Electromagnetic interactions of neutrinos

(Beyond Standard Model)

"Particle Physics and Cosmology"
XXV Rencontres de Blois
29/05/2013

Alexander Studenikin

Moscow State University
&
JINR -Dubna

2013

- the standard Higgs boson
  (... probably ...)

- the Standard Model
  experimental status
  confirmation

… all people should focus on

ν is the only known particle with properties Beyond Standard Model

… problem and puzzle

ν is quite

invisible

particle

ν exhibits unexpected properties (puzzles)

W. Pauli, 1930

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

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

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

H.Bethe, R.Peierls, «The 'neutrino'»
Nature 133 (1934) 532,

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

… puzzles …

- …up to now absolute value ?

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

… however …

… an optimistic view on the present and future of ν

Бруно Понтекорво

1913-1993

In 1946 Bruno Pontecorvo:

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

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

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

August 22, 2013

Centenary of the birth of Bruno Pontecorvo weak interactions are indeed weak

$\boxed{L \sim 10^{15} km}$ … free path in water…

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

$$E_{\nu} \sim 3MeV$$

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

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

- strong external electromagnetic fields

and

- dense background matter

Outline (I)

ν electromagnetic properties

(short review)

⇒ ① Carlo Giunti, Alexander Studenikin :
"Neutrino electromagnetic properties"
Phys.Atom.Nucl. 73, 2089-2125 (2009)

② A.Studenikin : "Neutrino magnetic moment: a window to new physics"
Nucl.Phys.B (Proc.Supl.) 188, 220 (2009)

③ C. Giunti, A. Studenikin : "Electromagnetic properties of neutrino"
J.Phys.: Conf.Series. 203 (2010) 012100

④ C.Broggini, C.Giunti, A.Studenikin :
"Electromagnetic properties of neutrinos", ●
in: Special issue "Neutrino Physics"
(Adv. iHigh Energy Phys. 2012 (2012) 459526 (49 pp)
arXiv: 1207.3980 July 17, 2012

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

Outline (II)

- results of recent experimental searches for upper bound on μ_ν

  (GEMMA Coll. JINR - ITEP)

- our corresponding theoretical studies of ν-e scattering
  - proper treatment of "atomic ionization effect"
- - new bounds on ν electrical millicharge from μ_ν

- A.Studenikin, arXiv: 1302.1168, May 13, 2013
  “New bounds on neutrino millicharge from limits on magnetic moment”
- K.Kouzakov, A.Studenikin,
  “Magnetic neutrino scattering on atomic electrons revisited”
  Phys.Lett. B 105 (2011) 061801,
- “Electromagnetic neutrino-atom collisions: The role of electron binding”
  Nucl.Phys.B (Proc.Suppl.) 217 (2011) 353
- K.Kouzakov, A.Studenikin, M.Voloshin,
  “Neutrino-impact ionization of atoms in search for neutrino magnetic moment”, **Phys.Rev.D** 83 (2011) 113001
- “On neutrino-atom scattering in searches for neutrino magnetic moments” **Nucl.Phys.B** (Proc.Supp.) 2011 (Proc. of Neutrino 2010 Conf.)
- “Testing neutrino magnetic moment in ionization of atoms by neutrino impact”, **JETP Lett.** 93 (2011) 699
- M.Voloshin,
  “Neutrino scattering on atomic electrons in search for neutrino magnetic moment”
  Phys.Rev.Lett. 105 (2010) 201801

Outline (III)

- ν quantum states in magnetized matter (new approach)

Spin Light of ν in matter

$SL\nu$

①

ν energy quantization in rotating matter

②

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

. . . basics of ν electromagnetic properties

$$m_\nu \neq 0$$

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

$m_\nu \neq 0$

Theory (Standard Model with ν_R)

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

Lee Shrock, 1977; Fujikawa Shrock, 1980

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

... much greater values are desired

for astrophysical or cosmology

visualization of μ_ν

- **Astrophysical bounds**

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

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

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

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

Lee
Shrock, 1977; Fujikawa
Shrok, 1980

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

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

...the present status...

to have visible $m_\nu \neq 0$

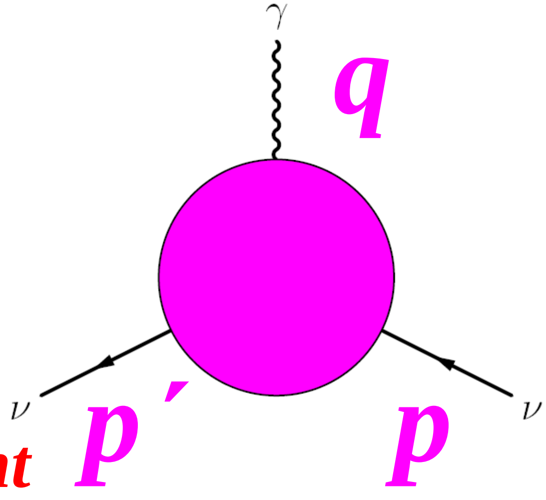
is not an easy task for

theoreticians

and experimentalists

… a bit of ν electromagnetic properties theory …

electromagnetic vertex function



$$< \psi(p')|J_\mu^{EM}|\psi(p) >= \bar{u}(p')\Lambda_\mu(q,l)u(p)$$

Matrix element of electromagnetic current is a Lorentz vector

$\Lambda_\mu(q,l)$ *should be constructed using*

matrices $\hat{1}, \quad \gamma_5, \quad \gamma_\mu, \quad \gamma_5\gamma_\mu, \quad \sigma_{\mu\nu},$

tensors $g_{\mu\nu}, \quad \epsilon_{\mu\nu\sigma\gamma}$

vectors q_μ **and** l_μ

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

Lorentz covariance (1) and electromagnetic gauge invariance (2) ⇒

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 $J_\mu^{\rm EM}$ 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:* $Imf_Q = Imf_M = Imf_A = 0$

Majoran ν

1) *from CPT invariance (regardless CP or $\cancel{CP}$).*

$$f_Q = f_M = f_E = 0$$

…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 $p^2=m_i^2,\ p'^2=m_j^2$:

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

… beyond SM…

and

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

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***

$\Downarrow$

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

are relatively real (no relative phases) .

