Overview on electromagnetic properties of neutrino ν

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&

JINR

(GEMMA Coll.)

Outline

1. (short) review of ν electromagnetic properties
2. experimental constraints on μ_ν and q_ν
3. ν electromagnetic interactions (new effects)
4. two new aspects of ν spin (flavour) oscillations
   - consistent treatment of ν flavour (spin) oscillations in B
   - generation of ν spin (flavour) oscillations by ν interaction with transversal matter current $j_\perp$!

Studenikin (2004, 2016, 2017)

Popov, Pustoshny, AS (2017, 2018)

REVIEWS OF MODERN PHYSICS, VOLUME 87, APRIL–JUNE 2015

Neutrino electromagnetic interactions: A window to new physics

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+ upgrade: AS, "ν electromagnetic interactions: A window to new physics – II", arXiv: 1801.18887

(published 16 June 2015)

A review is given of the theory and phenomenology of neutrino electromagnetic interactions, which provide powerful tools to probe the physics beyond the standard model. After a derivation of the general structure of the electromagnetic interactions of Dirac and Majorana neutrinos in the one-photon approximation, the effects of neutrino electromagnetic interactions in terrestrial experiments and in astrophysical environments are discussed. The experimental bounds on neutrino electromagnetic properties are presented and the predictions of theories beyond the standard model are confronted.

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CONTENTS

… the meaning of "new physics" is twofold:

1) a massive ν neutrino have nonzero electromagnetic properties that can be considered as manifestation of physics beyond Standard Model

2) in studies of ν electromagnetic interactions new phenomena are predicted

…

[1] C.Guinti and A.Studenikin, Neutrino electromagnetic interactions: a window to new physics, Rev. Mod. Phys. 87 (2015) 531-591
[2] A.Studenikin, Neutrino electromagnetic properties: a window to new physics – II, PoS (EPS-HEP2017) 137
[3] A.Grigoriev, A.Lokhov, A.Studenikin, A.Ternov, Spin light of neutrino in astrophysical environments, J. Cosm. Astropart. Phys. 11 (2017) 024
[4] K.Kouzakov, A.Studenikin, Electromagnetic properties of massive neutrinos in low-energy elastic neutrino-electron scattering, Phys. Rev. D 95 (2017) 055013
[5] P. Kurashvili, K.Kouzakov, L.Chotorlishvili, A.Studenikin, Spin-flavor oscillations of ultrahigh-energy cosmic neutrinos in interstellar space: The role of neutrino magnetic moments, Phys. Rev. D96 (2017) 103017
[6] A.Studenikin, New bounds on neutrino electric millicharge from limits on neutrino magnetic moment, Europhys. Lett. 107 (2014) 21001
[7] A.Studenikin, I.Tokarev, Millicharged neutrino with anomalous magnetic moment in rotating magnetized matter, Nucl. Phys. B 884 (2014) 396
[8] A.Popov, P. Pustoshny, A.Studenikin, Neutrino spin procession and oscillations in transversal matter currents, PoS EPS-HEP2017 (2018) 643
[9] A.Studenikin, From neutrino electromagnetic interactions to spin oscillations in transversal matter currents, PoS NOW2016 (2017) 070
[10] K.Stankevich, A.Studenikin, Neutrino quantum decoherence due to entanglement with magnetic field , PoS EPS-HEP2017 (2018) 645

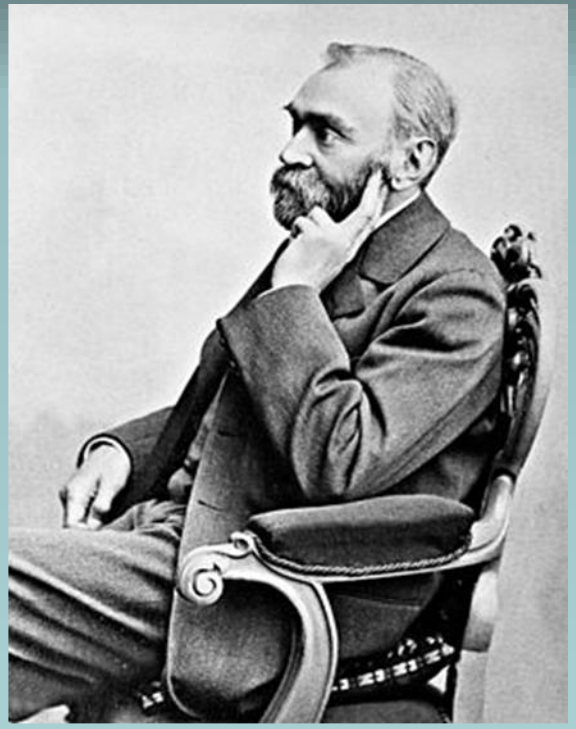
ν electromagnetic properties ?

... in spite of ...

- results of terrestrial lab experiments on μ_ν (and ν EM properties in general)
- as well as data from astrophysics and cosmology

are in agreement with "ZERO" ν EM properties

Nobel Prizes



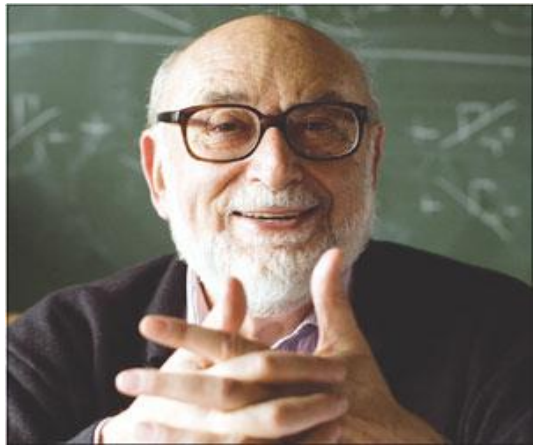
1833 – 1896

2013

&

2015

Robert Brout



François Englert

Peter Higgs

NP 2013

- Observation of Higgs boson confirms the symmetry breaking mechanism by Brout–Englert–Higgs (BEH)
- provides final glorious triumph of Standard Model

… new division in particle physics with special name BEH Physics

What is next ?

ν

unique particle
that is precursor of
BSM physics

BEH physics $\Longrightarrow$ BSM physics

ν is the only known particle with properties Beyond Standard Model

Arthur McDonald

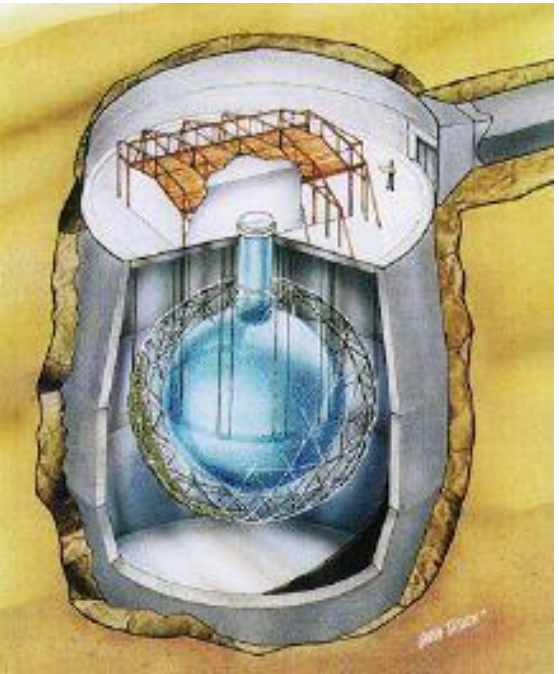
Sudbury Neutrino Observatory

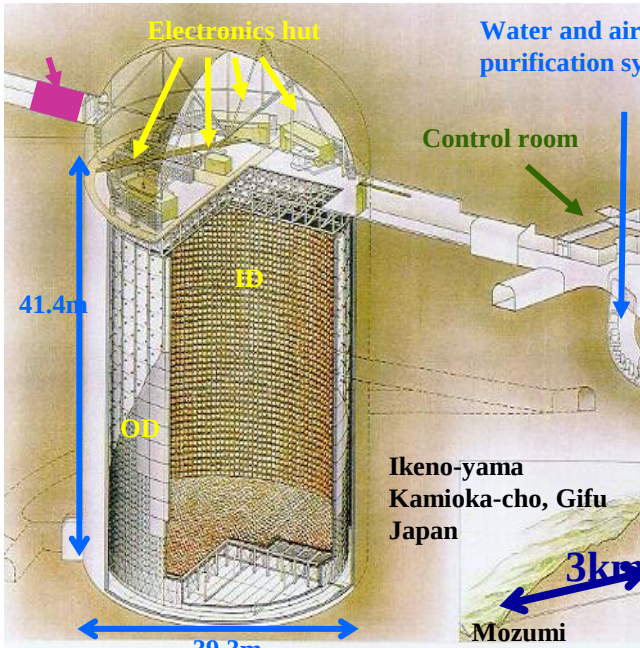
The Nobel Prize in Physics 2015

Takaaki Kajita

Super-Kamiokande Experiment

«for the discovery of neutrino oscillations, which shows that neutrinos have mass»





$m_\nu \neq 0$ ... a tool for studying physics Beyond Extended Standard Model...

Theory (Standard Model with ν_R)

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

Lee Shrock, 1977; Fujikawa Shrock, 1980

magnetic moment

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

... much greater values are desired

for astrophysical or cosmology

visualization of μ_ν

new physics

... hopes for physics BESM ...

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:

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

ν electromagnetic properties

(up to now nothing has been seen)

is a tool for studying

Beyond
Extended
Standard
Model physics...

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

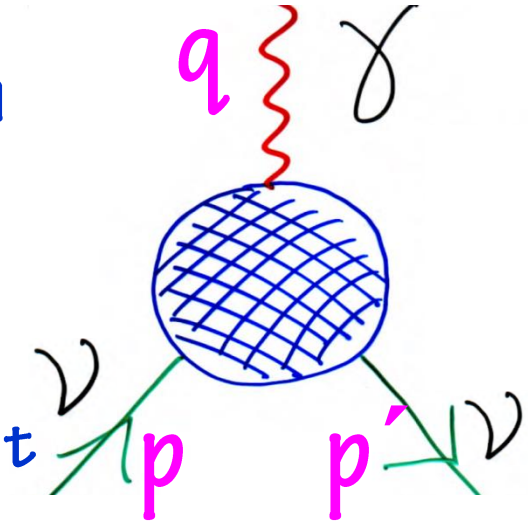
1

ν electromagnetic properties

(flash on theory)

$m_\nu \neq 0$

ν 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) $\Longrightarrow$

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 $\Rightarrow f_E = 0$,

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 $\Rightarrow$ three form factors are real: $Imf_Q = Imf_M = Imf_A = 0$

Majorana ν

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

$$f_Q = f_M = f_E = 0$$

...as early as 1939, W.Pauli...

- EM properties $\Rightarrow$ 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

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

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) .

... quite different EM properties ...

1) CP invariance + hermiticity

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

or

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

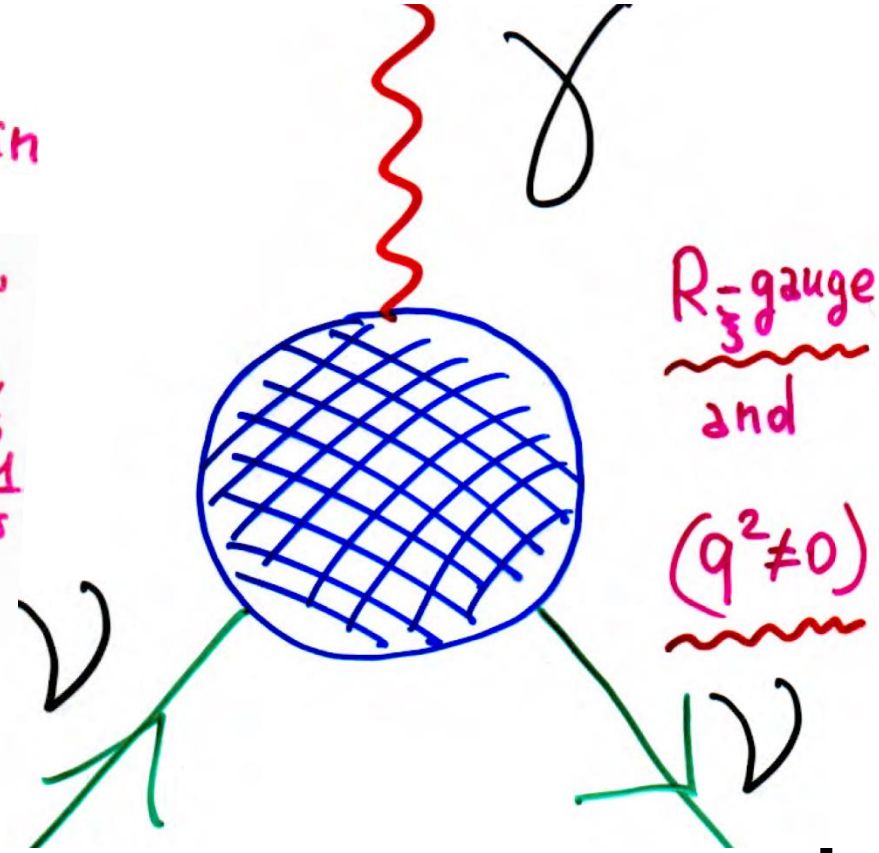
3.1 ν vertex function

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

M. Dvornikov, A. Studenikin

* Phys. Rev. D 63, 073001, 2004, "Electric charge and magnetic moment of massive neutrino"; JETP 126 (2004), N8, 1

* "Electromagnetic form factors of a massiv neutrino."



