…** $q_\nu \leq 3 \times 10^{-21} e$

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 …

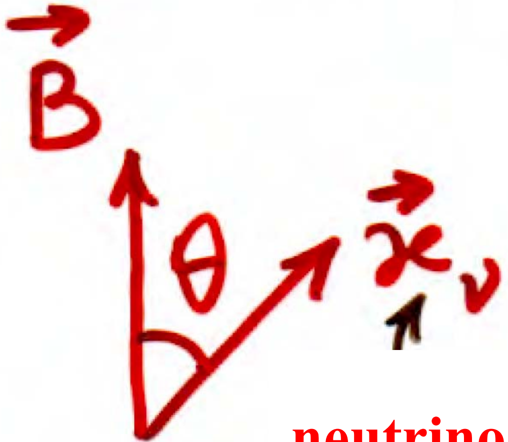
β-decay of neutron in magnetic field

{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

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

Outlook: Astrophysical applications?

3.12

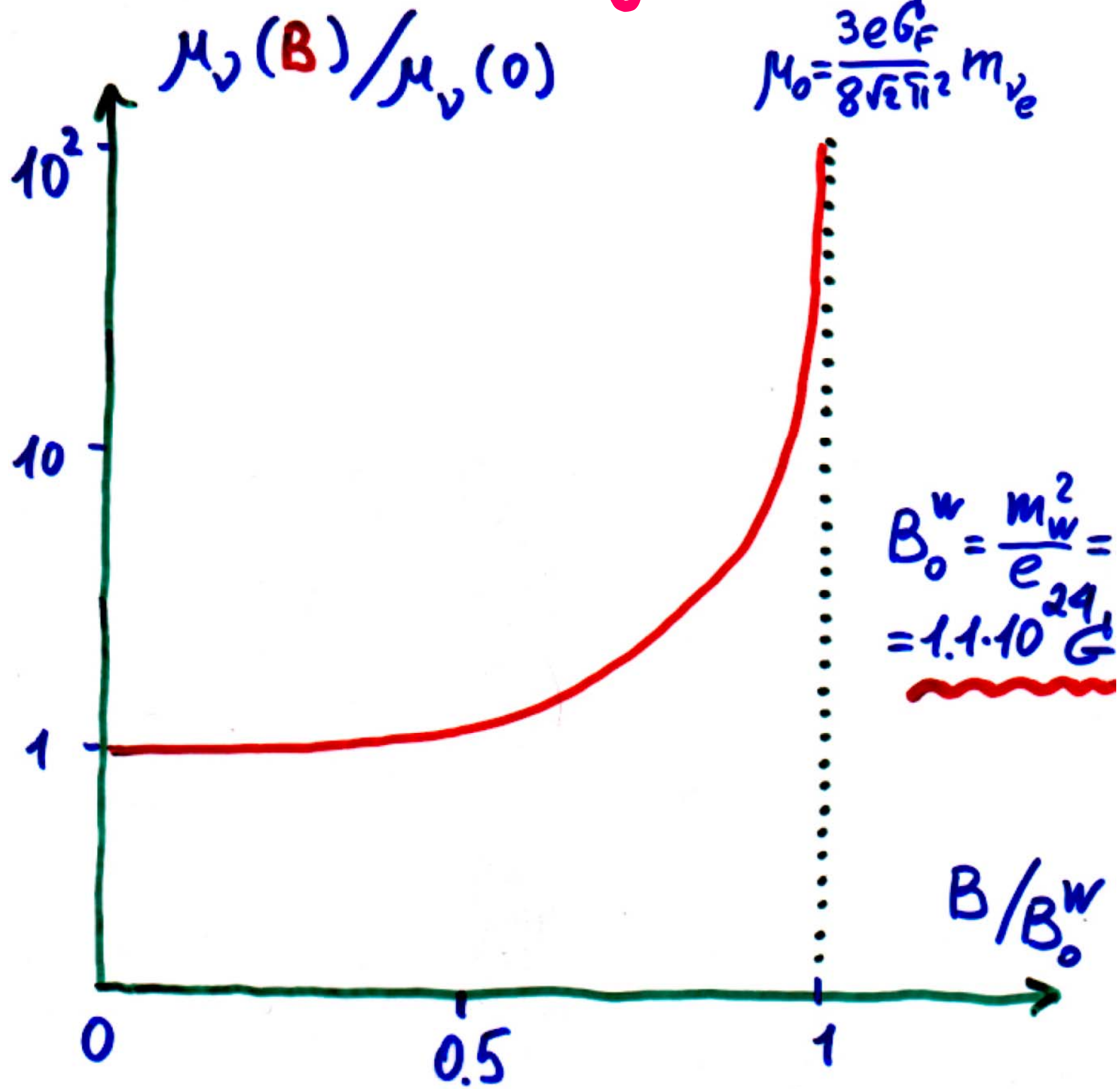
ν e.m. form factors are affected by matter and B