… quite different EM properties …

1) ***CP invariance + hermiticity***

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

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

… importance of μ_ν studies…

If diagonal $\mu_\nu \neq 0$

were confirmed

then ν Dirac

… for ν Majorana
non-diagonal = transitional
$\mu_\nu \neq 0$

… progress
in experimental
studies of μ_ν $\Longrightarrow$

ν magnetic moment in experiments

Samuel Ting
(have written 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

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

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

[redacted]

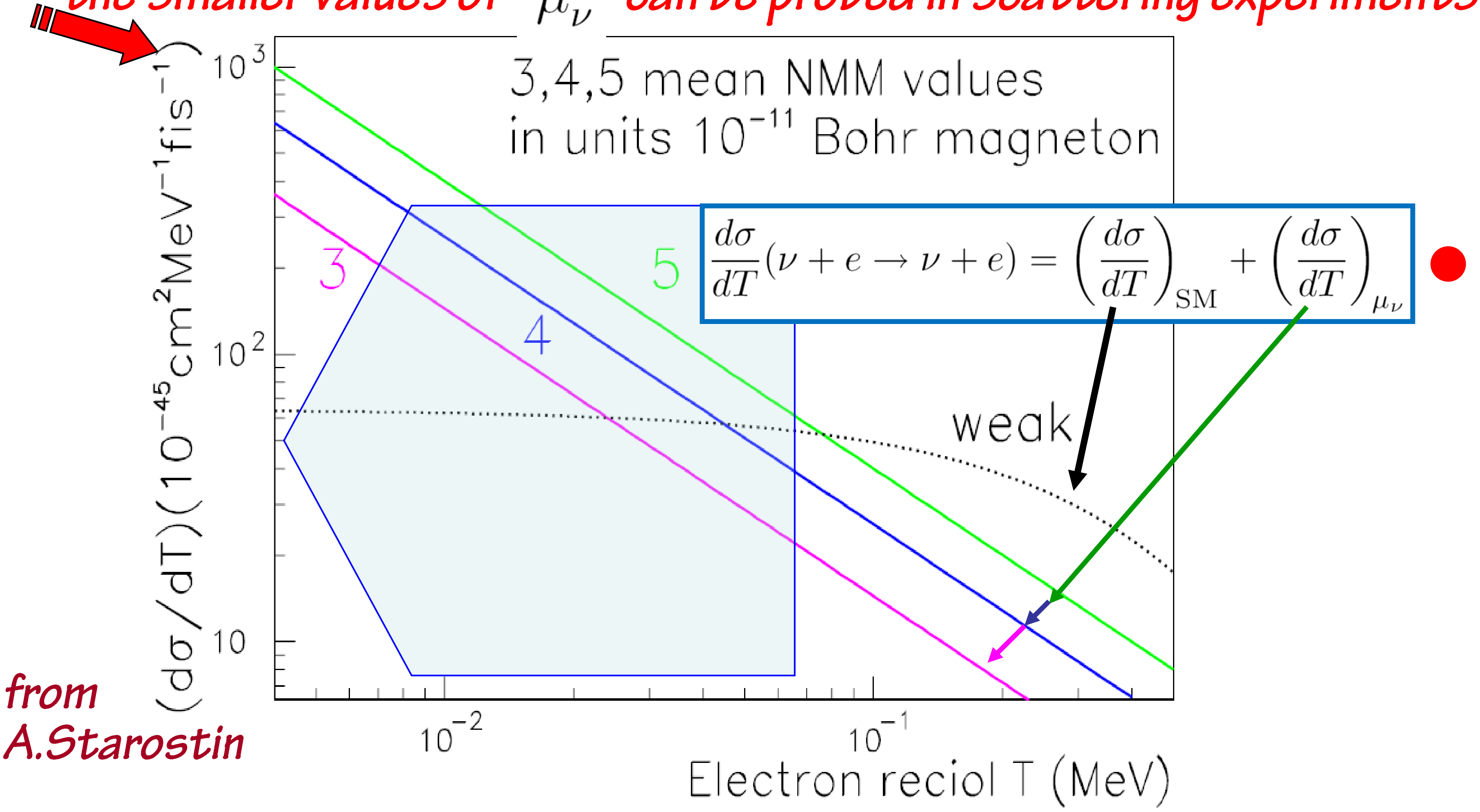
$$g_V = \begin{cases} 2\sin^2\theta_W + \dfrac{1}{2} & \text{for} \quad \nu_e\,, \\ 2\sin^2\theta_W - \dfrac{1}{2} & \text{for} \quad \nu_\mu, \nu_\tau\,, \end{cases} \qquad g_A = \begin{cases} \dfrac{1}{2} & \text{for} \quad \nu_e\,, \\ -\dfrac{1}{2} & \text{for} \quad \nu_\mu, \nu_\tau \end{cases}$$

for anti-neutrinos $g_A \to -g_A$

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

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

… the lower the smallest measurable electron recoil energy is, the smaller values of μ_ν^2 can be probed in scattering experiments …



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

from A.Starostin

MUNU experiment at Bugey reactor (2005)

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

TEXONO collaboration at Kuo-Sheng power plant (2006)

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

GEMMA (2007)

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

GEMMA I 2005 - 2007

BOREXINO (2008)