R_ξ-gauge and $(q^2 \neq 0)$

charge

magnetic moment

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

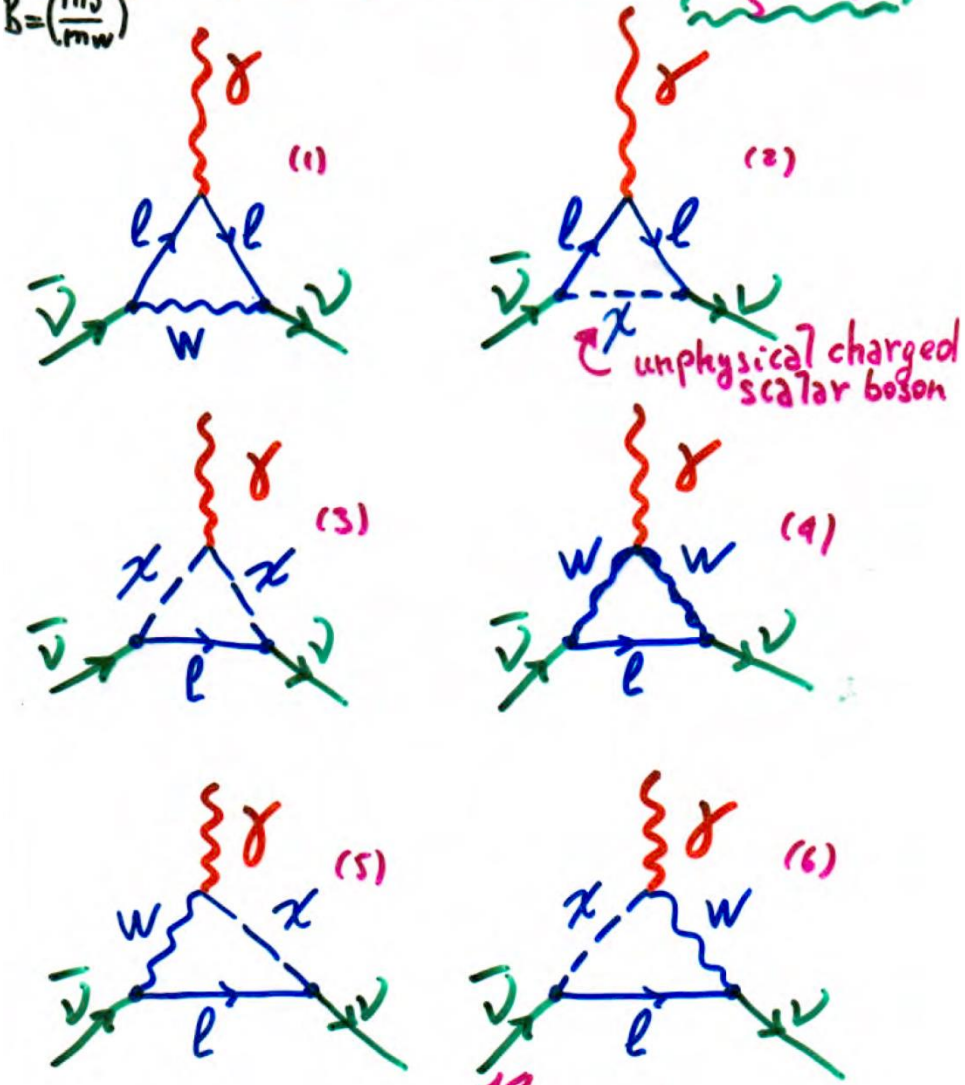
electric moment

anapole moment

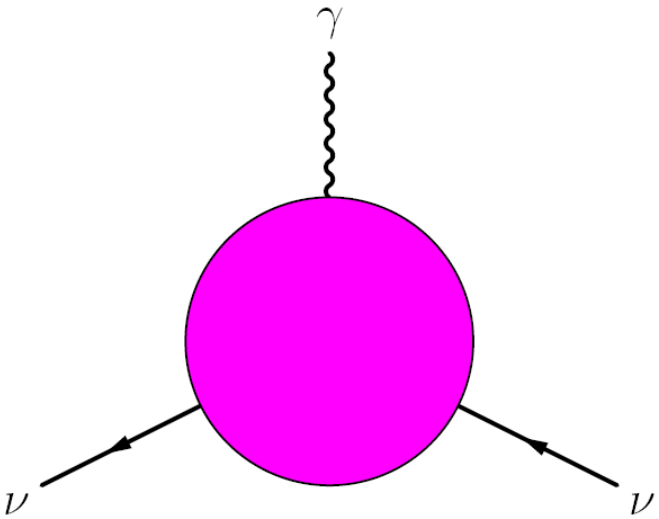
$a = \left(\frac{m_\ell}{m_W}\right)^2$, $b = \left(\frac{m_\nu}{m_W}\right)^2$

Proper vertices

R_ξ-gauge



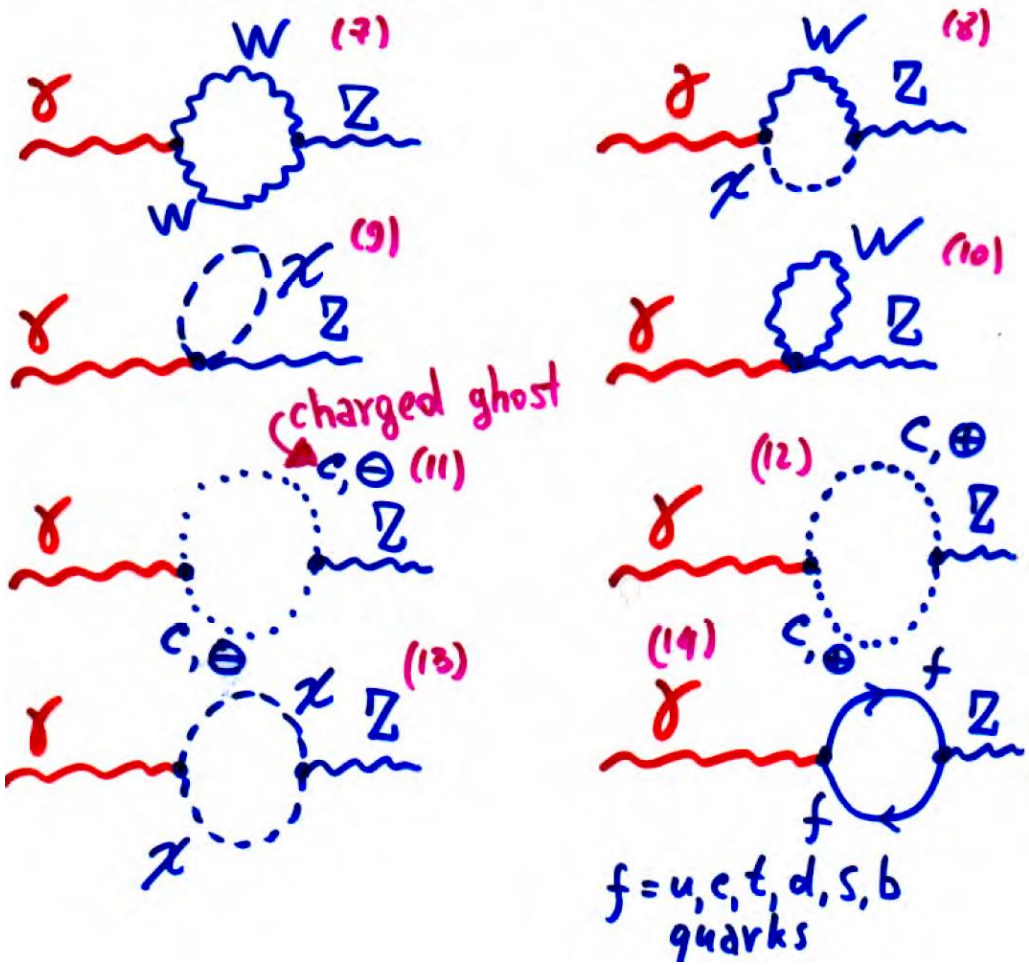
$$\Lambda_\mu(q) = \sum_{i=1}^{14} \Lambda_\mu^i(q)$$

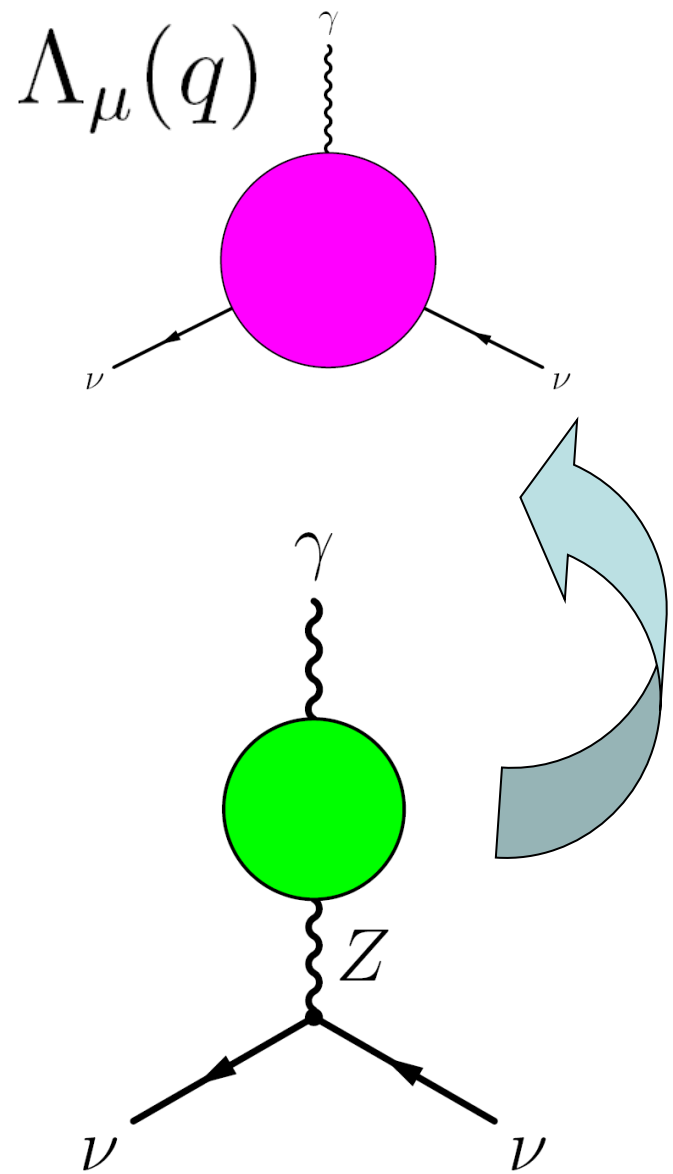


$$\Lambda_\mu(q)$$

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

γ-Z self-energy diagrams





$\gamma - Z$ self-energy diagrams

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

are most well studied and theoretically understood among form factors

...because in the limit $q^2 \to 0$ they have nonvanishing values

$$\mu_\nu = f_M(0)$$

ν magnetic moment

$$\epsilon_\nu = f_E(0)$$

ν electric moment ???

$m_\nu \ll m_e \ll M_W$ **light** ν

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

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

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

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

$m_e \ll M_W \ll m_\nu$

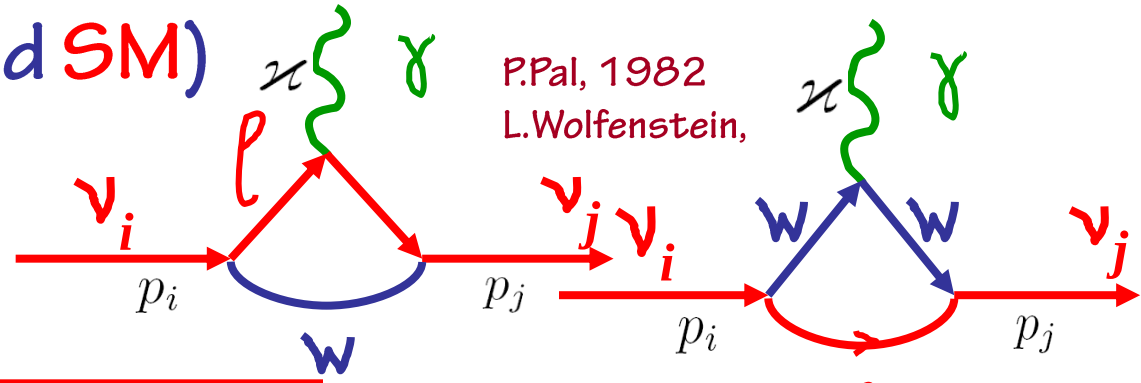
$$\boxed{\mu_\nu = \frac{eG_F}{8\pi^2\sqrt{2}} m_\nu}$$

heavy ν

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

. . . μ_ν *in case of mixing . . .*

Neutrino (beyond SM) dipole moments (+ transition moments)



- Dirac neutrino

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

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

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

- $m_i, m_j \ll m_l, m_W$

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

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

- Majorana neutrino only for

$$i \neq j$$

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

or

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

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

… depending on relative CP phase of ν_i and ν_j

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

$$\epsilon_{ii}^D = 0$$

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

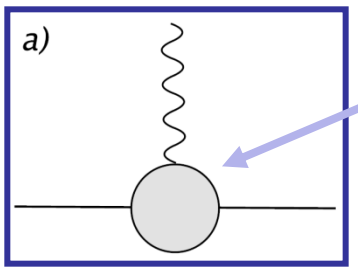
$\mu_{ii}^D = 0$ for massless ν (in the absence of right-handed charged currents)

