Neutrino electromagnetic properties

Neutrino
Oscillation Workshop
Conca Specchiulla
6-13/09/08

Alexander Studenikin

Moscow State
University

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

Neutrino mass

$$m_\nu \neq 0 \,!$$

$$\Rightarrow$$

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

In the Standard Model : $m_\nu = 0$,
there is no ν_R $\Longrightarrow$
ν magnetic moment $\mu_\nu = 0$.

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

● Outline ●

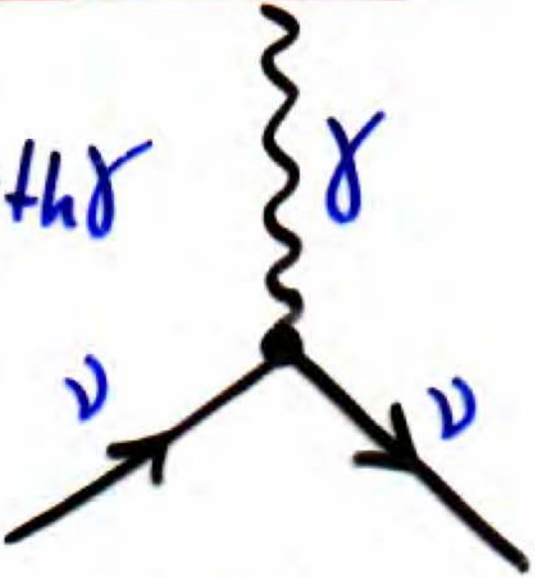
0. Introduction
1. ν magnetic moment in experiments
2. New experimental result on μ_ν
3. ν electromagnetic properties - theory
    - 3.1 ν vertex function
    - 3.2 μ_ν (arbitrary masses)
    - 3.3 relationship between m_ν and μ_ν
    - 3.4 ν vertex function in case of flavour mixing
    - 3.5 ν dipole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

Electromagnetic properties of ν

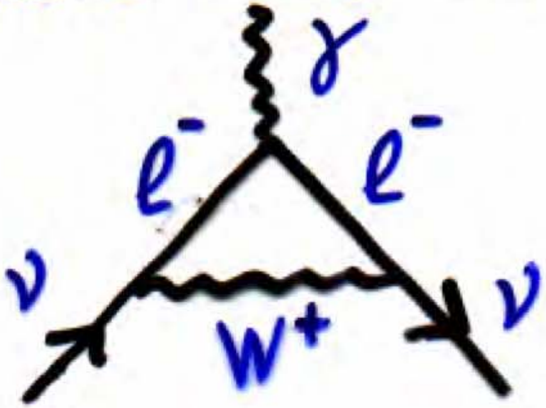
② Electromagnetic ν properties

gauge invariance and anomaly-free constraints of the model

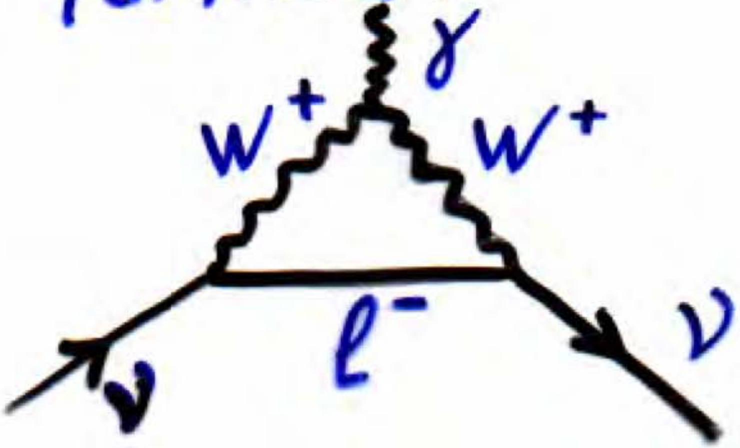
$Q_\nu = 0 \Rightarrow$ interaction with γ



entirely from loop effects through weak interactions with charged particles:



,



Effective Lagrangian for the spin component of ν vertex

$$L = \frac{1}{2}\bar{\nu}_j \sigma_{\eta\xi}(\beta_{ij} + \varepsilon_{ij}\gamma_5)\nu_i F^{\eta\xi} + \text{h.c.}\,,$$

e.m. field tensor

magnetic and **electric** moments
which couple together mass eigenstates

$(\nu_i)_L$ and $(\nu_j)_R$ ⇨ change of the helicity states

- $\nu_i = \nu_j$ ➡ diagonal moments
- $\nu_i \neq \nu_j$ ➡ transitional moments
- $\varepsilon_{ii} = \beta_{ii} = 0$ for Majorana ν

E.M. properties
↳ a way to distinguish Dirac and Majorana ν

1

ν magnetic moment in experiments

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

“Physics is an experimental science”

Studies of *ν-e* scattering - most sensitive method of experimental investigation of μ_ν

Cross-section:

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

see talk of Livia Ludhova (BOREXINO)

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

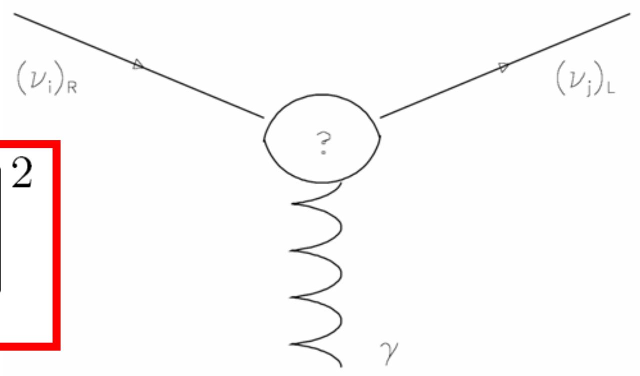
$$g_V = \begin{cases} 2\sin^2\theta_W + \frac{1}{2} & \text{for} \quad \nu_e\,, \\ 2\sin^2\theta_W - \frac{1}{2} & \text{for} \quad \nu_\mu, \nu_\tau\,, \end{cases} \qquad g_A = \begin{cases} \frac{1}{2} & \text{for} \quad \nu_e\,, \\ -\frac{1}{2} & \text{for} \quad \nu_\mu, \nu_\tau \end{cases}$$

for anti-neutrinos $g_A \to -g_A$,

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

ν magnetic moment in experiments

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



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

where neutrino mixing matrix $\mu_{ij} \equiv |\beta_{ij} - \varepsilon_{ij}|$

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 $^8\mathrm{B}$ and $^7\mathrm{Be}$) are different.