* magnetic moment $\mu_\nu = \mu_\nu(B)$ Egorov, Studenikin 1997; 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;

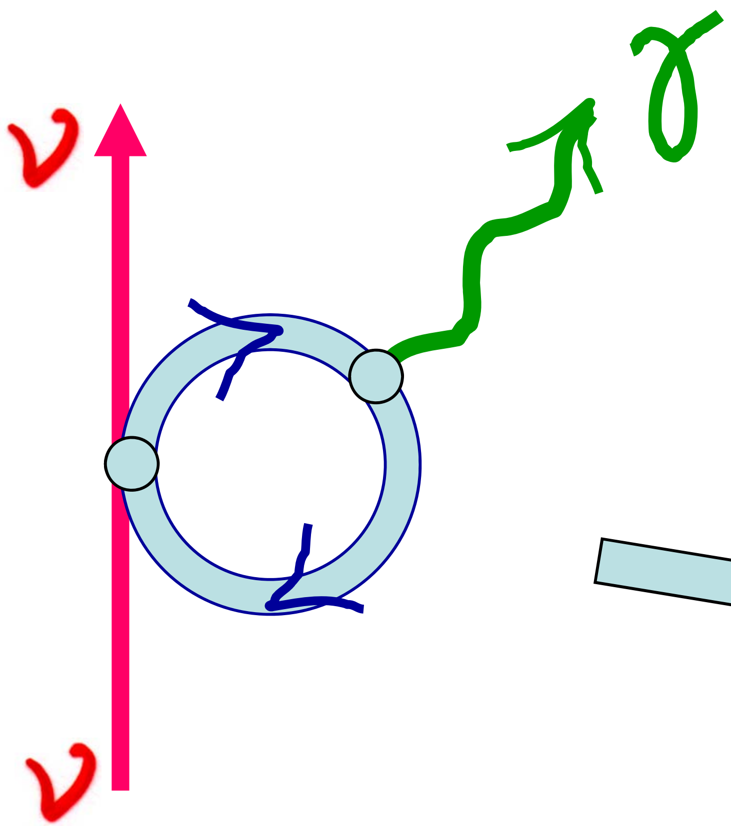
Masood, Perez Rojas, Gaitan, Rodrigues-Romo, 1999

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 $\nu\gamma$ interactions in astrophysical and cosmological media

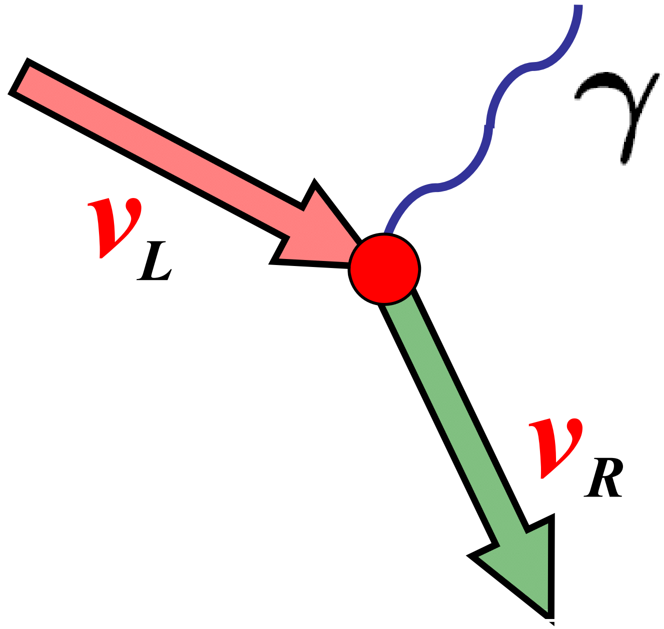
New mechanism of electromagnetic radiation

"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

New mechanism of electromagnetic radiation

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

Analogies with:

* classical electrodynamics

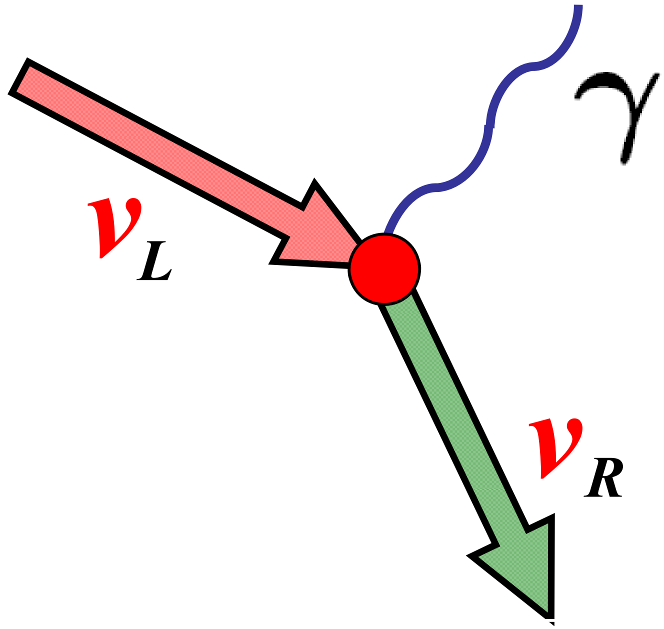
an object with charge $Q=0$ and magnetic moment $\vec{m} = \frac{1}{2}\sum_i e_i [\vec{r}_i \times \vec{v}_i] \neq 0$

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

← magnetic dipole radiation power

$SL\nu$

Spin light of neutrino in matter



(quantum approach)

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

A.Studenikin, A.Ternov, PLB 2005
A.Grigoriev, Studenikin, Ternov, PLB 2005

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

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

Modified Dirac equation for neutrino in matter

Addition to the vacuum neutrino Lagrangian

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

matter current

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

matter polarization

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

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**.

Quantum theory of spin light of neutrino (I)

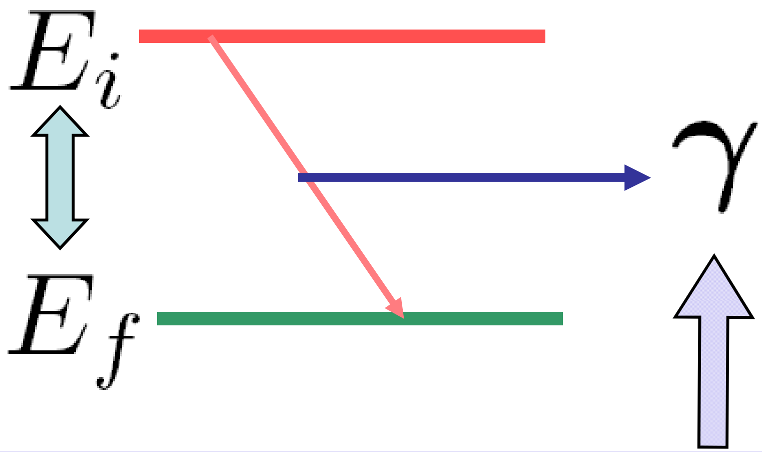
Quantum treatment of *spin light of neutrino* in matter shown**s** that this process originates from the **two subdivided phenomena:**

$SL\nu$

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

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

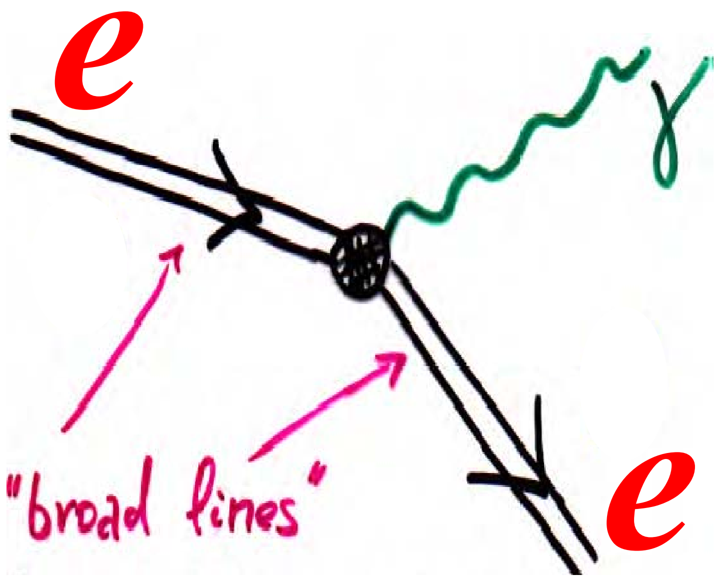
Potential of electromagnetic field

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

quantized part of potential

evolution **operator**

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



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** $A^{ext}_\mu(x)$

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

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

… evaluation of the **method**

- \- within a project of research of ν
  in dense matter and external fields
  \- stimulated by a need to obtain a consistent theory of "spin light of neutrino (electron) in matter"