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

…was considered as the world best constraint…

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

based on first release of
BOREXINO data

Montanino,
Picariello,
Pulido, PRD 2008

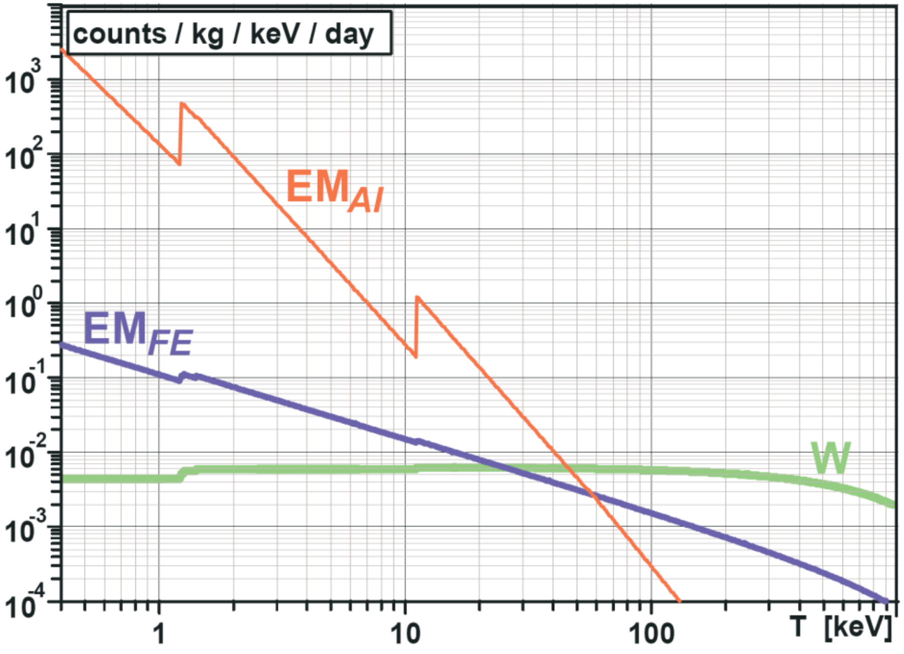
… attempts to
improve bounds

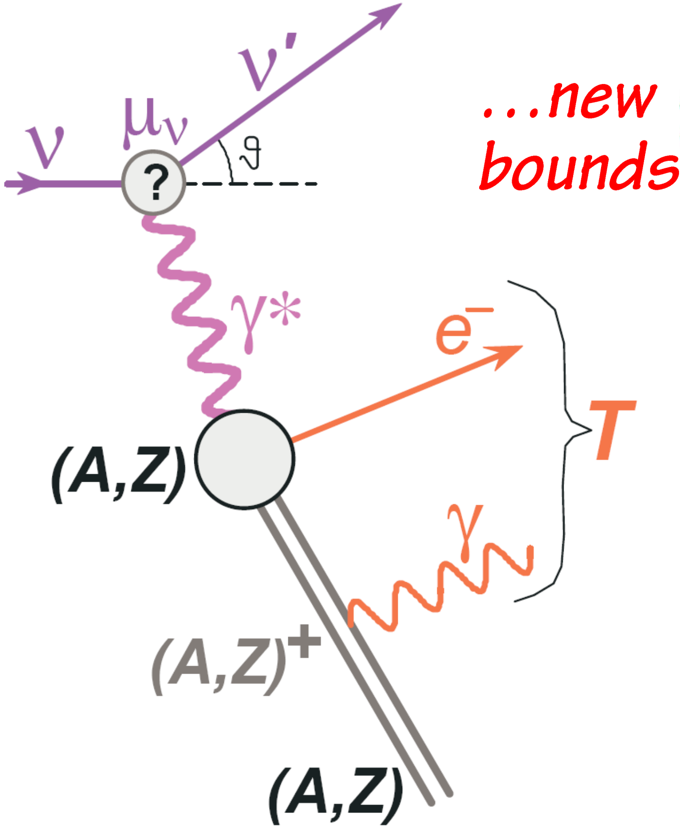
… quite recent claim that ν-e cross section should be increased by Atomic Ionization effect:

?

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

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 …

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

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 …⟹

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

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

… atomic ionization effect accounted for …

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

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

K.Kouzakov, A.Studenikin,

- “Magnetic neutrino scattering on atomic electrons revisited”
  Phys.Lett. B 105 (2011) 061801, arXiv: 1011.5847

- “Electromagnetic neutrino-atom collisions: The role of electron binding”
  Nucl.Phys.B (Proc.Suppl.) 217 (2011) 353

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

- “Neutrino-impact ionization of atoms in search for neutrino magnetic moment”, **Phys.Rev.D** 83 (2011) 113001

- “On neutrino-atom scattering in searches for neutrino magnetic moments” **Nucl.Phys.B** (Proc.Supp.) 2011 (Proc. of Neutrino 2010 Conf.)

- “Testing neutrino magnetic moment in ionization of atoms by neutrino impact”, **JETP Lett.** 93 (2011) 699

M.Voloshin,

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

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

... free electron approximation can be used ...

M.Voloshin, 23 Aug 2010;
K.Kouzakov, A.Studenikin, 26 Nov 2010;
● H.Wong et al, arXiv: 1001.2074 V3, 28 Nov 2010

GEMMA (2005-2012)

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

World best experimental limit

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

June 2012

A. Beda et al, in: Special Issue on "Neutrino Physics",
Advances in High Energy Physics (2012) 2012,
editors: J.Bernabeu, G. Fogli, A.McDonald, K. Nishikawa

… quite realistic prospects of the near future

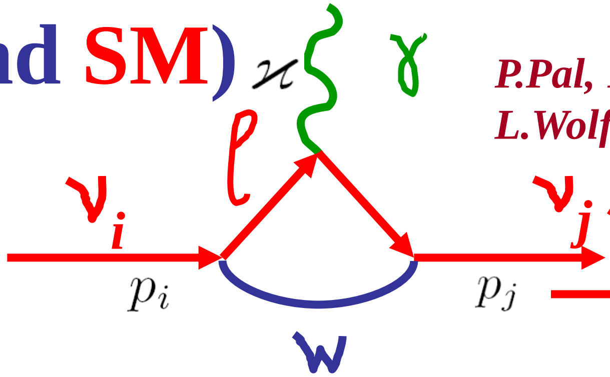
$$\boxed{\mu_\nu \sim 1 \times 10^{-11} \mu_B}$$

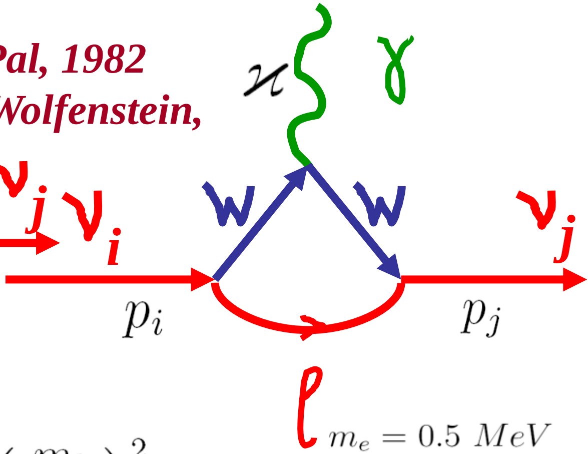
(V.Brudanin,
A.Starostin,
priv. comm.)

3.5 Neutrino (beyond SM) dipole moments

(+ transition moments)

P.Pal, 1982
L.Wolfenstein,





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

- **Dirac neutrino**

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

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

- $m_i, m_j \ll m_l, m_W$

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

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

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

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

or

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

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

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

The first nonzero contribution from **neutrino transition moments**

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

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**

$\epsilon^D_{ii} = 0$ **for CP-invariant interactions**

$\mu^M_{ii} = \epsilon^M_{ii} = 0$

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

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

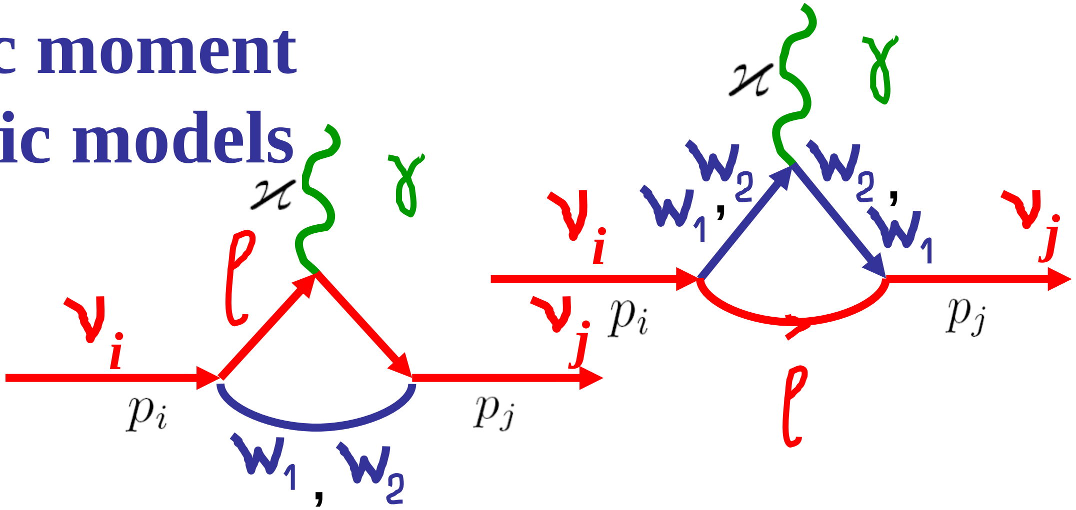
Lee, Shrock, Fujikawa, 1977

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

$\mu^D_{ii} = 0$ **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

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

… charged lepton mass …

… neutrino mass …

...the present status...