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)

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

reported at Neutrino'08 Conference (New Zealand),
see also talk of Livia Ludhova

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

Montanino,
Picariello,
Pulido, PRD 2008

2

New Result of
Neutrino Magnetic Moment Measurement
in GEMMA Experiment (2008)

A.Starostin et al, in: "Particle Physics on the Eve of LHC", ed. by A.Studenikin, World Scientific (Singapore), p.112, 2008,
www.icas.ru (13th Lomonosov Conference)

A.Beda et al, Phys.Atom.Nucl. 70 (2007) 1873

“The New Result of the Neutrino magnetic Moment measurement in the GEMMA Experiment”

A.Starostin et al, in: “Particle Physics on the Eve of LHC”, ed. by A.Studenikin,
World Scientific (Singapore), 2008, www.icas.ru (13th Lomonosov Conference)

GEMMA I (2008)

Status :
“on” (operation of reactor) 9426 hours
“off” (reactor shutdown) 2965 hours

!

$$\boxed{\mu_\nu \leq \; 3.1 \times 10^{-11} \mu_B}$$

and

$$\boxed{\mu_\nu \leq \; 4.9 \times 10^{-11} \mu_B}$$

…obtained with **more conservative data analysis** method

Astrophysics bounds on μ_ν

$$\boxed{\mu_\nu(\text{astro}) < 10^{-10}\text{–}10^{-12}\ \mu_{\text{B}}}$$

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.

The bounds depend on

- modeling of the 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

μ_ν is presently known to be in the range

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

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

3

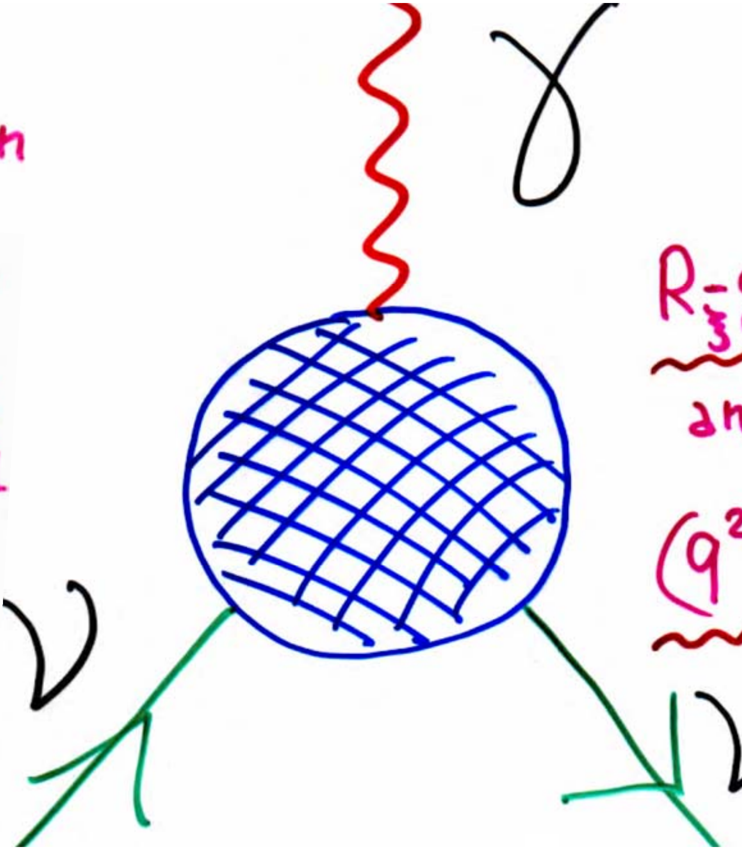
… a bit of ν electromagnetic properties theory

3.1 ν vertex function

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

M. Dvornikov, A. Studenikin

- ⊛ Phys. Rev. D 63, 073001, 2004,
  "Electric charge and magnetic moment of massive neutrino";
  JETP 126 (2004), N8, 1
- ⊛ "Electromagnetic form factors of a massiv neutrino."



R_ξ-gauge

and

$(q^2 \neq 0)$

$$\Delta_\mu(q) = \overset{\text{charge}}{\underline{f_Q(q^2)}}\gamma_\mu + \overset{\text{magnetic moment}}{\underline{f_M(q^2)}}\, i\sigma_{\mu\nu} q^\nu -$$

$$- \underset{\text{electric moment}}{\underline{f_E}}(q^2)\, i\sigma_{\mu\nu} q^\nu \gamma_5 - \underset{\text{anapole moment}}{\underline{f_A(q^2)}}(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

3.2

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

Dvornikov,
Studenikin, PRD 2004

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

magnetic moment

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

!