3.3 Naïve relationship between m_ν and μ_ν

… problem to get large μ_ν *and still acceptable* m_ν

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

P.Vogel e.a., 2006

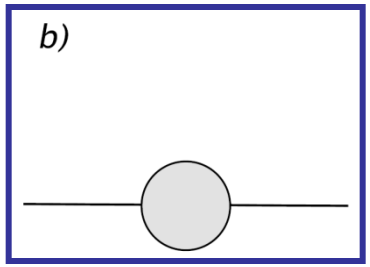


then

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

…combination of constants and loop factors…

contribution to m_ν given by



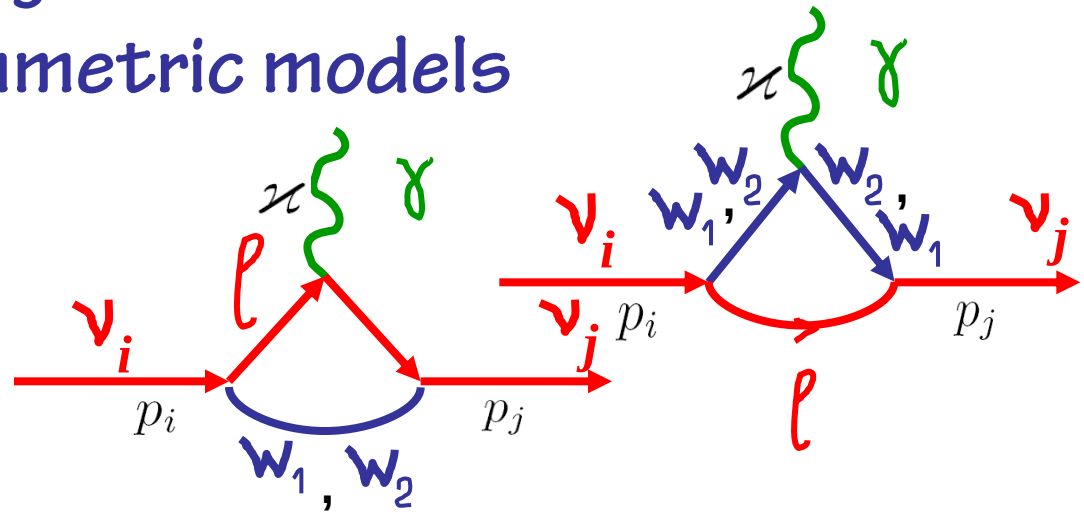
, then $m_\nu \sim G\Lambda$

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

Voloshin, 1988;
Barr, Freire,
Zee, 1990

3.6 Neutrino magnetic moment in left-right symmetric models

$$SU_L(2) \times SU_R(2) \times U(1)$$



Gauge bosons $W_1 = W_L \cos\xi - W_R \sin\xi$

mass states $W_2 = W_L \sin\xi + W_R \cos\xi$

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

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

… charged lepton mass … *… neutrino mass …*

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

Z.Z.Xing, Y.L.Zhou,
"Enhanced electromagnetic transition dipole moments and radiative decays of massive neutrinos due to the seesaw-induced non-unitary effects"
Phys.Lett.B 715 (2012) 178

- *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

2

ν magnetic moment in experiments

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

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

Cross-section:

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

where the Standard Model contribution

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

T is the electron recoil energy and

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

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

$$\mu_{ij} \to |\mu_{ij} - \epsilon_{ij}|$$

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

for anti-neutrinos $g_A \to -g_A$

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

K. Kouzakov, A. Studenikin,
Phys. Rev. D 95 (2017) 055013

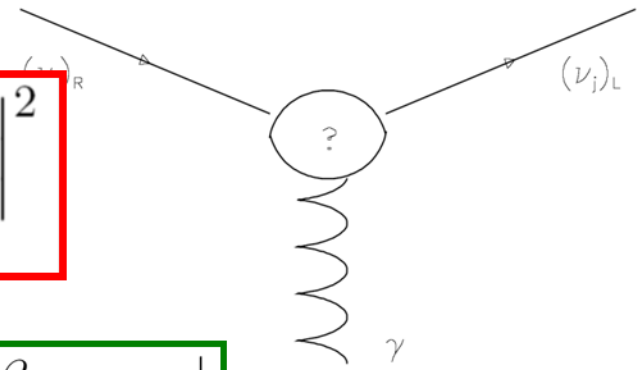
"Electromagnetic properties of massive neutrinos in low-energy elastic neutrino-electron scattering"

Abstract

A thorough account of electromagnetic interactions of massive neutrinos in the theoretical formulation of low-energy elastic neutrino-electron scattering is given. The formalism of neutrino charge, magnetic, electric, and anapole form factors defined as matrices in the mass basis is employed under the assumption of three-neutrino mixing. The flavor change of neutrinos arriving from the source to the detector is taken into account and the role of the source-detector distance is inspected. The effects of neutrino flavor-transition millicharges and charge radii in the scattering experiments are pointed out.

Effective ν magnetic moment in experiments

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



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

where neutrino mixing matrix

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

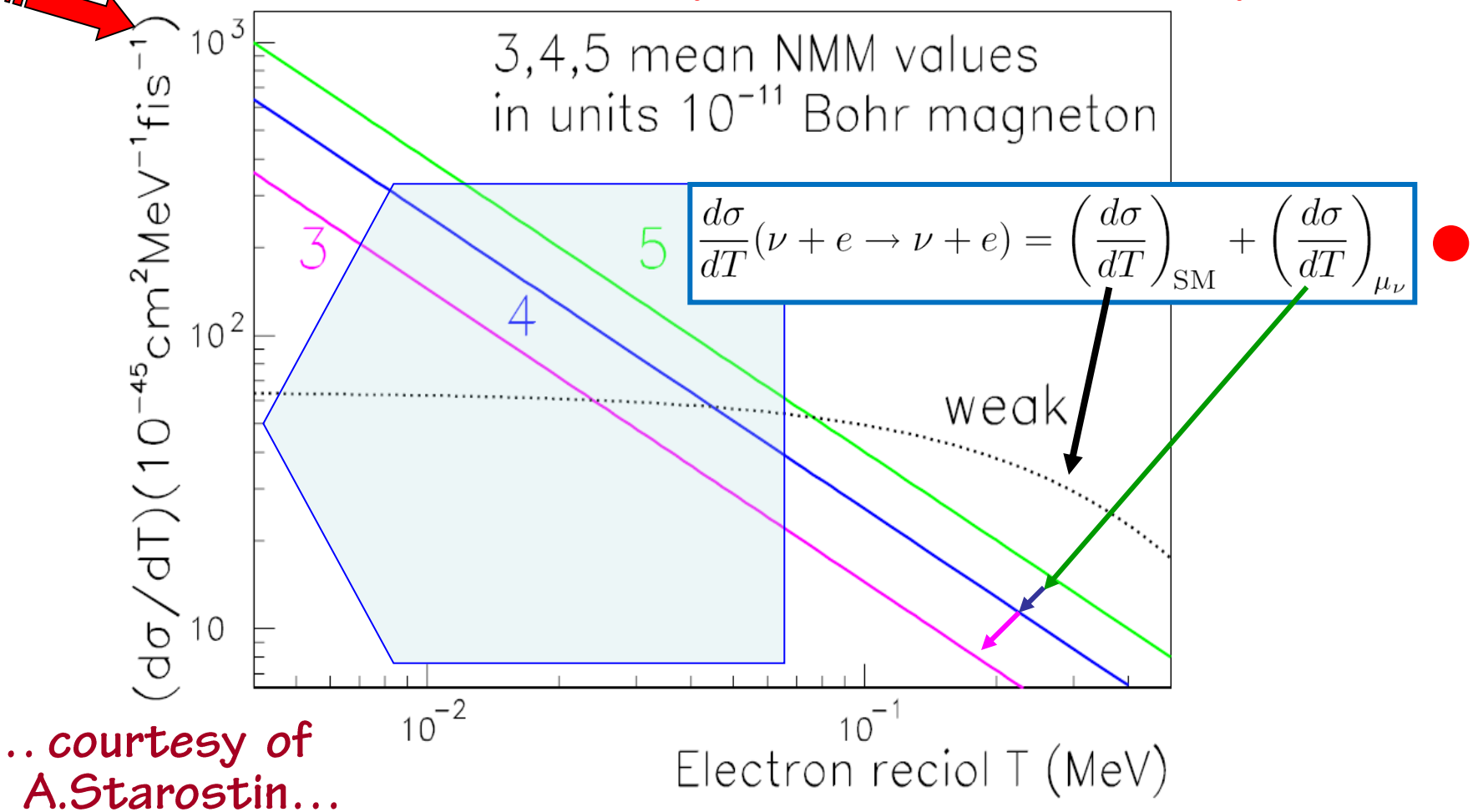
magnetic and **electric** moments

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

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

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

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



... courtesy of A.Starostin...

MUNU experiment at Bugey reactor (2005)

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

TEXONO collaboration at Kuo-Sheng power plant (2006)

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

GEMMA (2007) $$\mu_\nu \leq 5.8 \times 10^{-11} \mu_B$$

GEMMA I 2005 - 2007

BOREXINO (2008) $$\mu_\nu \leq 5.4 \times 10^{-11} \mu_B$$

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

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

based on first release of BOREXINO data

Montanino, Picariello, Pulido, PRD 2008

... attempts to improve bounds

GEMMA (2005-2012)
Germanium Experiment for Measurement of Magnetic Moment of Antineutrino

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

World best experimental limit

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

June 2012

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

... quite realistic prospects of the near future ... 2018

$$\mu_\nu^a \sim 0.7 \times 10^{-12} \mu_B$$

unprecedentedly low threshold

$$T \sim 200 \ eV$$

2

Experimental limits for different effective μ_ν

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

new 2017 PRD : $\mu_\nu^{eff} < 2.8 \cdot 10^{-11}\ \mu_B$ at 90% c.l.

C. Giunti, A. Studenikin, "Electromagnetic interactions of neutrinos: a window to new physics", Rev. Mod. Phys. 87 (2015) 531

… if one trusts ν

to be precursor for

BESM physics …

… A remark on electric charge of ν… Beyond Standard Model…

ν neutrality $Q=0$ is attributed to

gauge invariance + anomaly cancellation constraints

imposed in SM of electroweak interactions

Foot, Joshi, Lew, Volkas, 1990;
Foot, Lew, Volkas, 1993;
Babu, Mohapatra, 1989, 1990
Foot , He (1991)

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

- *…General proof:*
- *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**

2

Experimental limits for different effective q_ν

C. Giunti, A. Studenikin, "Electromagnetic interactions of neutrinos: a window to new physics", Rev. Mod. Phys. 87 (2015) 531

Limit	Method	Reference
$\lvert q_{\nu_\tau}\rvert \lesssim 3 \times 10^{-4}\, e$	SLAC e^- beam dump	Davidson *et al.* (1991)
$\lvert q_{\nu_\tau}\rvert \lesssim 4 \times 10^{-4}\, e$	BEBC beam dump	Babu *et al.* (1994)
$\lvert q_{\nu}\rvert \lesssim 6 \times 10^{-14}\, e$	Solar cooling (plasmon decay)	Raffelt (1999a)
$\lvert q_{\nu}\rvert \lesssim 2 \times 10^{-14}\, e$	Red giant cooling (plasmon decay)	Raffelt (1999a)
$\lvert q_{\nu_e}\rvert \lesssim 3 \times 10^{-21}\, e$	Neutrality of matter	Raffelt (1999a)
$\lvert q_{\nu_e}\rvert \lesssim 3.7 \times 10^{-12}\, e$	Nuclear reactor	Gninenko *et al.* (2007)
$\lvert q_{\nu_e}\rvert \lesssim 1.5 \times 10^{-12}\, e$	Nuclear reactor	Studenikin (2013)

A. Studenikin: "New bounds on neutrino electric millicharge from limits on neutrino magnetic moment", Eur.Phys.Lett. 107 (2014) 2100

C.Patrignani et al (Particle Data Group), "The Review of Particle Physics 2016" Chinese Physics C 40 (2016) 100001

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

2

ν-e cross-section

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

two not seen contributions:

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

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

Bounds on q_ν from

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

... yet nondetected effects of New Physics

Studenikin, Eurphys. Lett. 107 (2014) 21001

- Particle Data Group, 2016 -

Expected new constraints from GEMMA:

now $\mu_\nu^a < 2.9 \times 10^{-11} \mu_B$ ($T \sim 2.8\ keV$)

2018 (expected) ... unprecedentedly low threshold ...