to have visible $m_\nu \neq 0$

is not an easy task for

theoreticians

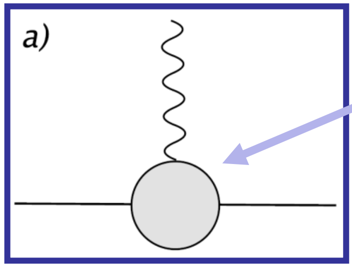
and experimentalists

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

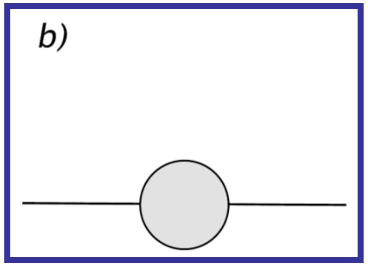


then

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

…combination of constants and loop factors…

contribution to m_ν given by



, then

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

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

Voloshin, 1988;
Barr, Freire,
Zee, 1990

Large magnetic moment

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

$$\Uparrow$$

- 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

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

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

for BSM ($\Lambda \sim 1\ \text{TeV}$) *without fine tuning and under the assumption that* $\boxed{\delta m_\nu \le 1\ \text{eV}}$

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

… A remark on electric charge of ν …

Beyond Standard Model…

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

gauge invariance
+
anomally cancellation constraints

imposed in SM of electroweak interactions

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

- *…General proof:*

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

- *In SM :*

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

- *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*

$\boxed{Q=0}$

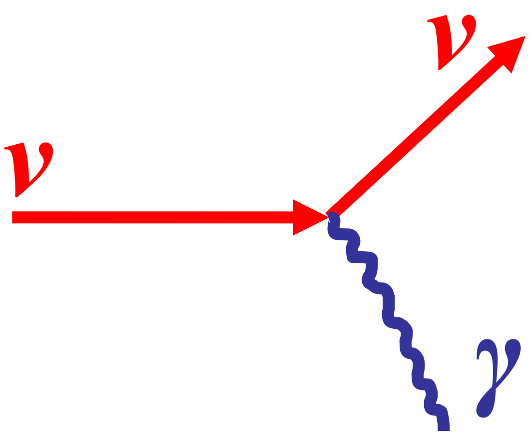
- $\boxed{Q=0}$ *is proven also by direct calculation in SM within different gauges and methods*

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

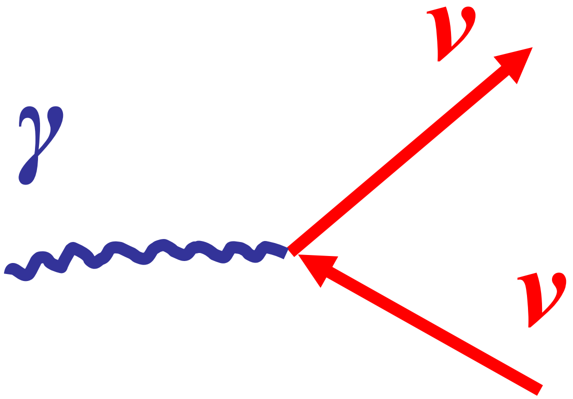
- *… However, strict requirements for **Q** quantization may disappear in extensions of standard $SU(2)_L \times U(1)_Y$ EW model if ν_R with $Y \neq 0$ are included : in the absence of Y quantization electric charges **Q** gets dequantized*

→ **millicharged ν**

ν electromagnetic interactions

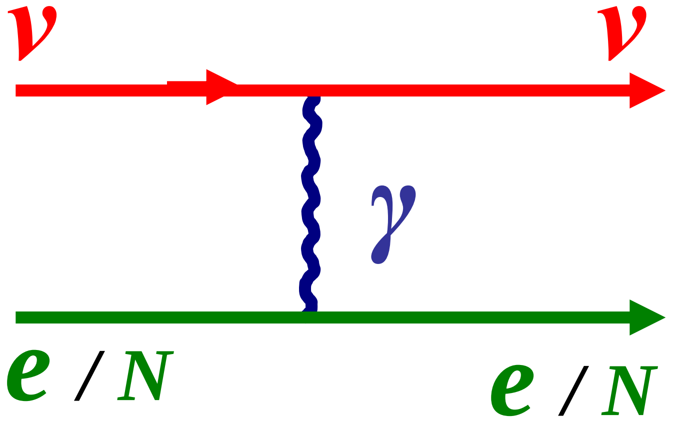


ν **decay, Cherenkov radiation**

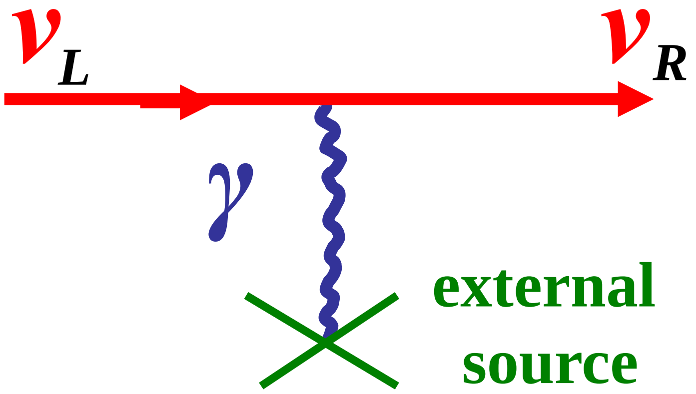


γ **decay in plasma**

!!!