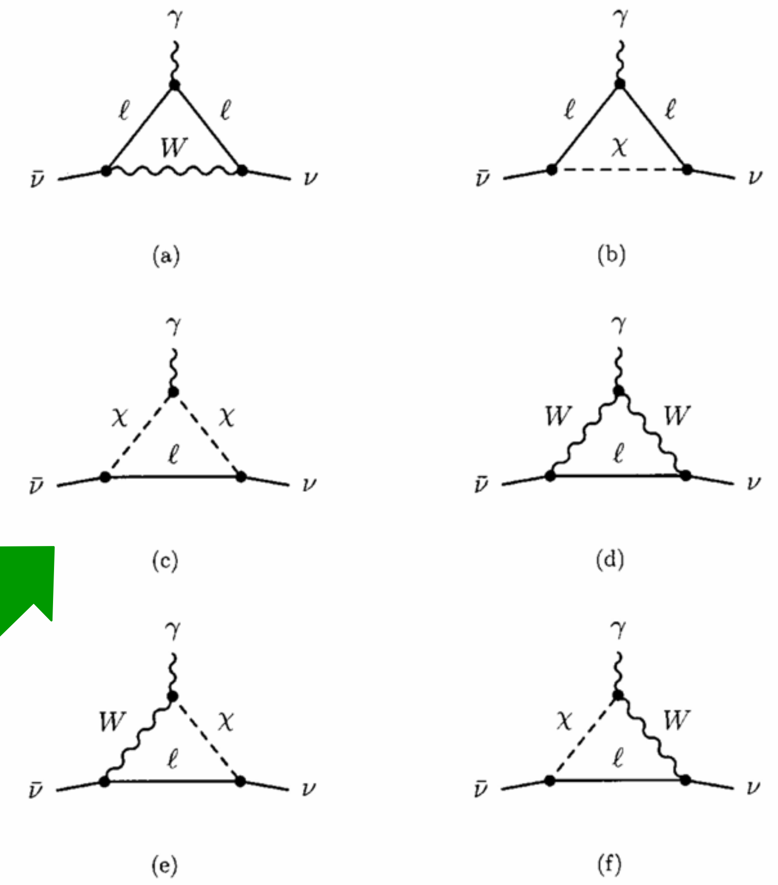
two mass parameters $a=\left(\frac{m_\ell}{M_W}\right)^2$ $b=\left(\frac{m_\nu}{M_W}\right)^2$

and gauge-fixing parameter $\alpha=\frac{1}{\xi}$

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

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

Proper vertices



ν magnetic moment

(heavy massive neutrino)

- LEP data →

only 3 light νs coupled to Z°,

for any additional neutrino

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

● $m_\nu \ll m_e \ll M_W$ **light** ν

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

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

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

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

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

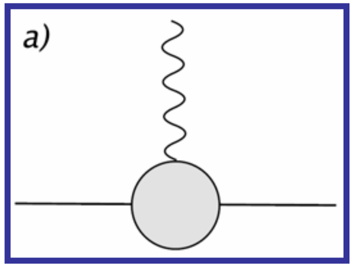
$$\boxed{\mu_\nu = \frac{3eG_F}{8\pi^2\sqrt{2}}\underline{m_\nu}\left\{1+\frac{5}{18}b\right\}}, \quad b = \left(\frac{m_\nu}{M_W}\right)^2$$

● $m_e \ll M_W \ll m_\nu$ **heavy** ν

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

3.3 Naïve relationship between the size of m_ν and μ_ν

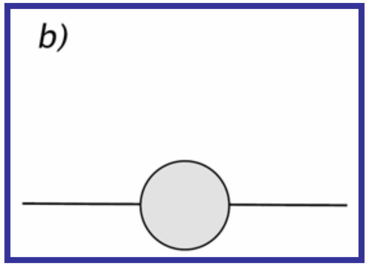
If μ_ν is generated by physics beyond the SM at energy scale Λ ,



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

P.Vogel e.a., 2006

contribution to m_ν given by



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

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

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

large magnetic moment

$$\mu_\nu = \underset{\Uparrow}{\mu_\nu}(m_\nu, m_{B^+}, m_{\ell^-})$$

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

Kim, 1976
Beg, Marciano, Ruderman, 1978

- **M.Voloshin (ITEP),**

“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

- supersymmetry

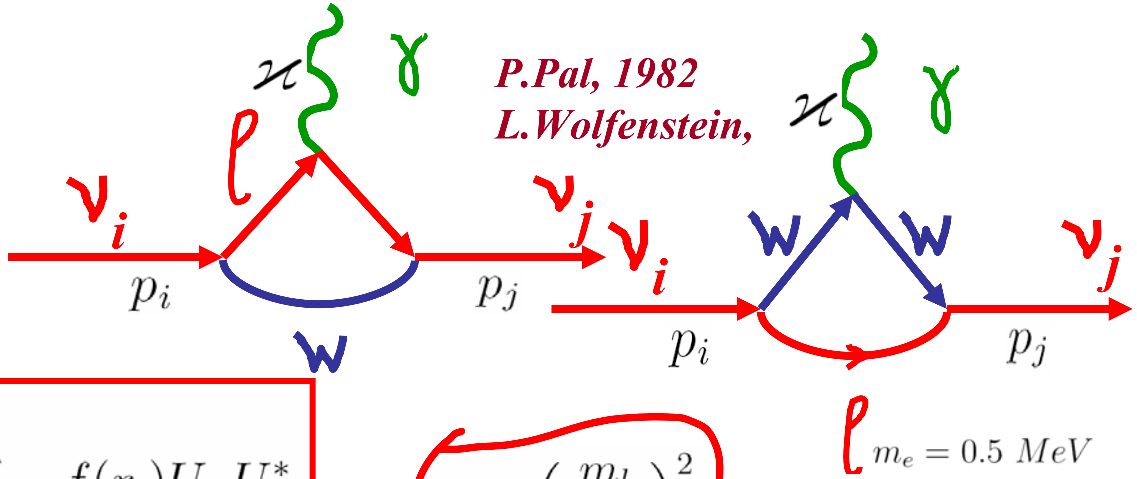
- extra dimensions

considerable enhancement of μ_ν to experimentally relevant range

3.5

Neutrino dipole moments

(+ transition moments)