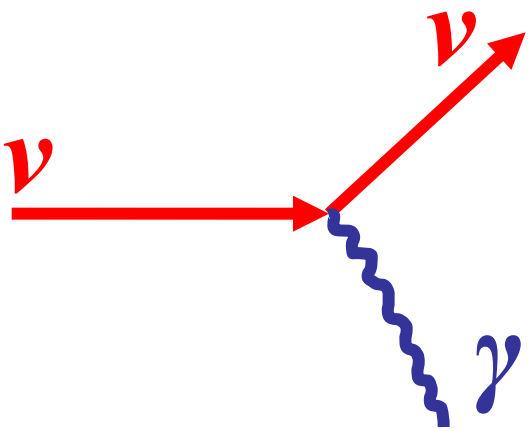
$\mu_\nu^a \sim 0.7 \times 10^{-12}\ \mu_B$ ($T \sim 200\ eV$)

Constraints on q_ν

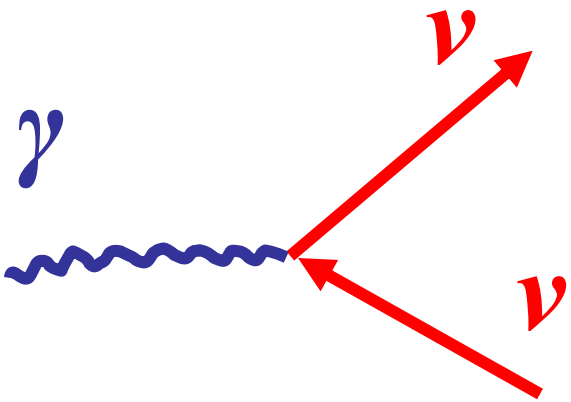
$$|\ q_\nu\ | < 1.5 \times 10^{-12} e_0$$

$$|q_\nu| < 1.1 \times 10^{-13} e_0$$

③ ν electromagnetic interactions

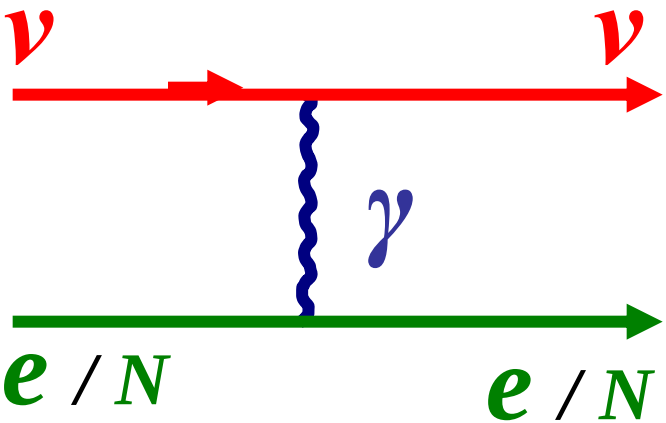


ν decay, Cherenkov radiation

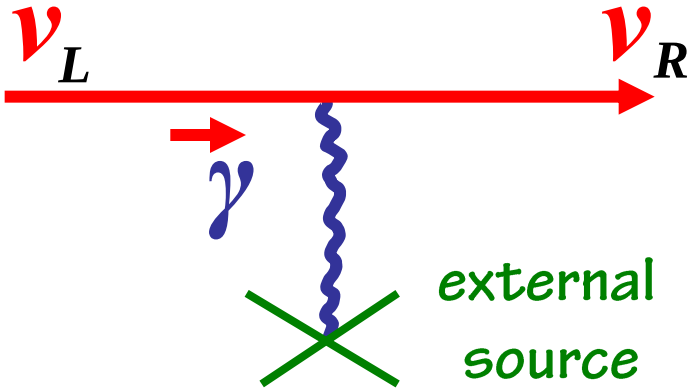


γ decay in plasma

!!!



Scattering

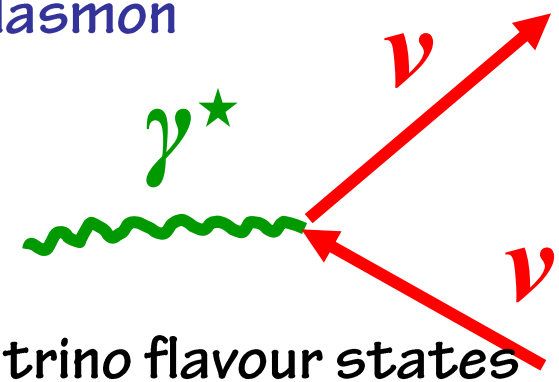


Spin precession

2 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

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

Matrix element

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

Decay rate

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

= 0 in vacuum $\quad \omega = k$

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

Energy-loss rate per unit volume

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

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

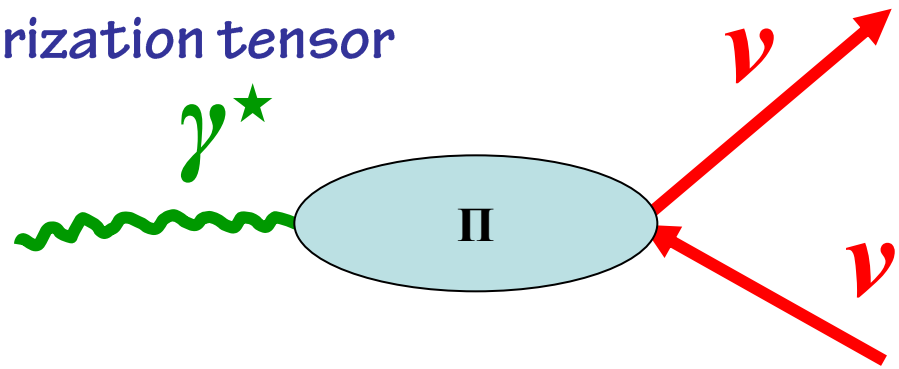
distribution function of plasmons

Astrophysical bound on μ_ν

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

Energy-loss rate per unit volume

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



more fast star cooling

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

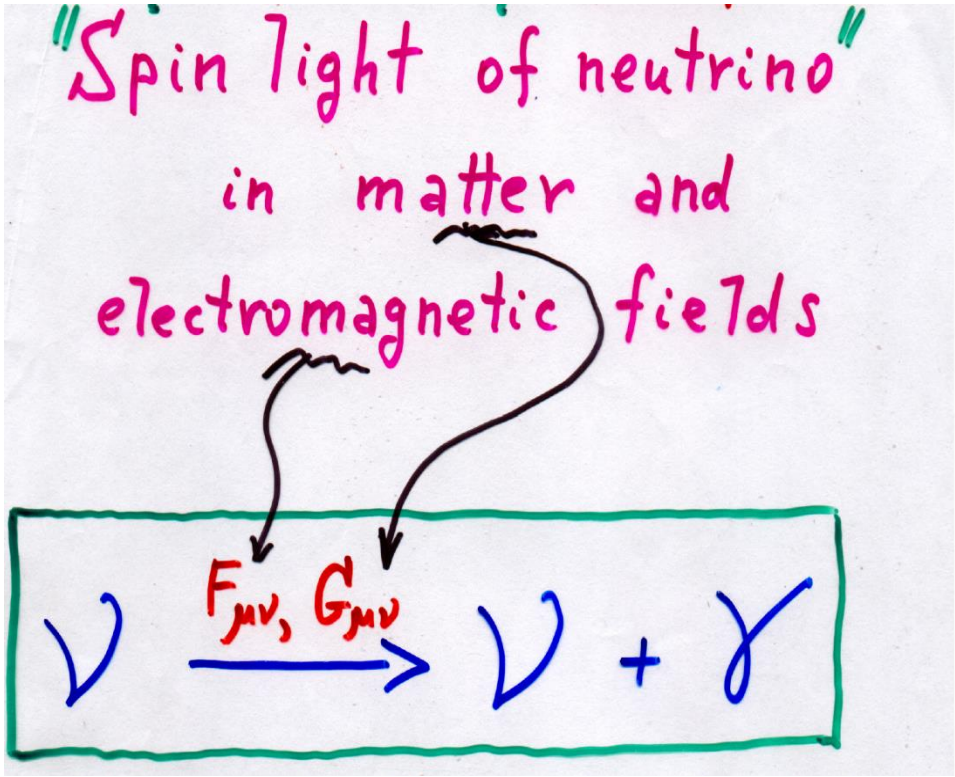
… best astrophysical limit on ν magnetic moment…

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

G.Raffelt, PRL 1990

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

• New mechanism of electromagnetic radiation



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

Lobanov, Studenikin,
Phys.Lett. B 515 (2001) 94
Phys.Lett. B 564 (2003) 27
Phys.Lett. B 601 (2004) 171

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

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

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

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

New mechanism of electromagnetic radiation

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

Analogies with:

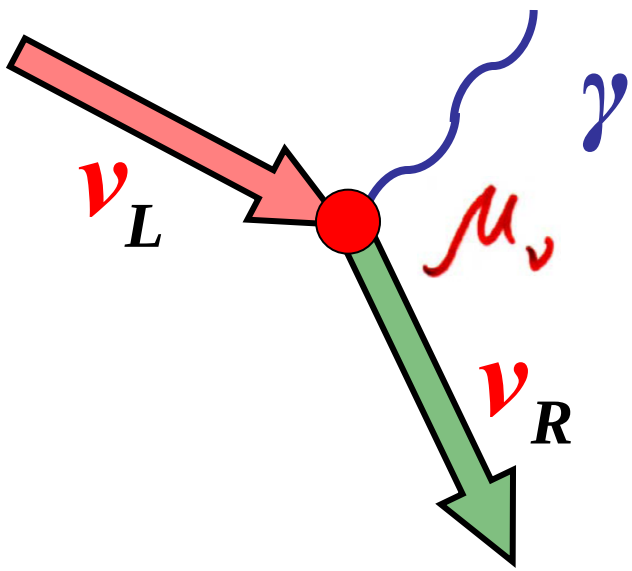
* classical electrodynamics

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 coupling



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 …

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

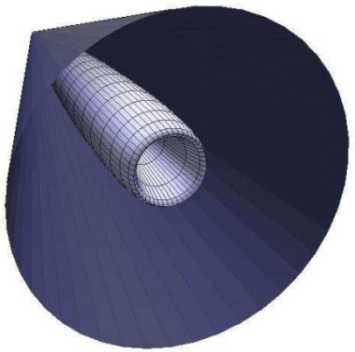


Figure 1: 3D representation of the radiation power distribution.

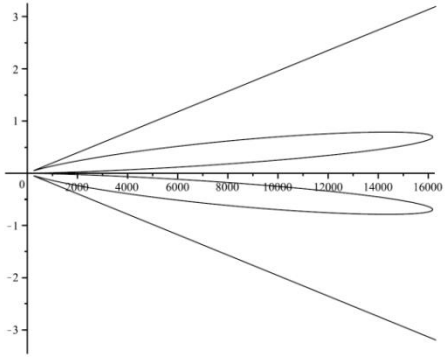


Figure 2: The two-dimensional cut along the symmetry axis. Relative units are used.

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].

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Spin light of neutrino in astrophysical environments

JCAP11(2017)024

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[c]Department of Theoretical Physics, Moscow Institute of Physics and Technology, 141701 Dolgoprudny, Russia
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[e]Dzhelepov Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, 141980 Dubna, Russia

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Published November 16, 2017

A.Grigoriev, A.Lokhov, A.Studenikin, A.Ternov, Spin light of neutrino in astrophysical environments, J. Cosm. Astropart. Phys. 11 (2017) 024

SLν in neutron matter of real astrophysical objects [4]

Plasma effects [5]

- Photon dispersion with plasmon mass in the degenerate electron gas: $\omega = \sqrt{\mathbf{k}^2 + m_\gamma^2}$

$$m_\gamma = \left(\frac{2\alpha}{\pi}\right)^{1/2} \mu_e \simeq 8.87 \times \left(\frac{n_e}{10^{37}\,\mathrm{cm}^{-3}}\right)^{1/3} \mathrm{MeV}$$

- Threshold condition for the *SLν* [10]: $\frac{m_\gamma^2 + 2\, m_\gamma m_\nu}{4\tilde{n} p} < 1$

($Y_e = n_e/n_n$)

- **Neutron matter:** $\tilde{n} = \frac{1}{2\sqrt{2}} G_F n_n \simeq 3.2 \times \left(\frac{n_n}{10^{38}\,\mathrm{cm}^{-3}}\right) \mathrm{eV},$

(antineutrinos act)

$$E > p_{\mathrm{th}} \simeq 28.5 \times \frac{Y_e^{2/3}}{1 - Y_e} \left(\frac{10^{38}\,\mathrm{cm}^{-3}}{n_n}\right)^{1/3} \mathrm{TeV} \Rightarrow E_{\mathrm{th}} \simeq 6.82\ \mathrm{TeV}.$$

$n_n = 10^{38}\mathrm{cm}^{-3}$, $Y_e = 0.1$

- Mean photon energy near the threshold: $\langle\omega\rangle = I/\Gamma \simeq p \simeq E_\nu.$

For most favorable conditions as low density of the charged matter component is needed as possible

W boson production $\bar{\nu}_e + e^- \to W^-$ [4]

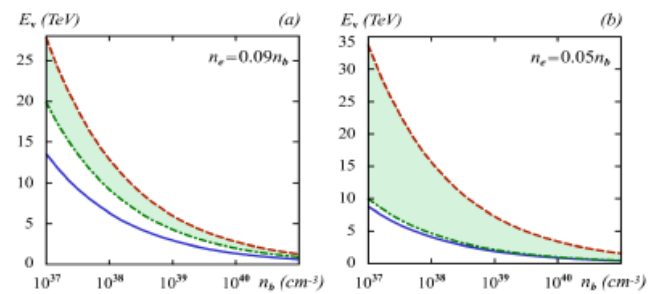


Figure 2. The allowed range of electron antineutrino energies for the *SLν* in the matter of a neutron star depending on the neutron density. Solid line: the *SLν* process threshold without account for the $\bar{\nu}_e e$-scattering; dash-dotted line: the *SLν* process threshold with account for the $\bar{\nu}_e e$-scattering; dashed line: the threshold for the W boson production. (a) $Y_e = 0.09$; (b) $Y_e = 0.05$. The allowed regions are marked in green.