Scattering



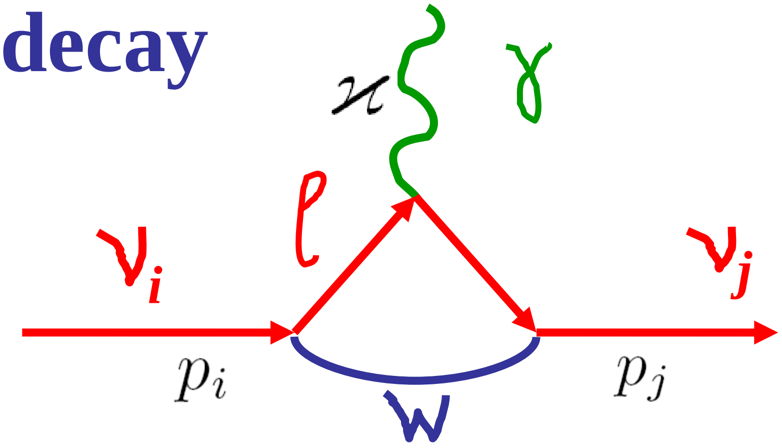
Spin precession

3.7 Neutrino radiative decay

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

$$m_i > m_j$$

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



Radiative decay rate

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

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

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

- 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

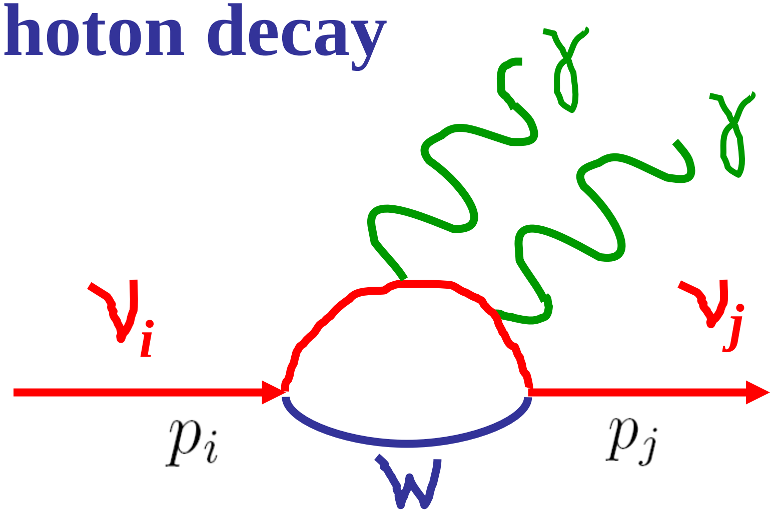
Kolb, Turner 1990;
Ressell, Turner 1990

3.8

Neutrino radiative two-photon decay

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

$m_i > m_j$



fine structure constant

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

… there is no GIM cancellation…

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

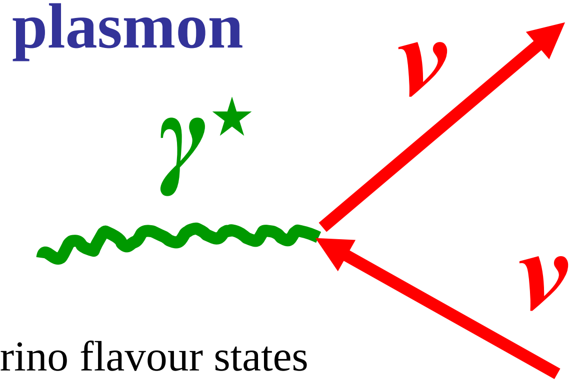
Nieves, 1983; Ghosh, 1984

… 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

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

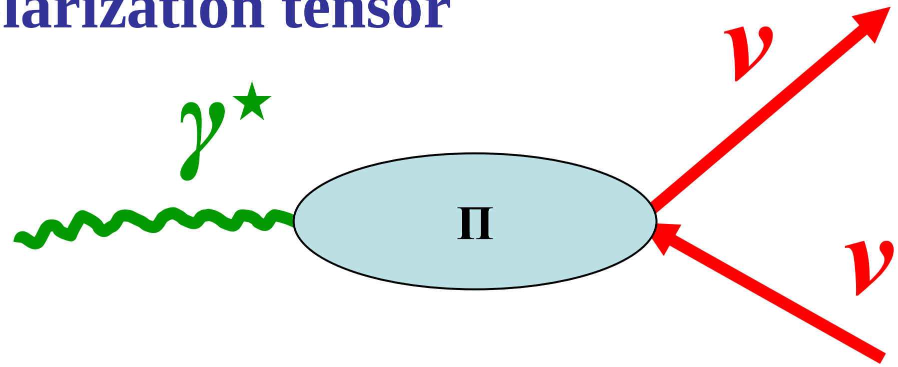
$$\mu^2 \to \sum_{a,b}\left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2\right)$$

distribution function of plasmons

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

Energy-loss rate per unit volume

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



more fast cooling of the star.

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

… best astrophysical limit on ν magnetic moment…

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

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

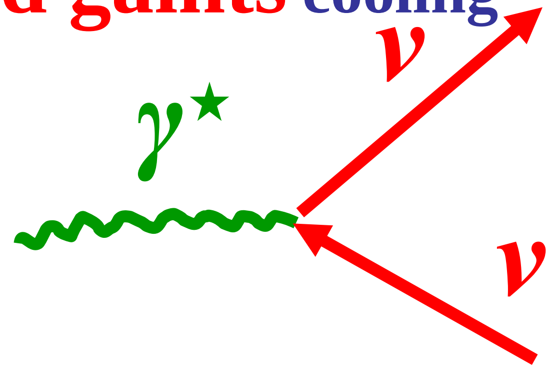
G.Raffelt, PRL 1990

3.10

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

● Constraints on neutrino millicharge from **red gaints** cooling

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



Interaction Lagrangian

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

millicharge

Decay rate

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

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

Halt, Raffelt, Weiss, PRL1994

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

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

Bounds on ν millicharge q_ν from μ_ν (GEMMA Coll. Data)

A.S.,
arXiv: 1302.1168,
May 13, 2013

ν-e cross-section

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

two not seen contributions:

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

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

Bounds on q_ν from

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

... no observable effects of New Physics

Constraints on μ_ν from GEMMA :

Constraints on q_ν

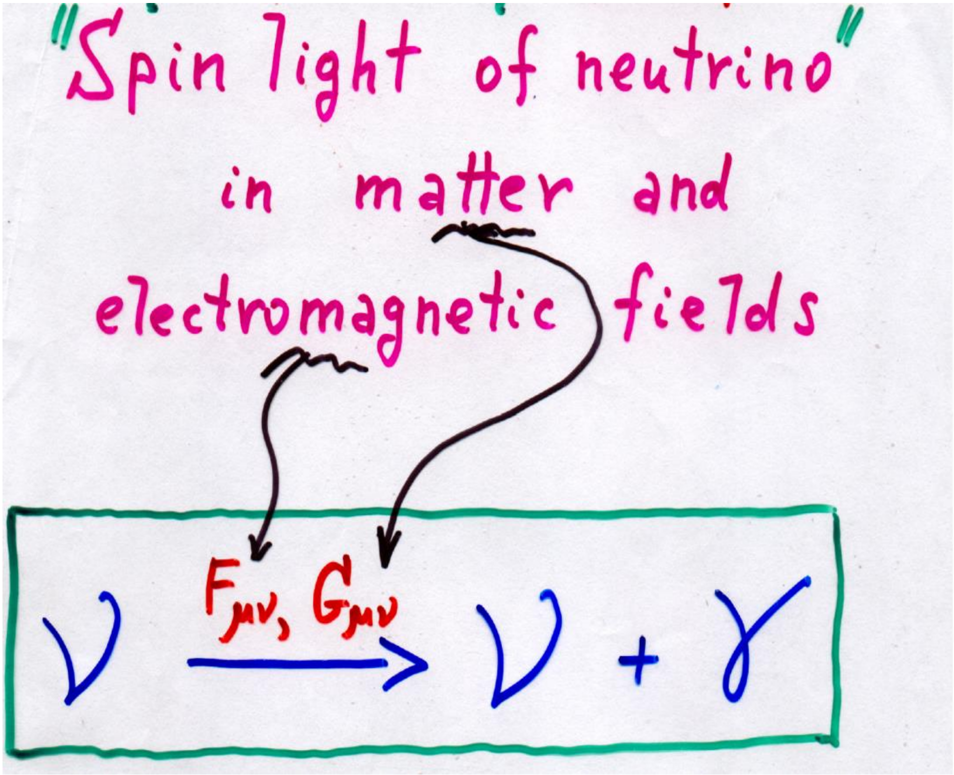
now $\mu_\nu^a < 2.9 \times 10^{-11}\mu_B$ ($T \sim 2.8\ keV$) $\boxed{|\ q_\nu\ | < 1.5 \times 10^{-12} e_0}$

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

2017 (expected) $\mu_\nu^a \sim 0.9 \times 10^{-12}\mu_B$ ($T = 400\ eV$) $\boxed{|\ q_\nu\ | < 2 \times 10^{-13} e_0}$