P.Pal, 1982
L.Wolfenstein,

- **Dirac neutrino**

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

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

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

- $m_i, m_j \ll m_l, m_W$

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

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

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

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

or

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

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

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

The first nonzero contribution from neutrino transition moments

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

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**

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

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

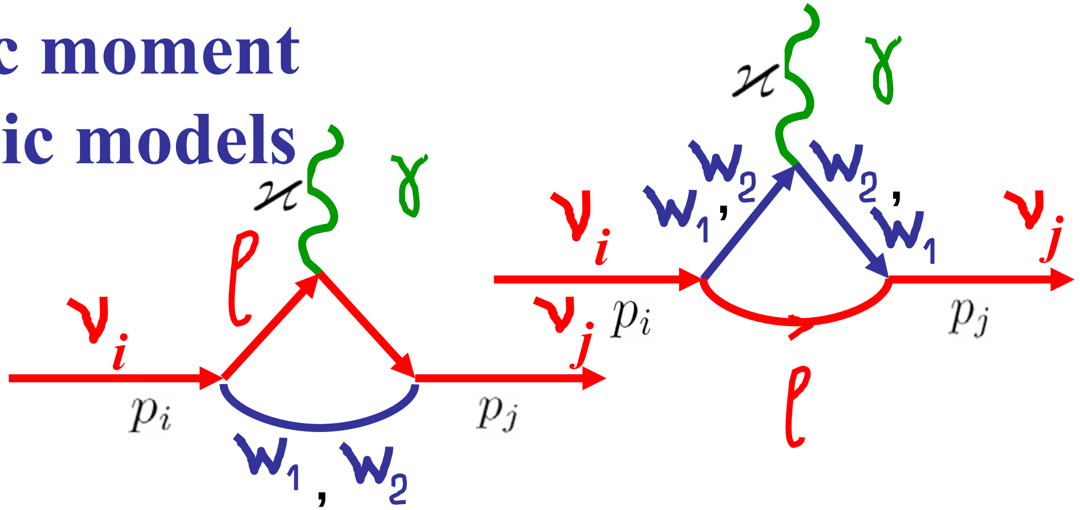
$$r_l = \left(\frac{m_l}{m_W}\right)^2$$

Lee, Shrock, Fujikawa, 1977

- *no GIM cancellation*
- μ^D_{ii} **- to leading order - independent on U_{li} and $m_{l=e,\ \mu,\ \tau}$**
- $$\mu_e^2 = \sum_{i=1,2,3} \mid U_{ie}\mid^2 \mu^2_{ii}$$
- $\mu^D_{ii} = 0$ **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

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

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

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

!

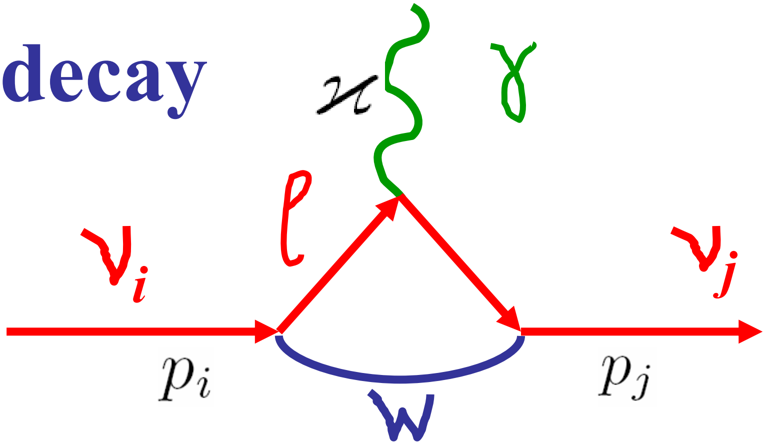
any indication for non-trivial electromagnetic properties of ν , that could be obtained within reasonable time in the future, would give evidence for interactions beyond extended Standard Model

3.7 Neutrino radiative decay

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

$$m_i > m_j$$

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



Matrix element squired :

$$| M |^2 = 8\mu_{eff}^2(\varkappa \cdot p_i)(\varkappa \cdot p_j)$$

Radiative decay rate

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

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

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

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

2) SN 1987A ν burst (all flavours),

3) spectral distortion of CMBR

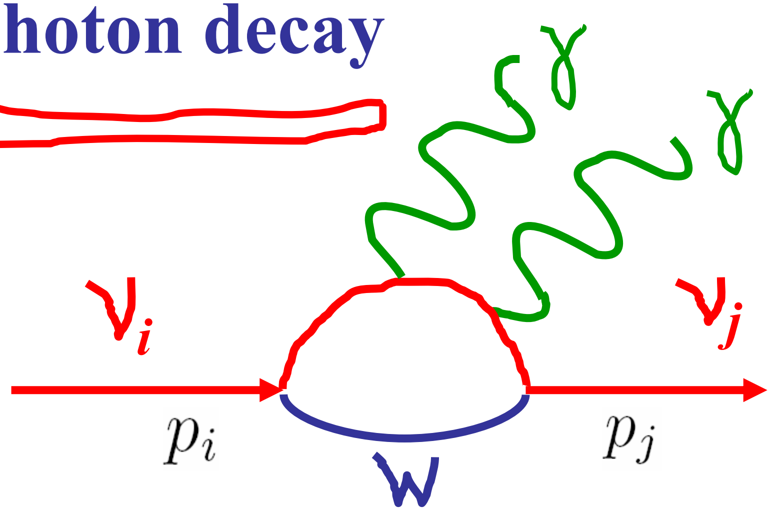
Raffelt 1999
Kolb, Turner 1990;
Ressell, Turner 1990

3.8

Neutrino radiative two-photon decay

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

$m_i > m_j$



fine structure constant $\ll 1$

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

✓ *… there is no GIM cancellation…*

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

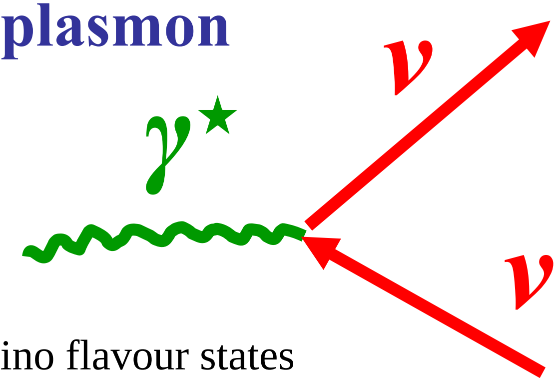
Nieves, 1983; Ghosh, 1984

… 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 **giant** stars by plasmon decay $\gamma^\star \longrightarrow \nu\nu$