W-boson threshold energy $\varepsilon_W = \frac{m_W^2}{4\mu_e} \simeq 5.77 \times \left(\frac{10^{38}\,\mathrm{cm}^{-3}}{Y_e n_n}\right)^{1/3} \mathrm{TeV}$

- Electron antineutrinos: s-channel interaction with matter through W-boson, importance of the propagator effects $\Rightarrow$ correction to the effective potential of neutrino motion → antineutrino energy shift up → *SLν* is suppressed at Y_e=0.1, but allowed already for Y_e=0.09
- μ and τ antineutrinos: only t-channel interaction with matter through Z-boson, no propagator effects $\Rightarrow$ the *SLν* is allowed if neutrino energy is greater than the W-boson threshold ε_W

Neutrino lifetime with respect to the *SLν* for most optimistic set of parameters:

$\tau_{SL\nu} = 10^{-4} - 10^{3}\,s$, for $n_b = 10^{41} - 10^{38}\,\mathrm{cm}^{-3}$

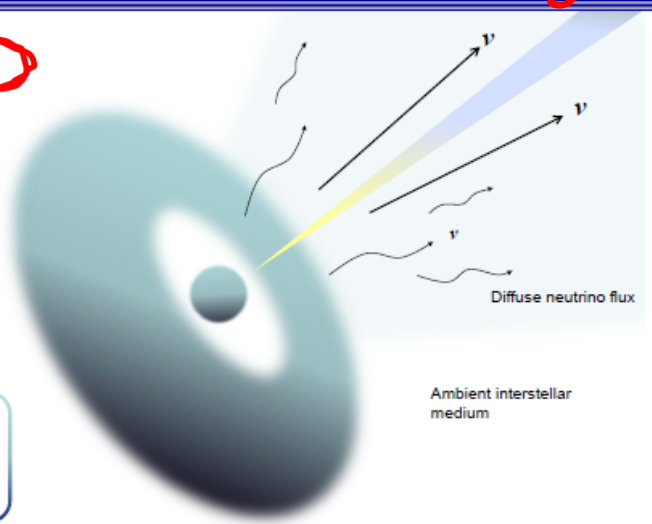
Neutrino 2018, Heidelberg, 3-9 June 2018

The *SLν* in short Gamma-Ray Bursts (SGRBs)

Factors for best *SLν* generation efficiency

- High neutrino energy and density
- High background neutral matter density
- Low density of the matter charged component
- Low temperature of the charged component
- Considerable extension of the medium

SLν radiation by ultra high-energy neutrino in the diffuse neutrino wind blown during neutron stars merger



Matter characteristics[6]:

- neutrinos $n_\nu \sim 10^{32}\ \mathrm{cm}^{-3}$
- electrons $Y_e = 0.01$, $T = 0.1$ MeV, $\rho = 5 \times 10^3\ \mathrm{g/cm}^3$

$\Rightarrow$ $n_e \simeq 3 \times 10^{25}\ \mathrm{cm}^{-3}$, $m_\gamma \simeq 10^{-3}$ MeV, $E_{\mathrm{th}} \simeq 1$ GeV

Radiation time

$$\tau_{SL\nu} \simeq 5.4 \times 10^{15} \left(\frac{10^{-11}\mu_B}{\mu}\right)^2 \left(\frac{10^{32}\,\mathrm{cm}^{-3}}{n_{\nu_e}}\right)^2 \left(\frac{1\,\mathrm{PeV}}{E_\nu}\right) \mathrm{s}$$

Neutrino parameters: $\mu \simeq 2.9 \times 10^{-11} \mu_B$, $E_\nu \sim 10^{12} - 10^{18}$ eV

$$\tau_{SL\nu} \simeq 6.4 \times (10^{11} - 10^{17})\ \mathrm{s} = 2 \times (10^4 - 10^{10})\ \mathrm{years}$$

- … astrophysical bound on millicharge q_ν from

2

ν energy quantization in rotating magnetized media

Grigoriev, Savochkin, Studenikin, Russ. Phys. J. 50 (2007) 845
Studenikin, J. Phys. A: Math. Theor. 41 (2008) 164047
Balantsev, Popov, Studenikin, J. Phys. A: Math. Theor. 44 (2011) 255301
Balantsev, Studenikin, Tokarev, Phys. Part. Nucl. 43 (2012) 727
Phys. Atom. Nucl. 76 (2013) 489
Studenikin, Tokarev, Nucl. Phys. B 884 (2014) 396

$\bar{\nu}$ in extreme external conditions (strong fields and dense matter)

A. Studenikin,

- "Quantum treatment of neutrino in background matter",
  J. Phys. A: Math. Gen. 39 (2006) 6769–6776

- "Neutrinos and electrons in background matter: a new approach",
  Ann.Fond. de Broglie 31 (2006) 289-316

- "Method of wave equations exact solutions in studies of neutrinos and electron interactions in dense matter",
  J.Phys.A: Math.Theor. 41 (2008) 164047

...«method of exact solutions»

Millicharged ν in rotating magnetized matter

Balatsev, Tokarev, Studenikin,
Phys.Part.Nucl., 2012,
Phys.Atom.Nucl., Nucl.Phys. B, 2013,
Studenikin, Tokarev, Nucl.Phys.B (2014)

Modified Dirac equation for ν wave function

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

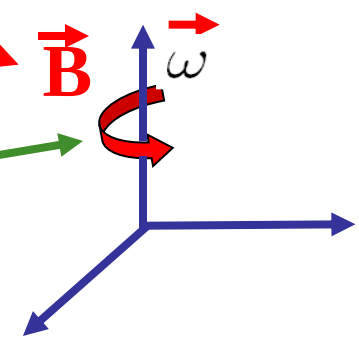
external magnetic field

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

$$c_l = 1$$

matter potential

rotating matter



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

rotation angular frequency

ν energy is quantized in rotating matter

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

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

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

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

integer number

matter rotation frequency

scalar potential of electric field

ν energy is quantized in rotating matter like electron energy 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

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

due to effective Lorentz force

A. Studenikin, J.Phys.A: Math.Theor. 41(2008) 164047

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

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

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

matter induced "charge", "electric" and "magnetic" fields

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

... we predict :

$E \sim 1\ eV$

1) low-energy ν are trapped in circular orbits inside rotating neutron stars

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

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

2) rotating neutron stars as filters for low-energy relic ν ?

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

… we predict :

3) high-energy ν are deflected inside a rotating astrophysical transient sources (GRBs, SNe, AGNs)

absence of light in correlation with ν signal reported by ANTARES Coll.

M.Ageron et al,
Nucl.Instrum.Meth. A692 (2012) 184

• Millicharged ν as star rotation engine

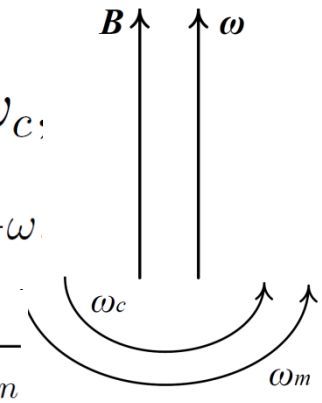
- Single ν generates feedback force with projection on rotation plane

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

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

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

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

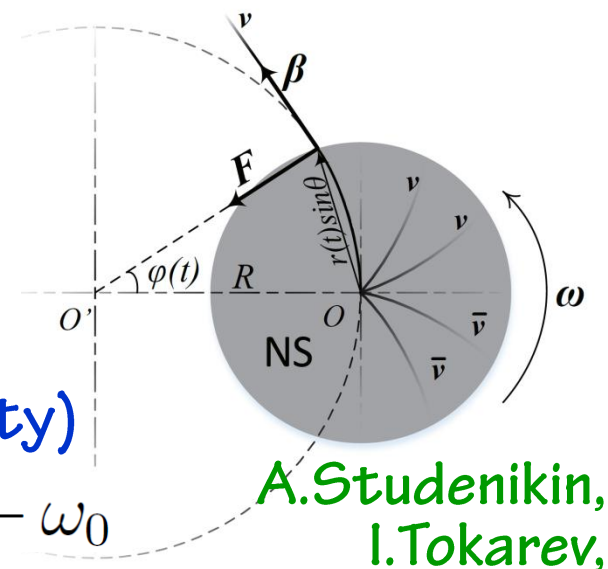


single ν torque

- $$M_0(t) = \sqrt{1 - \frac{r^2(t)\Omega^2\sin^2\theta}{4}}\, F r(t)\sin\theta$$

total N_ν torque

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



- Should effect initial star rotation (shift of star angular velocity)

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

$$\triangle\omega = \omega - \omega_0$$

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

• ν Star Turning mechanism (νST)

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

Escaping millicharged νs move on curved orbits inside magnetized rotating star and feedback of effective Lorentz force should effect initial star rotation

• New astrophysical constraint on ν millicharge

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

• $|\Delta\omega| < \omega_0$! ...to avoid contradiction of νST impact with observational data on pulsars ...

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

• ... best astrophysical bound ...

- ν spin and spin-flavour oscillations in transversal matter currents

Studenikin (2004)

Main steps in ν oscillations

1. $\nu_e \xleftrightarrow{\text{vac}} \bar{\nu}_e$, B. Pontecorvo, 1957

2. $\nu_e \xleftrightarrow{\text{vac}} \nu_\mu$, Z. Maki, M. Nakagava, S. Sakata, 1962

3. $\nu_e \xleftrightarrow{\text{matter, } \rho = \text{const}} \nu_\mu$, L. Wolfenstein, 1978

4. $\nu_e \xleftrightarrow{\text{matter, } \rho \neq \text{const}} \nu_\mu$, S. Mikheev, A. Smirnov, 1985

- resonances in ν flavour oscillations $\Rightarrow$ MSW-effect, solution for $\nu_\odot$-problem

5. $\nu_{e_L} \xleftrightarrow{B_\perp} \nu_{e_R}$, A. Cisneros, 1971; M. Voloshin, M. Vysotsky, L. Okun, 1986, $\nu_\odot$

6. $\nu_{e_L} \xleftrightarrow{B_\perp} \nu_{e_R}, \nu_{\mu_R}$, E. Akhmedov, 1988; C.-S. Lim & W. Marciano, 1988

- resonances in ν spin (spin-flavour) oscillations in matter

60 years!

Bruno Pontecorvo
1913–1993

only in $B_\perp$ and matter at rest

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

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

with magnetic moment interaction

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

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

ν evolution equation

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

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

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

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

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

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

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

- Resonance amplification of oscillations in matter:

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

Akhmedov, 1988
Lim, Marciano

... similar to MSW effect

In magnetic field

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

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

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

Neutrino conversions and oscillations in magnetic field

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

  Cisneros, 1971

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

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

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

  - Dar, 1987

  Fujikawa, Shrock, 1988
  Voloshin, 1988

...for recent analysis see

J.Pulido, 2006, TAUP-09; ●
A.Balantekin, C.Volpe, 2005

...subdominant contribution to LMA – MSW solution...

$\nu_{\odot}$

✷ Spin-flavour oscillations in early universe – strong $B_{\perp}$

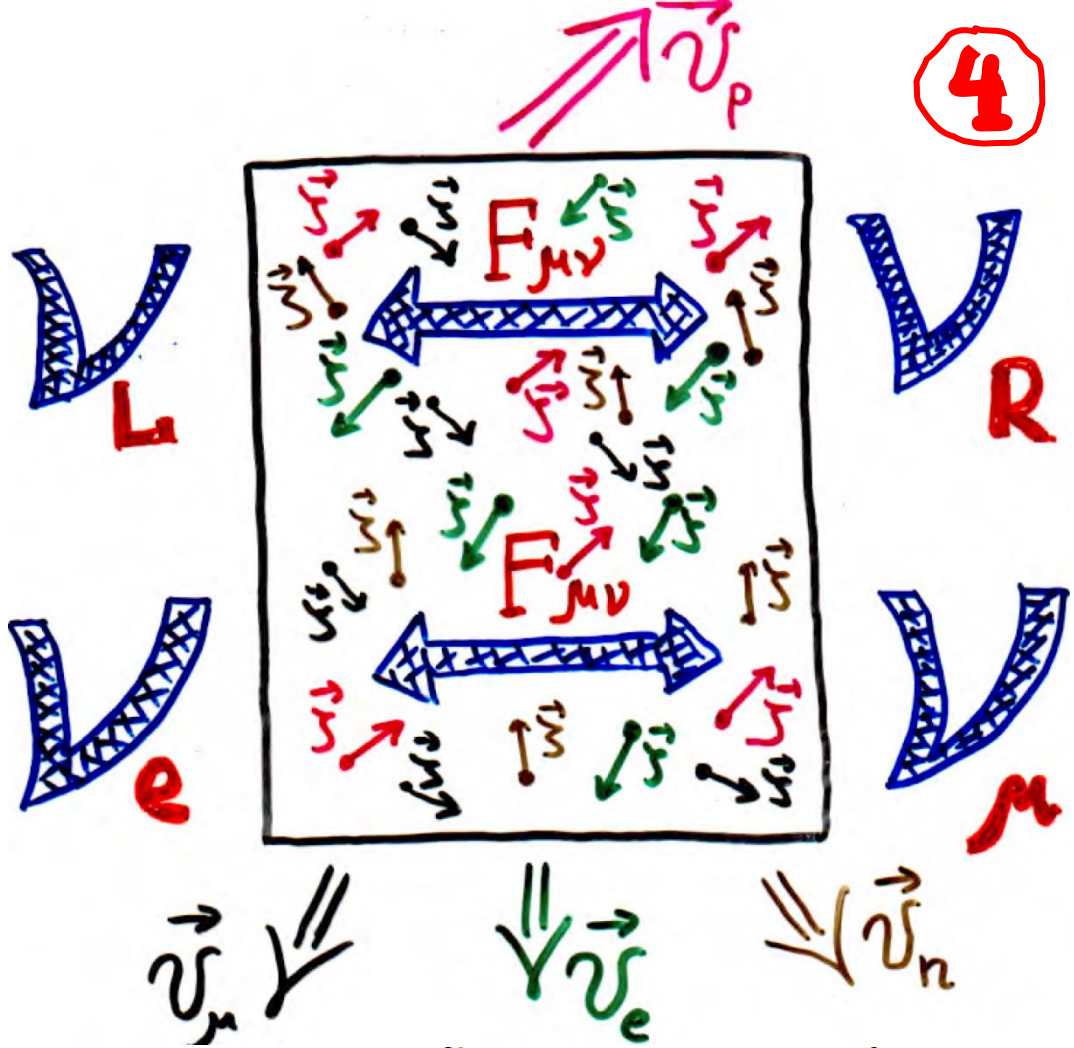
⇒ population of ν wrong-helicity states (r.h.) would accelerate expansion of universe (???)