New mechanism of electromagnetic radiation

$SL\nu$



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

Studenikin, A.Ternov,
Phys.Lett. B 608 (2005) 107

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

Studenikin,

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

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

ν spin evolution in presence of general external fields

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

General types non-derivative interaction with external fields

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

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

$$s, \pi, V^\mu = (V^0, \vec{V}), A^\mu = (A^0, \vec{A}),$$

$$T_{\mu\nu} = (\vec{a}, \vec{b}), \Pi_{\mu\nu} = (\vec{c}, \vec{d})$$

Relativistic (quasiclassical) equation for ν spin vector:

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

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

- **Electromagnetic interaction**

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

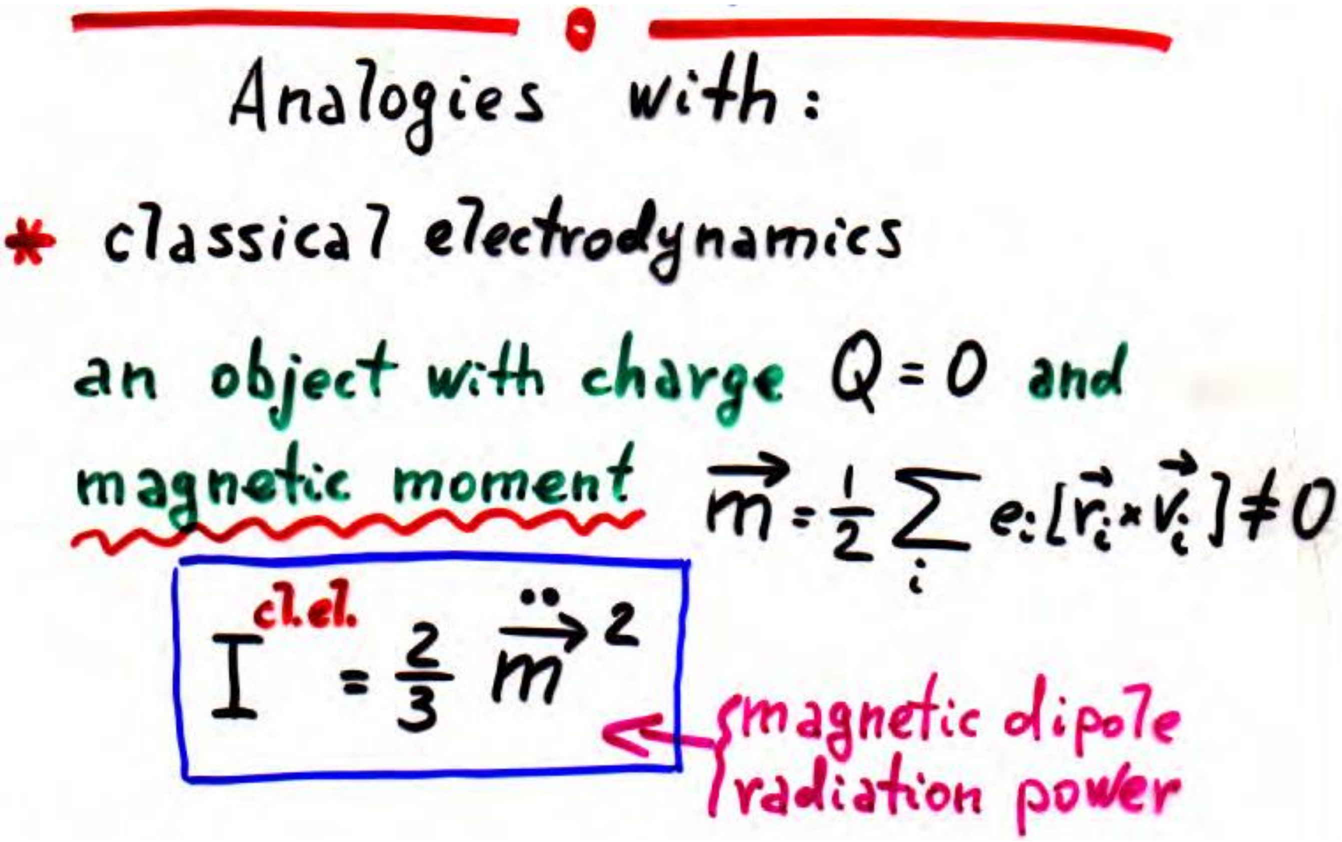
- **SM weak interaction**

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

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

New mechanism of electromagnetic radiation

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



Analogies with:

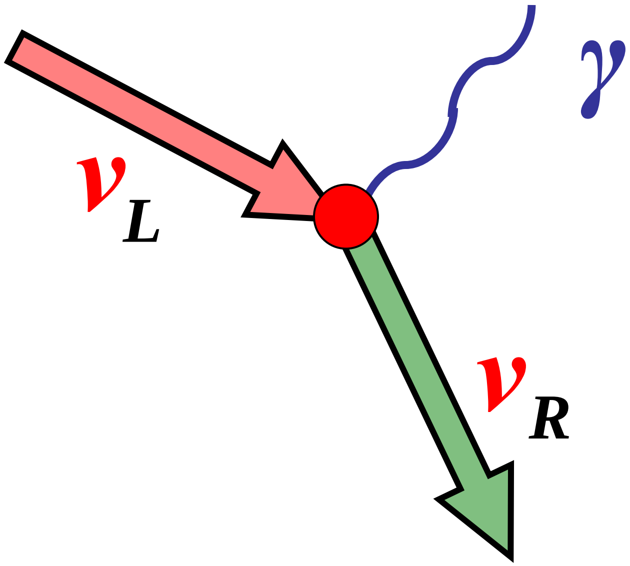
* classical electrodynamics

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

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

magnetic dipole radiation power

Neutrino – photon couplings



broad neutrino lines account for interaction with environment

"Spin light of neutrino in matter"

$SL\nu$

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

«method of exact solutions»

Interaction of particles in external electromagnetic fields

(Furry representation in quantum electrodynamics)

Potential of electromagnetic field

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

quantized part of potential

evolution operator

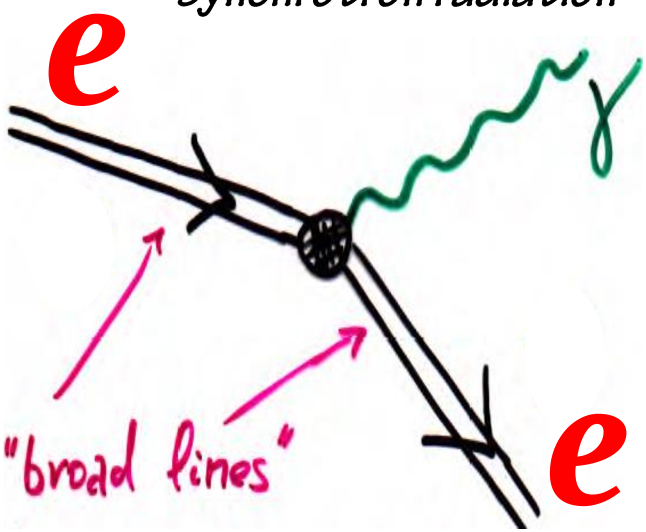
$$\boxed{U_F(t_1,t_2) = Texp\Big[-i\int\limits_{t_1}^{t_2} j^\mu(x)A^q_\mu(x)dx\Big]},$$

charged particles current $\boxed{j_\mu(x) = \frac{e}{2}[\overline{\Psi}_F\gamma_\mu, \Psi_F]}$,