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

neutrino flavour states

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

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

= 0 in vacuum $\omega = k$

In the classical limit $\gamma^\star$ - like a massive particle with $\omega^2 - k^2 = \omega_{pl}^2$

Energy-loss rate per unit volume

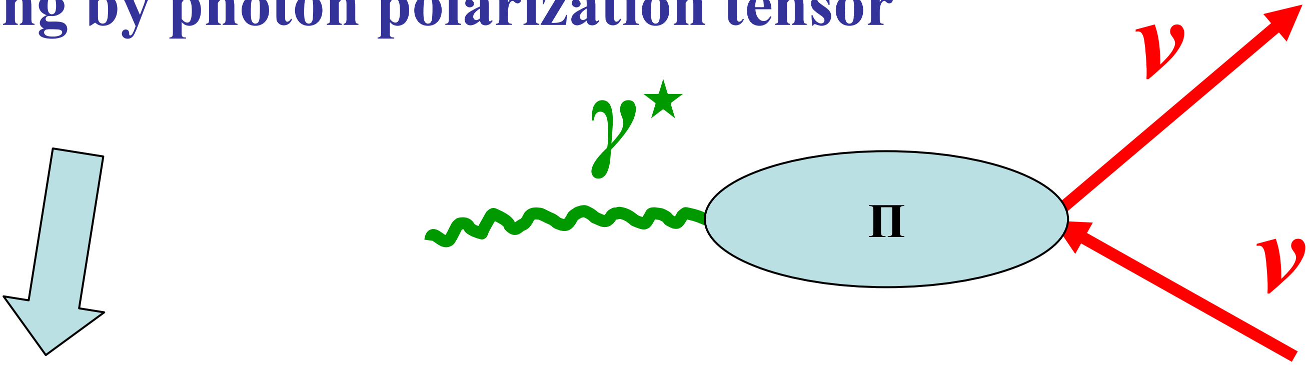
$$\boxed{Q_\mu = g\int\frac{d^3k}{(2\pi)^3}\omega f_{BE}\Gamma_{\gamma\to\nu\bar{\nu}}}$$

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

distribution function of plasmons

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

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)**

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

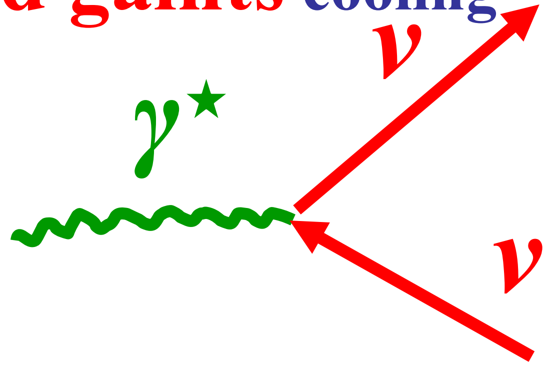
$$\mu^2 \to \sum_{a,b}\left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2\right)$$

G.Raffelt, PRL 1990

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

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

$\gamma^{\star} \longrightarrow \nu\nu$



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…** $q_\nu \leq 3 \times 10^{-21} e$

3.11

ν charge radius

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

1. electric

dipole

2. magnetic

3. electric

4. anapole

Although it is usually assumed that ν are electrically neutral (charge quantization implies $Q \sim \frac{1}{3}e$), ν can dissociates into charged particles so that $f_Q(q^2) \neq 0 \; for \; q^2 \neq 0$:

$$\boxed{f_Q(q^2) = f_Q(0) + q^2 \frac{df_Q}{dq^2}(0) + \cdots ,}$$

where the massive ν charge radius

$$\boxed{\langle r_\nu^2 \rangle = -6\, \frac{df_Q}{dq^2}(0)}$$

For massless ν

anapole moment

$$\boxed{a_\nu = f_A(q^2) = \frac{1}{6}\langle r_\nu^2 \rangle}$$

Interpretation of charge radius as an observable is rather delicate issue: $\langle r_\nu^2 \rangle$ represents a correction to tree-level electroweak scattering amplitude between ν and charged particles, which receives radiative corrections from several diagrams (including γ exchange) to be considered simultaneously → calculated CR is infinite and gauge dependent quantity.

For massless ν, a_ν and $\langle r_\nu^2 \rangle$ can be defined (finite and gauge independent) from scattering cross section.

For massive ν → ? ? ?

Direct calculation of γ - Z and proper-vertex diagrams contribution

ν anapole moment is infinite and gauge dependent

$m=0$,   *Lucio, Rosado, Zepeda, 1985*
$m\neq 0$,   *Dvornikov, Studenikin, 2004*

is not a static quantity,
can’t be measured with external field

Physical definition of anapole moment:

- through diagrammes contributing to $\boxed{\nu_l \; l' \to \nu_l \; l'}$
- with inclusion of all ν anapole diagrammes
- ● finite and gauge independent
- does not depend on charged lepton l' .