- neutrino spin and flavor oscillations in moving matter

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

A.Lobanov, A.Studenikin, Phys.Lett.B 515 (2001) 94

A.Lobanov, A.Grigoriev, A.Studenikin, Phys.Lett.B 535 (2002) 187



moving matter components

$f = e, n, p, \mu$, etc

with polarizations

$\vec{\zeta}, \vec{\zeta}, \vec{\zeta}, \vec{\zeta}$, etc

ν spin evolution in presence of general external fields

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

General types non-derivative interaction with external fields

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

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

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

Relativistic equation (quasiclassical) for ν spin vector:

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

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

- **Electromagnetic interaction**

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

- **SM weak interaction**

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

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

... once more ...

For SM+SU(2)-singlet ν_R and matter $f=e$

Bargmann-Michel-Telegdi eq

$$\boxed{\frac{d\vec{S}_\nu}{dt} = \frac{2\mu_\nu}{\gamma_\nu}\left[\vec{S}_\nu \times (\vec{B}_0 + \vec{M}_0)\right],}$$

interaction of neutrino with an electromagnetic field

in rest frame of neutrino

$$\vec{B}_0 = \gamma_\nu\left(\vec{B}_\perp + \frac{1}{\gamma_\nu}\vec{B}_\parallel + \sqrt{1-\frac{1}{\gamma_\nu^2}}\,[\vec{E}_\perp \times \vec{n}]\right),$$

interaction of neutrino with matter

$$\vec{M}_0 = \gamma_\nu \rho n_e \left(\vec{\beta}_\nu(1-\vec{\beta}_\nu\vec{v}_e) - \frac{1}{\gamma_\nu}\vec{v}_{e\perp}\right),$$

$$\rho_e^{(1)} = \frac{G_F}{2\mu\sqrt{2}}(1+4\sin^8\theta_W),$$

$$\gamma_\nu = \frac{E_\nu}{m_\nu},$$

matter density

$\parallel$ $\perp$

ν spin precession in moving matter !!!

without any magnetic field !!!

Physics of Atomic Nuclei, Vol. 67, No. 5, 2004, pp. 993–1002. Translated from Yadernaya Fizika, Vol. 67, No. 5, 2004, pp. 1014–1024.

ELEMENTARY PARTICLES AND FIELDS
Theory

Phys.Atom.Nucl. 67 (2004) 993-1002

Neutrino in Electromagnetic Fields and Moving Media

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Received March 26, 2003; in final form, August 12, 2003

Abstract—The history of the development of the theory of neutrino-flavor and neutrino-spin oscillations in electromagnetic fields and in a medium is briefly surveyed. A new Lorentz-invariant approach to describing neutrino oscillations in a medium is formulated in such a way that it makes it possible to consider the motion of a medium at an arbitrary velocity, including relativistic ones. This approach permits studying neutrino-spin oscillations under the effect of an arbitrary external electromagnetic field. In particular, it is predicted that, in the field of an electromagnetic wave, new resonances may exist in neutrino oscillations. In the case of spin oscillations in various electromagnetic fields, the concept of a critical magnetic-field-component strength is introduced above which the oscillations become sizable. The use of the Lorentz-invariant formalism in considering neutrino oscillations in moving matter leads to the conclusion that the relativistic motion of matter significantly affects the character of neutrino oscillations and can radically change the conditions under which the oscillations are resonantly enhanced. Possible new effects in neutrino oscillations are discussed for the case of neutrino propagation in relativistic fluxes of matter.

STUDENIKIN PHYSICS OF ATOMIC NUCLEI Vol. 67 No. 5 2004

Consider

$$\nu_{e_L} \to \nu_{e_R}, \quad \nu_{e_L} \to \nu_{\mu_R}$$

$$P(\nu_i \to \nu_j) = \sin^2(2\theta_{\rm eff}) \sin^2 \frac{\pi x}{L_{\rm eff}}, \quad i \neq j$$

$$L_{\rm eff} = \frac{2\pi}{\sqrt{E_{\rm eff}^2 + \Delta_{\rm eff}^2}}$$

$$\sin^2 2\theta_{\rm eff} = \frac{E_{\rm eff}^2}{E_{\rm eff}^2 + \Delta_{\rm eff}^2}, \quad \Delta_{\rm eff}^2 = \frac{\mu}{\gamma_\nu}\left|\mathbf{M}_{0\parallel} + \mathbf{B}_{0\parallel}\right|. \qquad E_{\rm eff} = \mu\left|\mathbf{B}_\perp + \frac{1}{\gamma_\nu}\mathbf{M}_{0\perp}\right|$$

- A.Studenikin, "Status and perspectives of neutrino magnetic moments" arXiv:1603.00337

$$\vec{M}_0 = \gamma_\nu \rho n_e \left(\vec{\beta}_\nu (1 - \vec{\beta}_\nu \vec{v}_e) - \frac{1}{\gamma_\nu} \vec{v}_{e_\perp}\right),$$

transversal matter current

$$\gamma_\nu = \frac{E_\nu}{m_\nu},$$

matter density

$\parallel$ $\perp$

where $$\rho = \frac{G_F}{2\mu_\nu\sqrt{2}}(1 + 4\sin^2\theta_W)$$

Physics of Atomic Nuclei, Vol. 67, No. 5, 2004, pp. 993–1002. Translated from Yadernaya Fizika, Vol. 67, No. 5, 2004, pp. 1014–1024.

ELEMENTARY PARTICLES AND FIELDS
Theory

Phys.Atom.Nucl. 67 (2004) 993-1002, hep-ph/04070100

Neutrino in Electromagnetic Fields and Moving Media

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Received March 26, 2003; in final form, August 12, 2003

The possible emergence of neutrino-spin oscillations (for example, $\nu_{eL} \leftrightarrow \nu_{eR}$) owing to neutrino interaction with matter under the condition that there exists a nonzero transverse current component or matter polarization (that is, $\mathbf{M}_{0\perp} \neq 0$) is the most important new effect that follows from the investigation of neutrino-spin oscillations in Section 4. So far, it has been assumed that neutrino-spin oscillations may arise only in the case where there exists a nonzero transverse magnetic field in the neutrino rest frame.

$\nu_{e_L} \to \nu_{e_R}, \quad \nu_{e_L} \to \nu_{\mu_R}$

... the effect of ν helicity conversions and oscillations induced by transversal matter currents has been recently confirmed:

- J. Serreau and C. Volpe, "Neutrino-antineutrino correlations in dense anisotropic media", Phys .Rev. D90 (2014) 125040
- V. Cirigliano, G. M. Fuller, and A. Vlasenko, "A new spin on neutrino quantum kinetics" Phys. Lett. B747 (2015) 27
- A. Kartavtsev, G. Raffelt, and H. Vogel, "Neutrino propagation in media: flavor-, helicity-, and pair correlations", Phys. Rev. D91 (2015) 125020
- A. Dobrynina, A. Kartavtsev, and G. Raffelt, "Helicity oscillations of Dirac and Majorana neutrinos", Phys. Rev. D93 (2016) 125030

Neutrino spin (spin-flavour) oscillations in transversal matter currents

... quantum treatment ...

Studenikin

- PoS (2017) NOW2016_070 arXiv:1610.06563
- J.Phys.Conf.Ser. 888 (2017) 012221 arXiv:1706.01100

Popov, Pustoshny, Studenikin,

Two flavour ν states

$$\nu_e^{\pm} = \nu_1^{\pm}\cos\theta + \nu_2^{\pm}\sin\theta, \quad \nu_\mu^{\pm} = -\nu_1^{\pm}\sin\theta + \nu_2^{\pm}\cos\theta$$

two ν mass

$$\nu_\alpha^{\pm} = C_\alpha\sqrt{\frac{E_\alpha + m_\alpha}{2E_\alpha}}\begin{pmatrix} u^{\pm} \\ \frac{\sigma \mathbf{p}_\alpha}{E_\alpha + m_\alpha}u^{\pm}\end{pmatrix} e^{i\mathbf{p}_\alpha \mathbf{x}}, \alpha = 1, 2$$

two helicities

$$u^+ = \begin{pmatrix}1\\0\end{pmatrix}, \quad u^- = \begin{pmatrix}0\\1\end{pmatrix}$$

ν interaction with moving matter composed of neutrons :

$$L_{eff} = -f^\mu\left(\bar{\nu}\gamma_\mu\frac{1+\gamma_5}{2}\nu\right)$$

transversal and longitudinal currents

$$\vec{j}_\perp + \vec{j}_{\parallel}$$

$$f^\mu = -\frac{G_F}{2\sqrt{2}}j_n^\mu \qquad j_n^\mu = n(1, \mathbf{v}) \qquad n = \frac{n_0}{\sqrt{1-v^2}}$$

Two flavour ν with two helicities in moving matter

$$i\frac{d}{dt}\begin{pmatrix}\nu_e^+\\ \nu_e^-\\ \nu_\mu^+\\ \nu_\mu^-\end{pmatrix} = \left\{H^{eff}_{vac} + \Delta H^{eff}\right\}\begin{pmatrix}\nu_e^+\\ \nu_e^-\\ \nu_\mu^+\\ \nu_\mu^-\end{pmatrix}$$

$$\Delta H^{eff} = \Delta H^{eff}_{v=0} + \Delta H^{eff}_{\vec{j}_{\parallel}+\vec{j}_{\perp}}$$

$\vec{j}_{\perp} + \vec{j}_{\parallel}$

Contribution of matter currents

$$\Delta H^{eff} = \begin{pmatrix}\Delta^{++}_{ee} & \Delta^{+-}_{ee} & \Delta^{++}_{e\mu} & \Delta^{+-}_{e\mu}\\ \Delta^{-+}_{ee} & \Delta^{--}_{ee} & \Delta^{-+}_{e\mu} & \Delta^{--}_{e\mu}\\ \Delta^{++}_{\mu e} & \Delta^{+-}_{\mu e} & \Delta^{++}_{\mu\mu} & \Delta^{+-}_{\mu\mu}\\ \Delta^{-+}_{\mu e} & \Delta^{--}_{\mu e} & \Delta^{-+}_{\mu\mu} & \Delta^{--}_{\mu\mu}\end{pmatrix}$$

$$\Delta^{ss'}_{kl} = \langle \nu^s_k | \Delta H^{SM} | \nu^{s'}_l \rangle \quad k,l = e,\mu \qquad s,s' = \pm$$

$$\Delta H^{SM} = -\frac{G_F}{2\sqrt{2}}\frac{n}{\sqrt{1-v^2}}\left(1-\gamma_0\boldsymbol{\gamma}\mathbf{v}\right)\left(1+\gamma_5\right)$$

$$\nu_e^\pm = \nu_1^\pm\cos\theta + \nu_2^\pm\sin\theta, \quad \nu_\mu^\pm = -\nu_1^\pm\sin\theta + \nu_2^\pm\cos\theta$$

$$\gamma_{\alpha\alpha'}{}^{-1} = \frac{1}{2}(\gamma_\alpha^{-1}+\gamma_{\alpha'}^{-1}) \quad \tilde{\gamma}^{-1}_{\alpha\alpha'} = \frac{1}{2}(\gamma_\alpha^{-1}-\gamma_{\alpha'}^{-1})$$

$$\Delta^{ss'}_{\alpha\alpha'} = \frac{G_F}{2\sqrt{2}}\frac{n_0}{\sqrt{1-v^2}}\left\{u^{s\,T}_\alpha\left[(1-\sigma_3)(v_{\parallel}-1) + \left(\gamma_{\alpha\alpha'}{}^{-1}\sigma_1 + i\tilde{\gamma}^{-1}_{\alpha\alpha'}\sigma_2\right)v_\perp\right]u^{s'}_{\alpha'}\right\}\alpha = 1,2$$

$$\Delta^{ss'}_{\alpha\alpha'} = \frac{G_F}{2\sqrt{2}}\frac{n_0}{\sqrt{1-v^2}}\left\{u^{s\,T}_\alpha\left[\begin{pmatrix}0&0\\0&2\end{pmatrix}(v_{\parallel}-1) + \begin{pmatrix}0&\gamma_\alpha^{-1}\\ \gamma_{\alpha'}^{-1}&0\end{pmatrix}v_\perp\right]u^{s'}_{\alpha'}\right\}$$

$$u^+ = \begin{pmatrix}1\\0\end{pmatrix}, \quad u^- = \begin{pmatrix}0\\1\end{pmatrix}$$

two helicity states

$$\gamma_\alpha^{-1} = \frac{m_\alpha}{E_\alpha}$$

- longitudinal current $j_{\parallel}$ does not change ν helicity
- transversal current $j_{\perp}$ does change ν helicity

Studenikin, 2004, 2016; Popov, Pustoshny, Studenikin, 2017

- New phenomena in ν flavour, spin and spin-flavour oscillations in magnetic field

$\nu_e^L \leftrightarrow \nu_\mu^L$ $\nu_e^L \leftrightarrow \nu_e^R$ $\nu_e^L \leftrightarrow \nu_\mu^R$