A.Studenikin,

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

"Method of wave equations exact solutions in studies of neutrino and electron interactions in dense matter",
J.Phys.A: Math.Theor. 41 (2008) 164047 ***QFEXT'07***

ν and e in matter being treated within the method of exact solutions of quantum wave equations -

«method of exact solutions »

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

Neutrino energy quantization in rotating media: new mechanism for neutrino trapping inside dense rotating stars

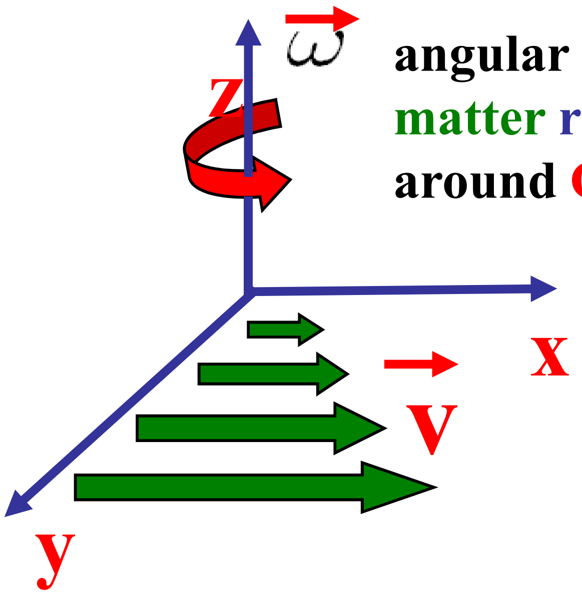
Neutrino'08, Christchurch, May 25-31, 2008

Alexander Studenikin

Moscow State University

A.Studenikin, "Method of exact solutions in studies of neutrinos and electrons in dense matter" J.Phys.A:Math.Theor. 41 (2008) 164047 (20 pp)

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

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

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

Energy spectra

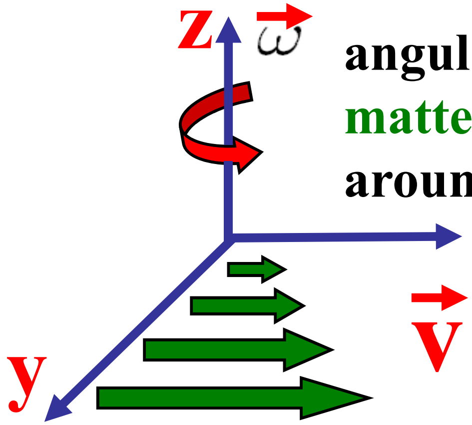
$$p_0 = \sqrt{m^2 + p_3^2 + 4N\rho} - Gn$$ *for* ν

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

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

for this set

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

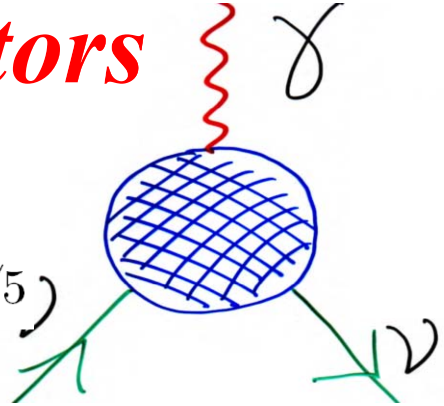
if $N \leq N_{max} = 10^{10}$, $\tilde{\nu}$ **with** $N \leq 10^{10}$ can be bound inside the star

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

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

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

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

- ***Limits from reactor ν-e scattering experiments (2010):***

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

  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 known to be in the range

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

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

… *situation with*

ν electromagnetic properties

is better that it was for ν
in the time of W. Pauli, 1930

… once they will be observed experimentally

… are important in astrophysics

… there is a need for further theoretical and experimental studies