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

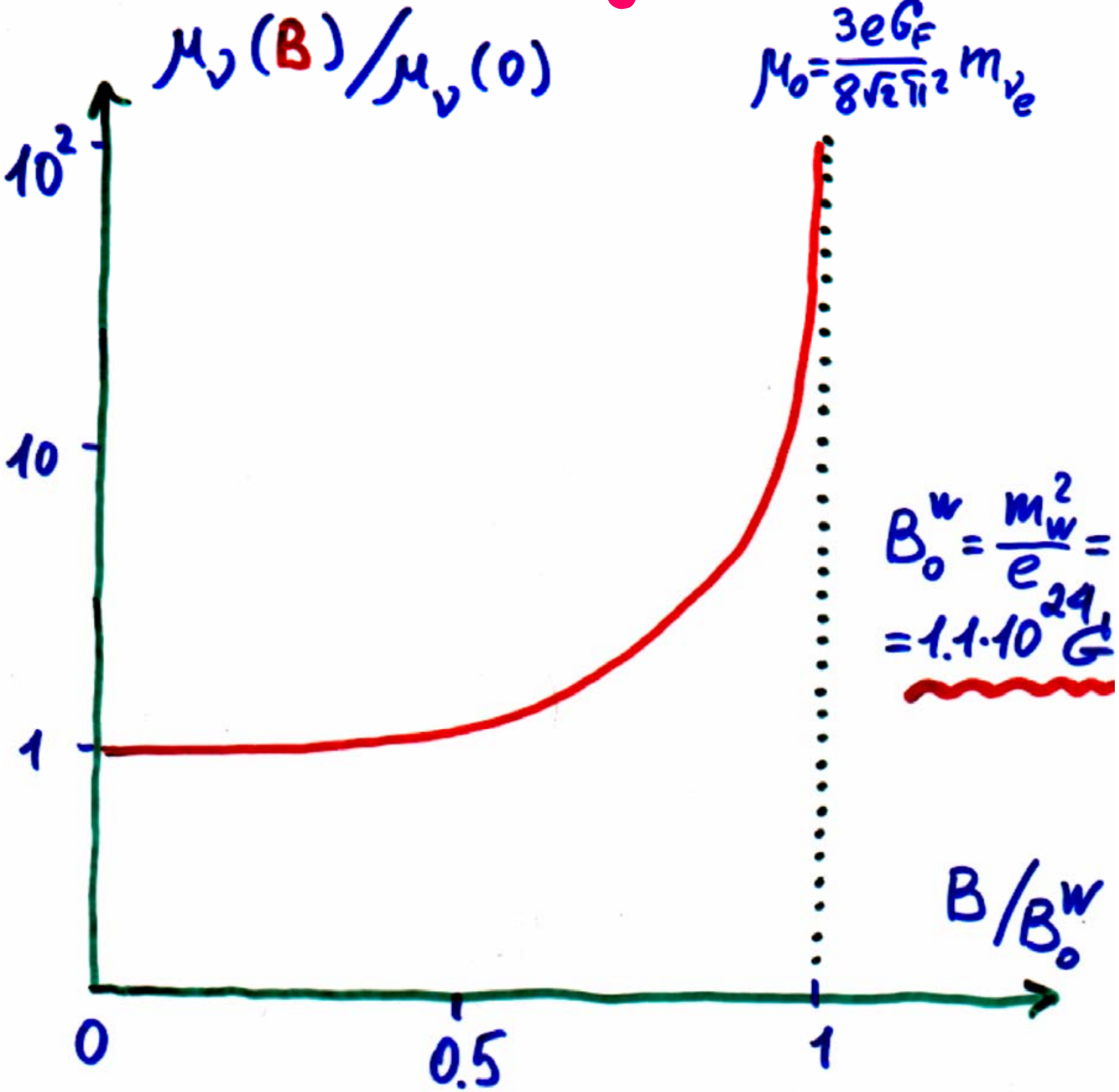
⊛ induced electric charge of ν in magnetized matter

⊛ Oraevsky, Semikoz, Smorodinsky, 1986

Bhattacharaya, Ganguly, Konar, 2002

Nieves, 2003

Neutrino magnetic moment



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

$B_0^W = \frac{m_W^2}{e} = 1.1 \cdot 10^{24}$ G

Borisov,
Zhukovsky,
Kurilin,
Ternov, 1985;

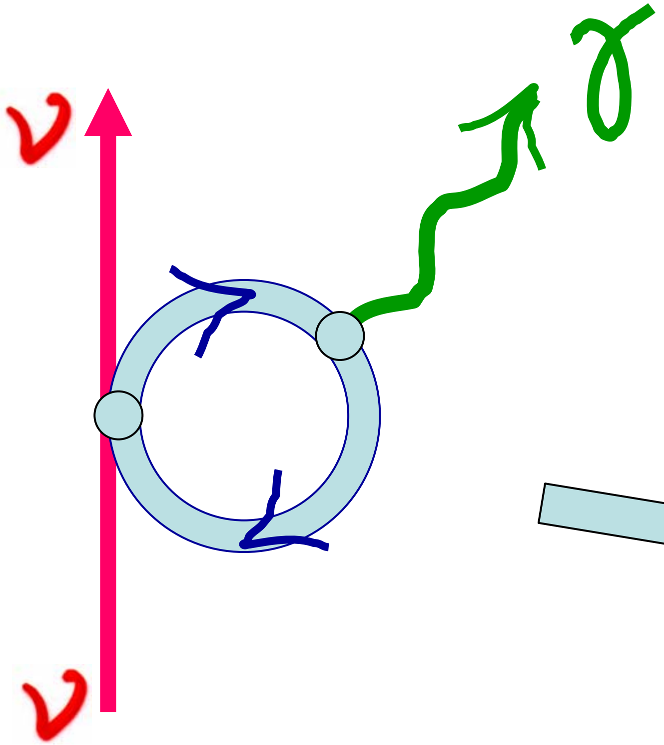
***Masood,
Perez Rojas,
Gaitan,
Rodrigues-Romo,
1999***

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

4 ν spin and spin-flavour oscillations in $B_\perp$

Consider **two different neutrinos**: $\nu_{e_L}, \quad \nu_{\mu_R}, \quad m_L \neq m_R$

with **magnetic moment interaction**

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

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

ν **evolution equation**

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

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

!