Dmitriev, Fabbricatore, Studenikin, arXiv: 1506.05311 Studenikin, arXiv: 1705.05944

ν eigenstates in $\vec{B} = \vec{B}_\perp + \vec{B}_{||}$ are used for classification ν spin states

Two ν states with two chiralities

$$\nu_e^{L(R)} = \nu_1^{L(R)} \cos\theta + \nu_2^{L(R)} \sin\theta$$
$$\nu_\mu^{L(R)} = -\nu_1^{L(R)} \sin\theta + \nu_2^{L(R)} \cos\theta$$

$i = 1, 2$ mass states

- (are non-stationary in B)

- ν stationary states in B

$$(\gamma p - m_i - \mu_i \mathbf{\Sigma B})\nu_i^s(p) = 0$$

ν spin operator

$$\hat{S}_i = \frac{m_i}{\sqrt{m_i^2 \boldsymbol{B}^2 + \boldsymbol{p}^2 B_\perp^2}} \left[\mathbf{\Sigma} \boldsymbol{B} - \frac{i}{m_i} \gamma_0 \gamma_5 [\mathbf{\Sigma} \times \boldsymbol{p}] \boldsymbol{B} \right]$$

- $$\nu_i^L(t) = c_i^+ \nu_i^+(t) + c_i^- \nu_i^-(t)$$
$$\nu_i^R(t) = d_i^+ \nu_i^+(t) + d_i^- \nu_i^-(t)$$

$$E_i^s = \sqrt{m_i^2 + p^2 + \mu_i{}^2 \mathbf{B}^2 + 2\mu_i s \sqrt{m_i^2 \mathbf{B}^2 + p^2 B_\perp^2}}$$

ν energy

- chiral ν are expanded over stationary ν states in B

Probabilities of ν oscillations

$\nu_e^L \leftrightarrow \nu_\mu^L$ $\quad P_{\nu_e^L \to \nu_\mu^L}(t) = \left|\langle \nu_\mu^L | \nu_e^L(t)\rangle\right|^2 \qquad \mu_\pm = \frac{1}{2}(\mu_1 \pm \mu_2)$

flavour

$$P_{\nu_e^L \to \nu_\mu^L}(t) = \sin^2 2\theta \Big\{ \cos(\mu_1 B_\perp t)\cos(\mu_2 B_\perp t)\sin^2 \frac{\Delta m^2}{4p} t + \\ + \sin^2(\mu_+ B_\perp t)\sin^2(\mu_- B_\perp t) \Big\}$$

spin

$$P_{\nu_e^L \to \nu_e^R} = \Big\{ \sin(\mu_+ B_\perp t)\cos(\mu_- B_\perp t) + \cos 2\theta \sin(\mu_- B_\perp t)\cos(\mu_+ B_\perp t) \Big\}^2 \\ - \sin^2 2\theta \sin(\mu_1 B_\perp t)\sin(\mu_2 B_\perp t)\sin^2 \frac{\Delta m^2}{4p} t.$$

spin-flavour

$$P_{\nu_e^L \to \nu_\mu^R}(t) = \sin^2 2\theta \Big\{ \sin^2 \mu_- B_\perp t \cos^2(\mu_+ B_\perp t) + \\ + \sin(\mu_1 B_\perp t)\sin(\mu_2 B_\perp t)\sin^2 \frac{\Delta m^2}{4p} t \Big\}$$

.. interplay of oscillations on vacuum and magnetic frequencies

Popov, AS, arXiv: 1803.05755

- For the case $\mu_1 = \mu_2$: probability of flavour oscillations

$$P_{\nu_e^L \to \nu_\mu^L} = \left(1 - \sin^2(\mu B_\perp t)\right) \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4p} t = \left(1 - P^{cust}_{\nu_e^L \to \nu_e^R}\right) P^{cust}_{\nu_e^L \to \nu_\mu^L}$$

flavour

- Popov, AS, arXiv: 1803.05755

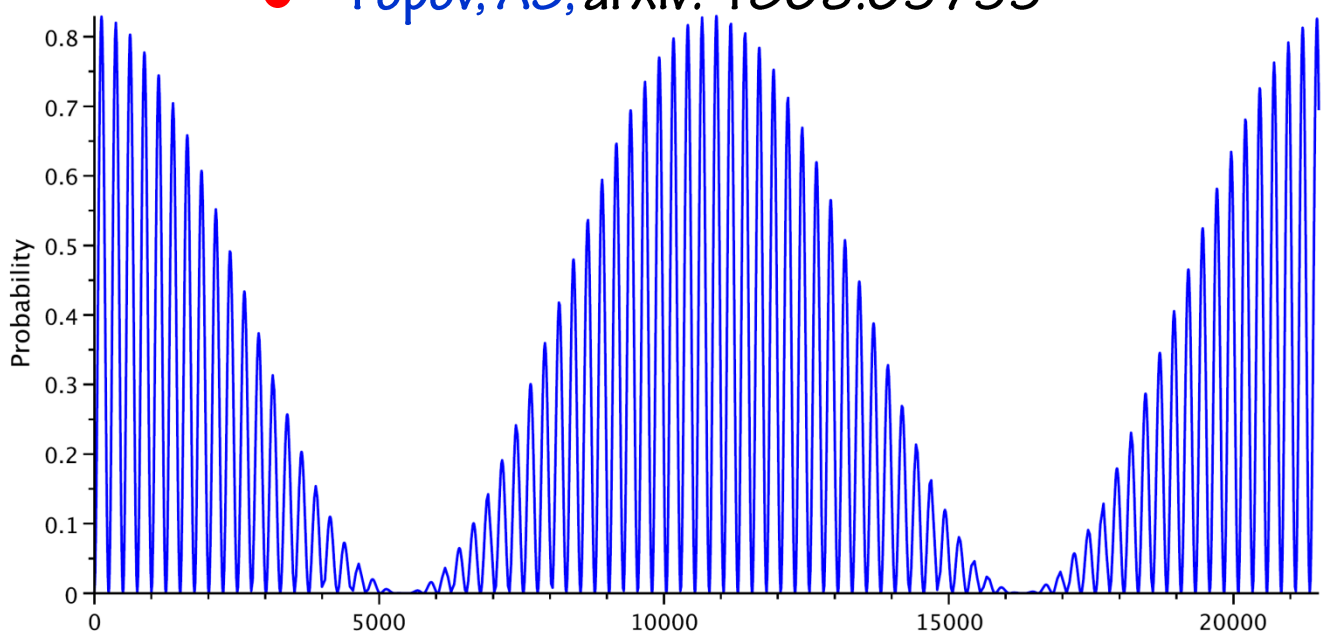


Figure 1: The probability of the neutrino flavour oscillations $\nu_e^L \to \nu_\mu^L$ in the transversal magnetic field $B_\perp = 10^8\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-12} \mu_B$.

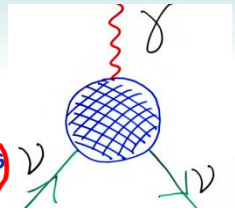
Chotorlishvili, Kouzakov, Kurashvili, AS,

- Spin-flavor oscillations of ultrahigh-energy cosmic neutrinos in interstellar space: The role of neutrino magnetic moments, Phys. Rev. D96 (2017) 103017

Conclusions

C.Giunti, A.Studenikin,
" ν electromagnetic interactions: A window to new physics",
Rev.Mod.Phys, 2015

A.S.
" ν electromagnetic interactions: A window to new physics-II",
arXiv: 1801.18887



① νEP theory - ν vertex function

matrices in ν mass eigenstates space

$$\Lambda^{if}_\mu(q) = f^{if}_Q(q^2)\gamma_\mu + f^{if}_M(q^2) i\sigma_{\mu\nu}q^\nu + f^{if}_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f^{if}_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5,$$

electric charge
magnetic moment
electric moment
anapole moment

form factors $f^{if}_X(q^2)$ at $q^2 = 0$
static EP of ν

Dirac ν	Majorana
q_{if}	$q_{if} = 0$
μ_{if}	$\mu_{if}(i \neq f)$
ε_{if}	$\varepsilon_{if}(i \neq f)$
a_{if}	a_{if}

0_+

CPT + charge concervation

Hermiticity and discrete symmetries of EM current put constraints on form factors

$$\langle \nu(p')|J^{EM}_\mu|\nu(p)\rangle = \bar{u}(p')\Lambda_\mu(q)u(p)$$

② $$\mu^D_{jj} = \frac{3e_0 G_F m_j}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19}\mu_B \left(\frac{m_j}{1\ \text{eV}}\right)$$

- much greater values are Beyond Minimally Extended SM
- transition moments $\mu_{i\neq f}$, $\varepsilon_{i\neq f}$ are GIM suppressed

③ νEP experimental bounds

$\mu^{eff}_\nu < 2.8 \times 10^{-11}\ \mu_B$ (2.9; ~0.1)

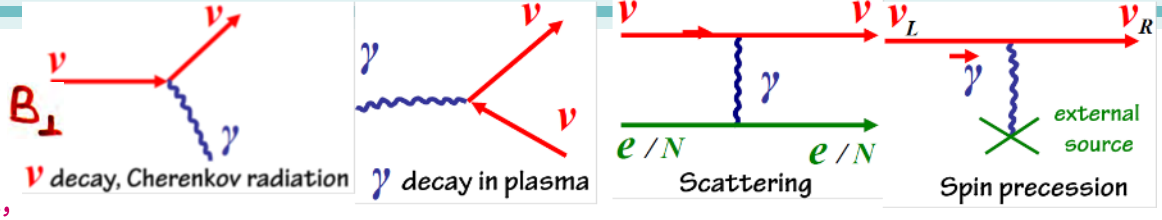
GEMMA Coll. 2012
Borexino Coll. 2017
Astrophysics, Raffelt ea 1988
Arcoa Dias ea 2015

$q_{\nu_e} < \sim 10^{-12}$, $\sim 10^{-19}$, $\sim 10^{-21}$ e_0

reactor ν scattering: AS '14, Chen ea '14
νST '14 (astrophysics)
neutrality of matter

Effects of ν magnetic moment:

- spin precession and oscillations in $B_\perp$



Cisneros, Okun, Voloshin, Vysotsky, Valle, Raffelt, Schechter, Petkov, Akhmedov, Lim, Marciano, Smirmov, Pulido, Dvornikov, Grigoriev, Lobanov, Lokhov, Kouzakov, Ternov, Studenikin et al

New effects reported at QUARKS 2018

1. Electromagnetic interactions and oscillations of ultrahigh-energy cosmic ν in interstellar space

Kouzakov & AS
PRD 96 (2017) $L_B = \pi/\mu_\nu B$

$$P_{\nu^L\to\nu^R}(x) = \sin^2\left(\frac{\pi x}{L_B}\right)$$

$$P_{\nu_e^L\to\nu_\mu^L}(x) = [1 - P_{\nu^L\to\nu^R}(x)]\sin^2 2\theta\,\sin^2\left(\frac{\pi x}{L_{\rm vac}}\right)$$

amplitude of flavour oscillations is modulated by $\mu_\nu B$ frequency

2. ν flavour, spin and spin-flavour oscillations and consistent account for a constant magnetic field

Popov & AS,
arXiv: 1803.05766
probability of spin oscillations depends on Δm^2

$$P_{\nu_e^L\to\nu_e^R} = \left\{\sin(\mu_+B_\perp t)\cos(\mu_-B_\perp t) + \cos 2\theta\sin(\mu_-B_\perp t)\cos(\mu_+B_\perp t)\right\}^2 - \sin^2 2\theta\sin(\mu_1B_\perp t)\sin(\mu_2B_\perp t)\sin^2\frac{\Delta m^2}{4p}t$$

3. ν spin and spin-flavour oscillations engendered by transversal matter current

Pustoshny & AS,
arXiv: 1801.08911
Studenikin 2004, 2017

!