$\mathbf{B}_\perp$

$e \longrightarrow e + \gamma$

synchrotron radiation



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

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

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

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

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",

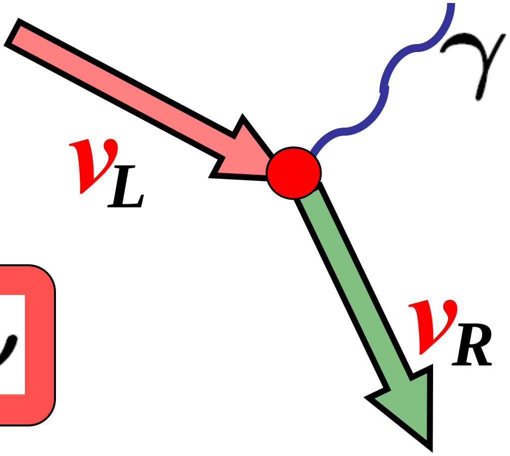
- arXiv : 1209.3245 v2, May 27, 2013

● ν *energy quantization in rotating matter …*

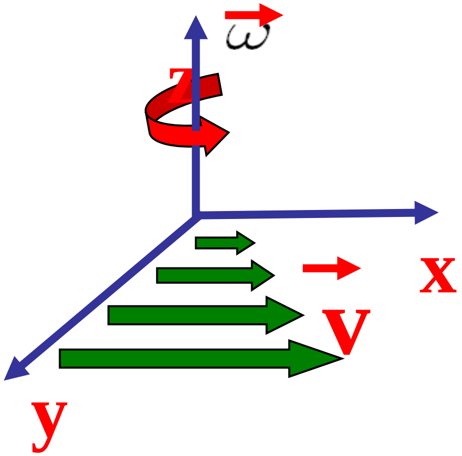
2 problems:

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

Modified Dirac equation for neutrino in matter

Addition to the vacuum neutrino Lagrangian

matter current

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

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

matter polarization

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

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)

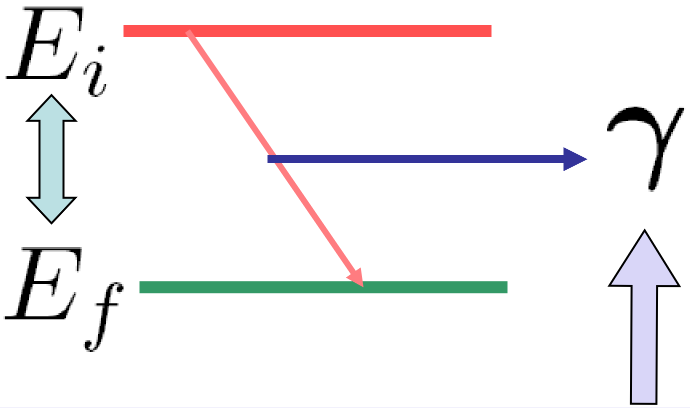
Quantum treatment of *spin light of neutrino* in matter shown**s** that this process originates from the **two subdivided phenomena:**

$SL\nu$

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

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

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

$$p \gg m_{plasmon}$$

also discussed by A.Kuznetsov, N.Mikheev, 2007

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

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

it follows that

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

A.Grigoriev, A.Lokhov,
A.Ternov, A.Studenikin

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

Phys.Lett.B 718 (2012) 512-515

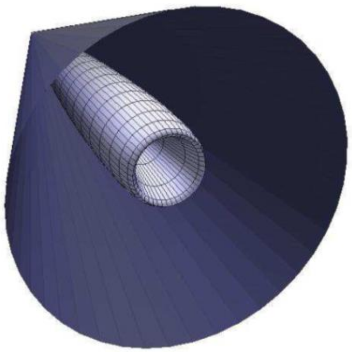


Figure 1: 3D representation of the radiation power distribution.

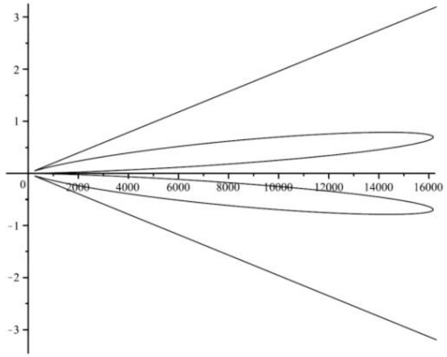


Figure 2: The two-dimensional cut along the symmetry axis. Relative units are used.

4. Conclusions

We developed a detailed evaluation of the spin light of neutrino in matter accounting for effects of the emitted plasmon mass. On the base of the exact solution of the modified Dirac equation for the neutrino wave function in the presence of the background matter the appearance of the threshold for the considered process is confirmed. The obtained exact and explicit threshold condition relation exhibit a rather complicated dependance on the matter density and neutrino mass. The dependance of the rate and power on the neutrino energy, matter density and the angular distribution of the $SL\nu$ is investigated in details. It is shown how the rate and power wash out when the threshold parameter $a = m_\gamma^2/4\tilde{n}p$ approaching unity. From the performed detailed analysis it is shown that the $SL\nu$ mechanism is practically insensitive to the emitted plasmon mass for very high densities of matter (even up to $n = 10^{41} cm^{-3}$) for ultra-high energy neutrinos for a wide range of energies starting from $E = 1$ TeV. This conclusion is of interest for astrophysical applications of $SL\nu$ radiation mechanism in light of the recently reported hints of $1 \div 10$ PeV neutrinos observed by IceCube [17].

ν energy quantization in rotating media: new mechanism for ν trapping inside compact objects

Grigoriev, Savochkin, Studenikin, Russ.Phys.J. 50 (2007) 845
Studenikin, J.Phys. A: Math.Theor. 41 (2008) 164047
Balantsev, Popov, Studenikin,
J.Phys. A:Math.Theor. 44 (2011) 255301
Balantsev, Studenikin, Tokarev, Phys.Part.Nucl. 43 (2012), 727
Phys.Atom.Nucl. 76 (2013) 489
Studenikin, Tokarev, arXiv: 1209.3245 v 2, May 28, 2013

Millicharged magnetic ν in rotating magnetized matter

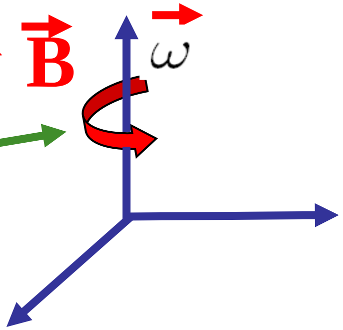
Balatsev, Tokarev, Studenikin,
Phys.Part.Nucl., 2012,
Phys.Atom.Nucl., Nucl.Phys. B, 2013,

- Studenikin, Tokarev, arXiv: 1209.3245, V 2, May 27, 2013

Modified Dirac equation for ν wave function

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

external magnetic field



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

matter potential

rotating matter

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

wave function (exact solution)

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

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

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

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

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

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

energy :