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

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

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

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

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

- **Resonance amplification of oscillations in matter:**

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

Akhmedov, 1988
Lim, Marciano

In magnetic field

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

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

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

Neutrino conversions and oscillations in magnetic field

- ⊛ $\nu_\odot$ problem $\nu_L \overset{B}{\leftrightarrow} \nu_R$ ← …for recent analysis see

  Cisneros, 1971

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

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

  J.Pulido, 2006

  A.Balantekin,
  C.Volpe, 2005

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

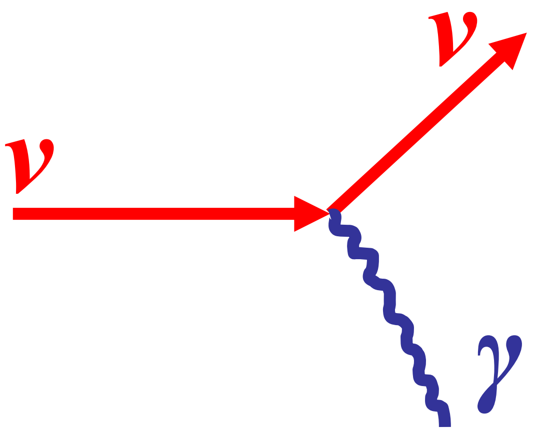
  Dar, 1987

  Fujikawa, Shrock, 1988
  Voloshin, 1988

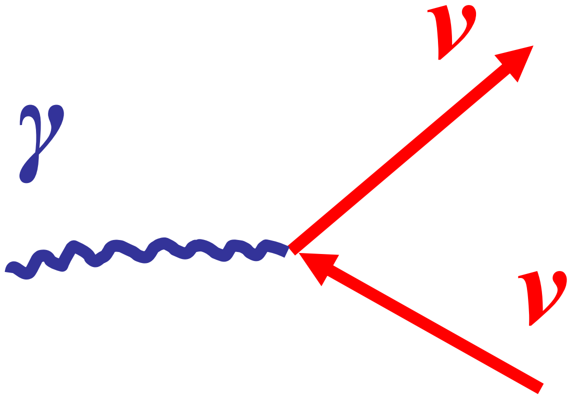
✳ *Spin-flavour oscillations in early universe – strong* $B_\perp$
→ *population of* ν *wrong-helicity states (r.h.) would accelerate expansion of universe (???)*

Conclusion

Neutrino – photon couplings (I)

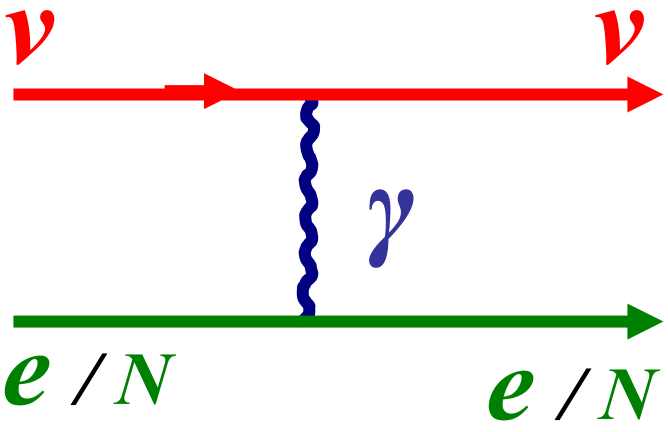


ν decay, Cherenkov radiation

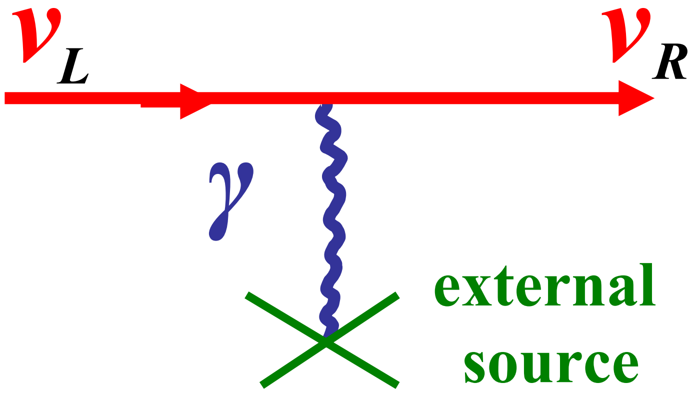


γ decay in plasma

!!!



Scattering



Spin precession

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

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

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

$$s, \pi, V^\mu = (V^0, \vec{V}), A^\mu = (A^0, \vec{A}),$$
$$T_{\mu\nu} = (\vec{a}, \vec{b}), \Pi_{\mu\nu} = (\vec{c}, \vec{d})$$

Relativistic equation (quasiclassical) for ν *spin vector:*

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

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

- **Electromagnetic interaction**

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

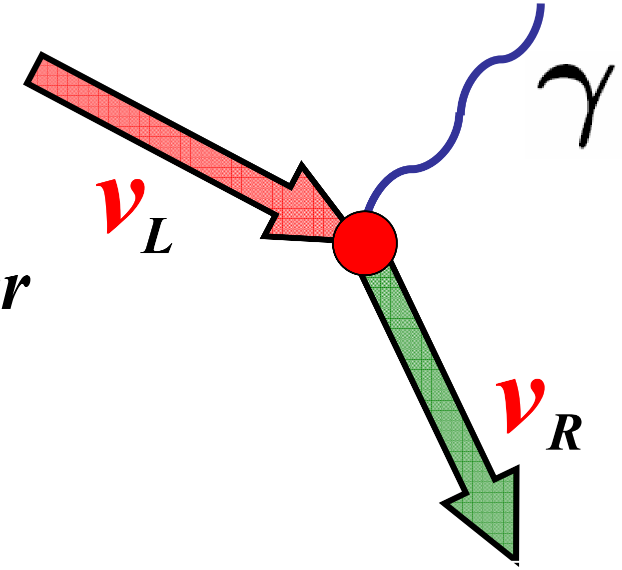
- **SM weak interaction**

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

New mechanism of electromagnetic radiation

$SL\nu$

Spin light of neutrino in matter



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

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

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

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

A.Studenikin, **J.Phys.A: Math.Gen. 39** (2006) 6769; **Ann.Fond. de Broglie 31** (2006) 289
A.Studenikin, **Phys.Atom.Nucl. 70** (2007) 1275; *ibid* **67** (2004)1014
A.Grigoriev, A.Savochkin, A.Studenikin, **Russ.Phys. J. 50** (2007) 845
A.Grigoriev, S.Shinkevich, A.Studenikin, A.Ternov, I.Trofimov, **Russ.Phys. J. 50** (2007) 596
A.Studenikin, A.Ternov, **Phys.Lett.B 608** (2005) 107; **Grav. & Cosm. 14** (2008)
A.Grigoriev, A.Studenikin, A.Ternov, **Phys.Lett.B 622** (2005) 199
Grav. & Cosm. 11 (2005) 132 ; **Phys.Atom.Nucl. 6 9** (2006)1940
K.Kouzakov, A.Studenikin, **Phys.Rev.C 72** (2005) 015502
M.Dvornikov, A.Grigoriev, A.Studenikin, **Int.J Mod.Phys.D 14** (2005) 309
S.Shinkevich, A.Studenikin, **Pramana 64** (2005) 124
A.Studenikin, **Nucl.Phys.B** (Proc.Suppl.) **143** (2005) 570

M.Dvornikov, A.Studenikin, **Phys.Rev.D 69** (2004) 073001
Phys.Atom.Nucl. 64 (2001) 1624
Phys.Atom.Nucl. **67** (2004) 719
JETP 99 (2004) 254; **JHEP 09** (2002) 016

A.Lobanov, A.Studenikin, **Phys.Lett.B 601** (2004) 171

Phys.Lett.B 564 (2003) 27

Phys.Lett.B 515 (2001) 94
A.Grigoriev, A.Lobanov, A.Studenikin, **Phys.Lett.B 535** (2002) 187

A.Egorov, A.Lobanov, A.Studenikin, **Phys.Lett.B 491** (2000) 137

Experimental and theoretical studies of
ν electromagnetic properties
is a tedious task

↓

important impact on understanding of
fundamentals of particle physics
(Dirac ↔ Majorana etc) and
applications in astrophysics

Moscow State University

Faculty of Physics

FOURTEENTH
LOMONOSOV
CONFERENCE
ON
ELEMENTARY
PARTICLE
PHYSICS

Moscow, August 19 - 25, 2009

Mikhail Lomonosov
1711-1765

Electroweak Theory
Tests of Standard Model & Beyond
Neutrino Physics
Astroparticle Physics
Gravitation and Cosmology
Developments in QCD (Perturbative and Non-Perturbative Effects)
Heavy Quark Physics
Physics at the Future Accelerators

EIGHTH
INTERNATIONAL
MEETING
ON
PROBLEMS
OF INTELLIGENTSIA

August 25, 2009

International Advisory Committee

E.Akhmedov (Max Plank, Heidelberg)
S.Belayev (Kurchatov Inst., Moscow)
V.Belokurov (MSU)
V.Berezinsky (LNGS, Gran Sasso)
S.Bilenky (JINR, Dubna)
J.Bleimaier (Princeton)
M.Danilov (ITEP, Moscow)
G.Diambrini-Palazzi (Univ. of Rome)
A.Dolgov (INFN, Ferrara & ITEP, Moscow)
C.Giunti (INFN, Turin)
V.Kadyshevsky (JINR, Dubna)
A.Logunov (IHEP, Protvino)
A.Masiero (INFN, Padua)
V.Matveev (INR, Moscow)
L.Okun (ITEP, Moscow)
M.Panasyuk (MSU)
V.Rubakov (INR, Moscow)
D.Shirkov (JINR,Dubna)
J.Silk (Univ. of Oxford)
A.Sissakian (JINR, Dubna)
A.Skrinsky (INP, Novosibirsk)
A.Slavnov (MSU & Steklov Math. Inst.)
A.Smirnov (ICTP, Trieste & INR, Moscow)
P.Spillantini (INFN, Florence)
A.Starobinsky (Landau Inst., Moscow)
V.Trukhin (MSU)

V.Sadovnichy (Rector of MSU) - **Chairman**

Organizing Committee

V.Bagrov (Tomsk Univ.)
V.Braginsky (MSU)
A.Egorov (ICAS)
D.Galtsov (MSU)
A.Grigoriev (MSU)
S.Kapitza (EAPS)
A.Kataev (INR, Moscow)
A.Lakhov (MSU)
O.Lunkova (ICAS)
V.Mikhailin (MSU & ICAS)
A.Mourao (IST/CENTRA, Lisbon)
N.Narozhny (MEPHI, Moscow)
N.Nikiforova (MSU)
A.Nikishov (Lebedev Phys. Inst., Moscow)
V.Ritus (Lebedev Phys. Inst., Moscow)
M.Polyakova (MSU)
Yu.Popov (MSU)
V.Savrin (MSU)
A.Studenikin (MSU & ICAS)

Organizers and sponsors

Faculty of Physics, Moscow State University
Skobeltsyn Institute of Nuclear Physics, Moscow State University
Joint Institute for Nuclear Research (Dubna)
Institute for Nuclear Research (Moscow)
Institute of Theoretical and Experimental Physics (Moscow)
Institute for High Energy Physics (Protvino)
Budker Institute of Nuclear Physics (Novosibirsk)
Russian Foundation for Basic Research
Agency for Science and Innovations of Russia
Russian Academy of Sciences
Russian Agency for Atomic Energy
The Dmitry Zimin "Dynasty" Foundation

INTERREGIONAL CENTRE
FOR ADVANCED STUDIES

For contact: Alexander Studenikin, Chairman, studenik@srd.sinp.msu.ru; Alexander Grigoriev, Scientific Secretary, ane@srd.sinp.msu.ru

Department of Theoretical Physics,
Moscow State University, 119992 Moscow, Russia
Phone (007-495) 939-16-17 Fax (007-495) 932-88-20 http://www.icas.ru

14th Lomonosov Conference on Elementary Particle Physics

Moscow, August 19-25, 2009

www.icas.ru