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

$\boxed{N = 0, 1, 2, \dots}$ energy quantization in rotating magnetized matter

ν energy is quantized in rotating matter

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

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

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

matter rotation frequency

scalar potential of electric field

Transversal motion of ν is quantized in rotating medium like electron motion is quantized in magnetic field (Landau energy levels):

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

In quasi-classical approach

- ✓ quantum states in rotating matter
- ✓ motion in circular orbits

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

due to effective Lorentz force

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

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

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

matter induced “charge”, “electric” and “magnetic” fields

Neutrino Star Turning (νST) mechanism

Studenikin, Tokarev,
arXiv:1209.3245

…Due to effective Lorentz force
feedback of neutrinos on rotating star

Escaping ν s move on curved orbits inside rotating star should effect initial rotation of star

… To avoid contradiction between impact νST mechanism on pulsar rotation and observational data on pulsars

…the shift of rotation frequency (for realistic choice of the star characteristics)

$$\boxed{\frac{|\triangle\omega_0|}{\omega_0} \simeq 10^{17}\varepsilon\left(\frac{P_0}{10\ \mathrm{s}}\right)}$$

$$\varepsilon = q_\nu / e_0$$

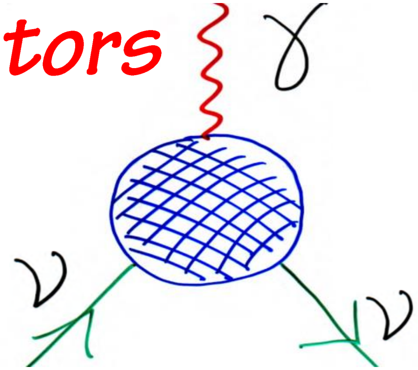
From $|\triangle\omega_0| < \omega_0$ (for slowly rotating stars $P_0 \sim 10\ s$)

new astrophysical limit

$$\boxed{q_\nu < 10^{-17} e_0}$$

Conclusions

ν e.m. vertex function → 4 form factors



charge dipole magnetic and electric

- $$\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2)i\sigma_{\mu\nu}q^\nu + f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5$$
  $$f_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$ anapole
- EM properties → a way to distinguish Dirac and Majorana ν
- Standard Model with ν_R $(m_\nu \neq 0)$: $\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e} \sim 3\cdot 10^{-19}\mu_B\left(\frac{m_{\nu_e}}{1eV}\right)$
- In extensions of SM → enhancement of ν magnetic moment, even electrically millicharged ν
- Limits from reactor ν-e scattering experiments (2012):

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

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

- Limits from astrophysics, star cooling (1990):

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

$$\boxed{q_\nu < 10^{-17} e_0}$$ νST mechanism

16th Lomonosov Conference on Elementary Particle Physics, www.icas.ru Moscow State University, August 22-27, 2013

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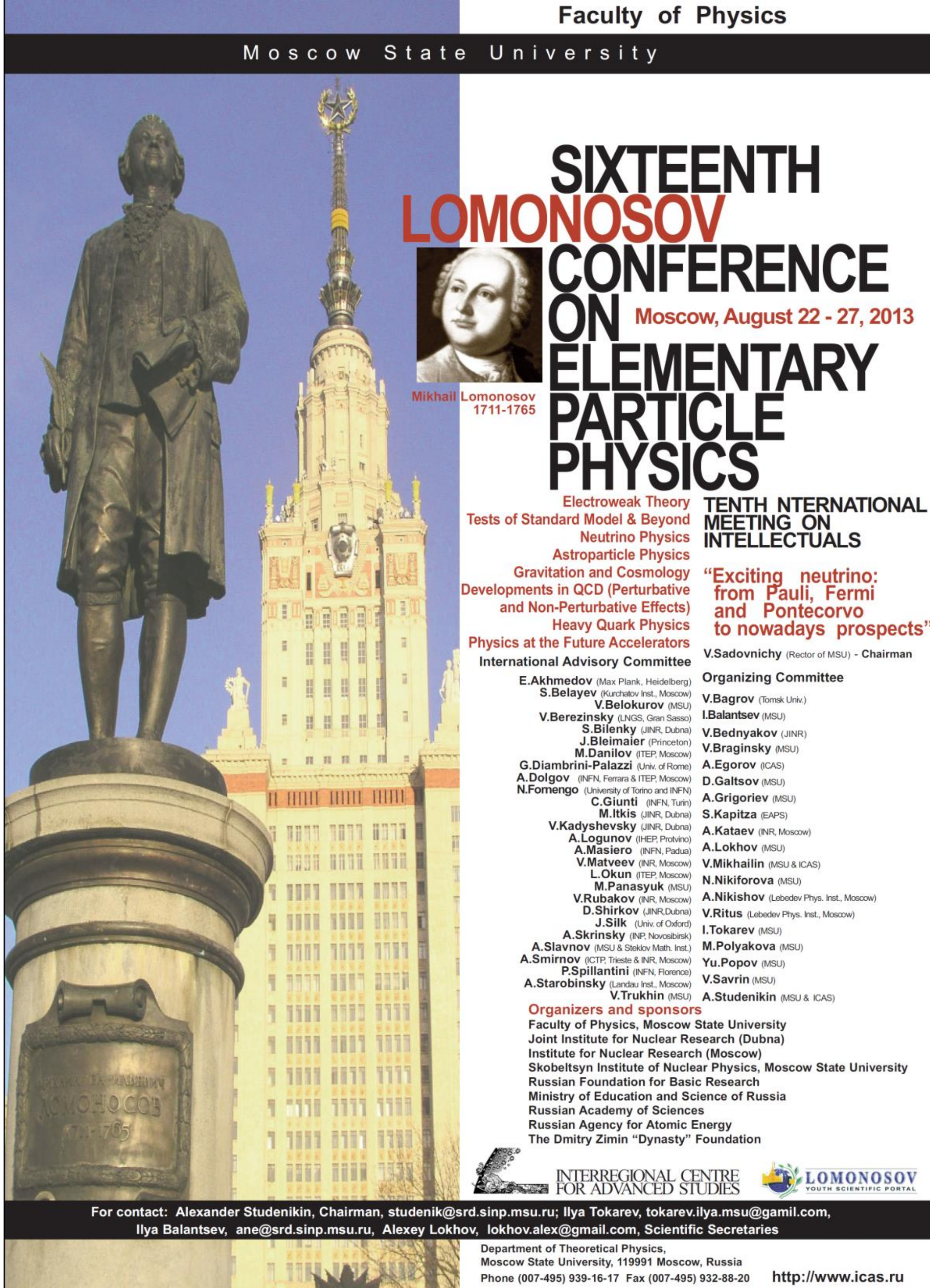
1913-1993

centennial anniversary



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For contact: Alexander Studenikin, Chairman, studenik@srd.sinp.msu.ru; Ilya Tokarev, tokarev.ilya.msu@gamil.com, Ilya Balantsev, ane@srd.sinp.msu.ru, Alexey Lokhov, lokhov.alex@gmail.com, Scientific Secretaries

Department of Theoretical Physics,
Moscow State University, 119991 Moscow, Russia
Phone (007-495) 939-16-17 Fax (007-495) 932-88-20

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