- **transversal matter currents $j_\perp$ do change ν helicity**

4. Spin-light of ν in Gamma-Ray Bursts

new mechanism of EM radiation by ν
JCAP 1711 (2017) no. 11, 024

Grigoriev, Lokhov, Studenikin, Trenov

μ_ν interactions could have important effects in astrophysical and cosmological environments

future high-precision observations of supernova ν fluxes (for instance, in JUNO experiment) may reveal effect of collective spin-flavour oscillations due to Majorana

$$\mu_\nu \sim 10^{-21} \mu_B$$

- A. de Gouvea, S. Shalgar, Cosmol. Astropart. Phys. 04 (2013) 018

back up slides

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

H.Wong et al. (TEXONO Coll.), PRL 105 (2010) 061801

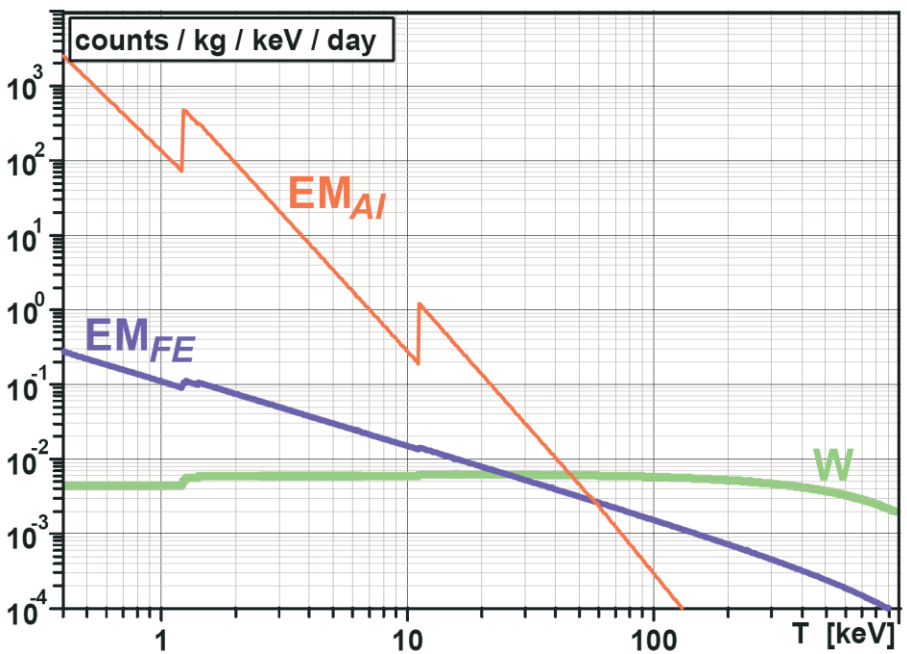
(ν scattering on bound e)

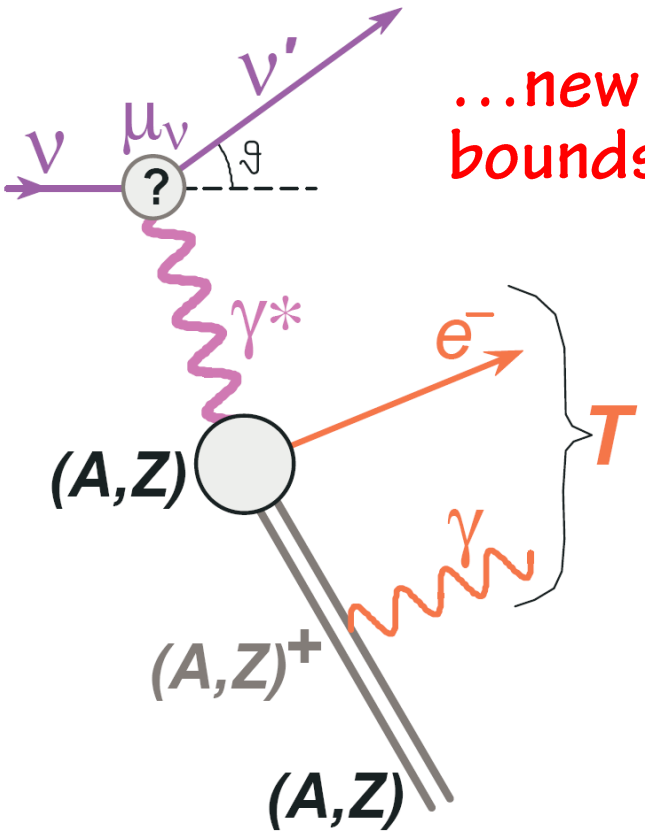
$$\nu + (A,Z) \longrightarrow \nu' + (A,Z)^+ + e^-$$

$$\downarrow \text{recombination}$$

$$(A,Z) \quad + \gamma$$

… an interesting hypothetical possibility to improve bounds…





…new bounds …

… better limits on ν effective magnetic moment …

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

H.Wong et al., (TEXONO Coll.), PRL 105 (2010) 061801

… atomic ionization effect accounted for …

… however …

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

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

… atomic ionization effect accounted for …

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

… 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,
- "Electromagnetic neutrino-atom collisions: The role of electron binding" **Nucl. Phys.** (Proc.Suppl.) 217 (2011) 353

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

- "Neutrino electromagnetic properties and new bounds on neutrino magnetic moments" **J. Phys.: Conf. Ser.** 375 (2012) 042045
- "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

3.11 ν charge radius and anapole moment

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

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 $f_Q(q^2) \neq 0 \; for \; q^2 \neq 0$:

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

where the massive ν charge radius

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

For massless ν anapole moment

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

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 ? ? ?

Bernabeu, Papavassiliou, Vidal, Nucl.Phys. B 680 (2004) 450

… A remark on electric charge of ν… Beyond Standard Model…

ν neutrality $Q=0$ is attributed to

gauge invariance + anomaly cancellation constraints

imposed in SM of electroweak interactions

Foot, Joshi, Lew, Volkas, 1990;
Foot, Lew, Volkas, 1993;
Babu, Mohapatra, 1989, 1990
Foot , He (1991)

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

- *…General proof:*
- *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**

Astrophysics bounds on μ_ν

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

Mostly derived from consequences of helicity-state change in astrophysical medium:

- **available degrees of freedom in BBN,**
- **stellar cooling via plasmon decay,**
- **cooling of SN1987a**

Red Giant lumin.
$\mu_\nu \lesssim 3 \cdot 10^{-12} \mu_B$
G. Raffelt, D. Dearborn, J. Silk, 1989.

Bounds depend on

- **modeling of astrophysical systems,**
- **on assumptions on the neutrino properties.**

Generic assumption:

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

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

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

Z.Z.Xing, Y.L.Zhou,
"Enhanced electromagnetic transition dipole moments and radiative decays of massive neutrinos due to the seesaw-induced non-unitary effects"
Phys.Lett.B 715 (2012) 178

- *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

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

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

with magnetic moment interaction

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

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

ν evolution equation

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

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

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

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

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

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

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

- Resonance amplification of oscillations in matter:

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

Akhmedov, 1988
Lim, Marciano

... similar to MSW effect

In magnetic field

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

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

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

Neutrino conversions and oscillations in magnetic field

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

  Cisneros, 1971

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

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

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

  - Dar, 1987

  Fujikawa, Shrock, 1988
  Voloshin, 1988

...for recent analysis see

J.Pulido, 2006, TAUP-09; ●
A.Balantekin, C.Volpe, 2005

...subdominant contribution to LMA – MSW solution...

$\nu_{\odot}$

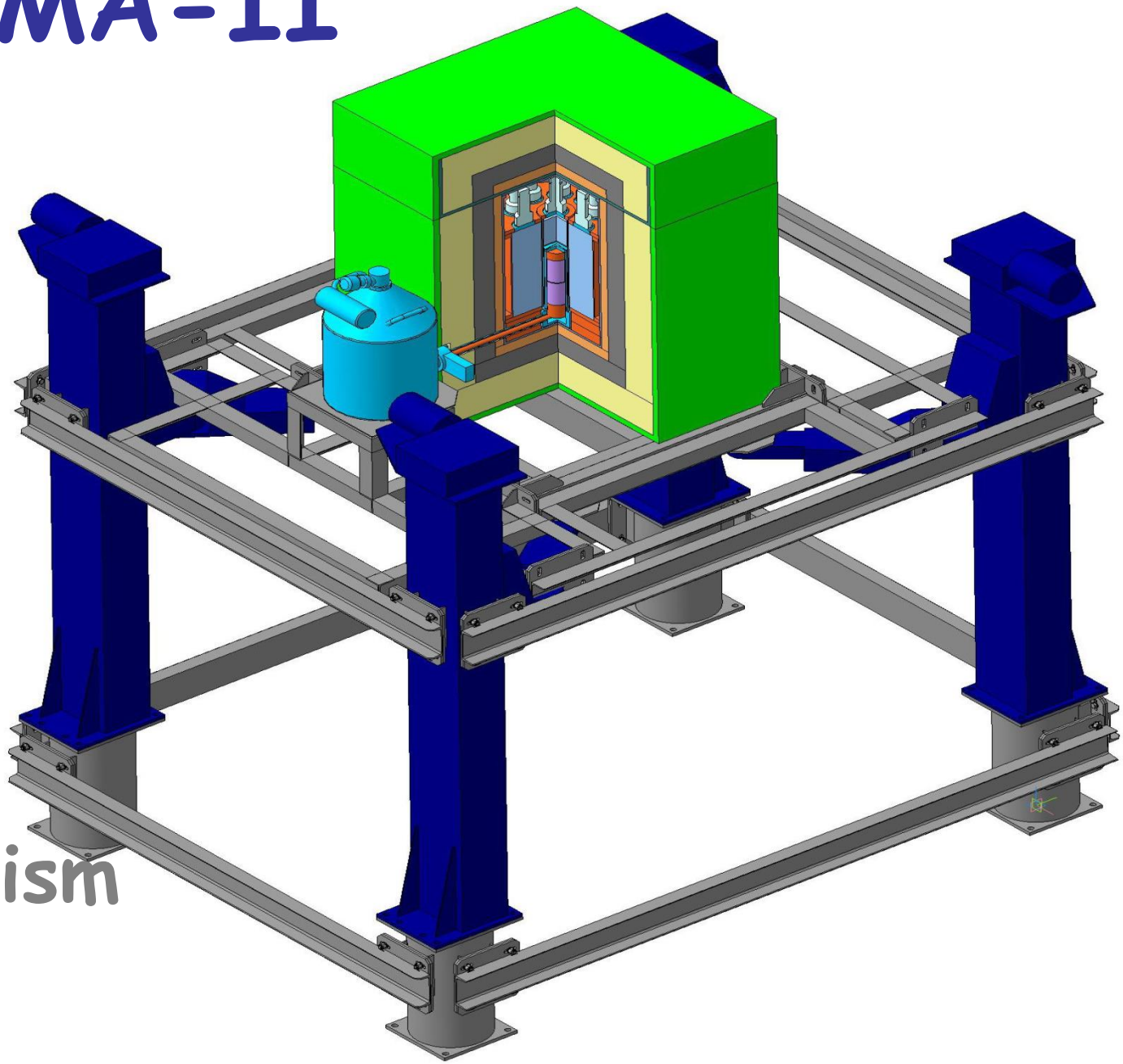
✷ Spin-flavour oscillations in early universe – strong $B_{\perp}$

⇒ population of ν wrong-helicity states (r.h.) would accelerate expansion of universe (???)

GEMMA


#2: 14 m
#3: 10 m
KNPP
Udomlya
Russia

GEMMA-II



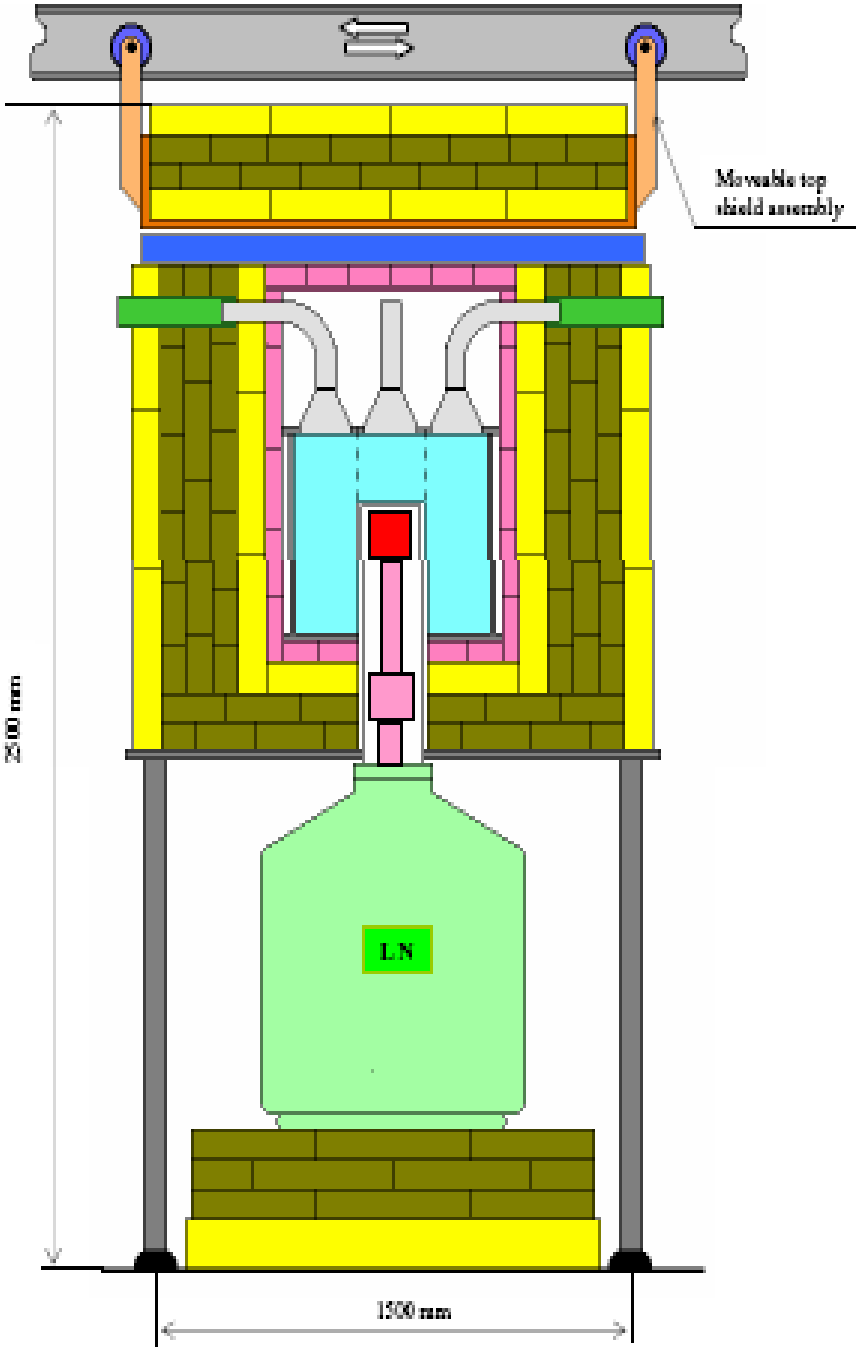
Lifting mechanism

Experiment GEMMA

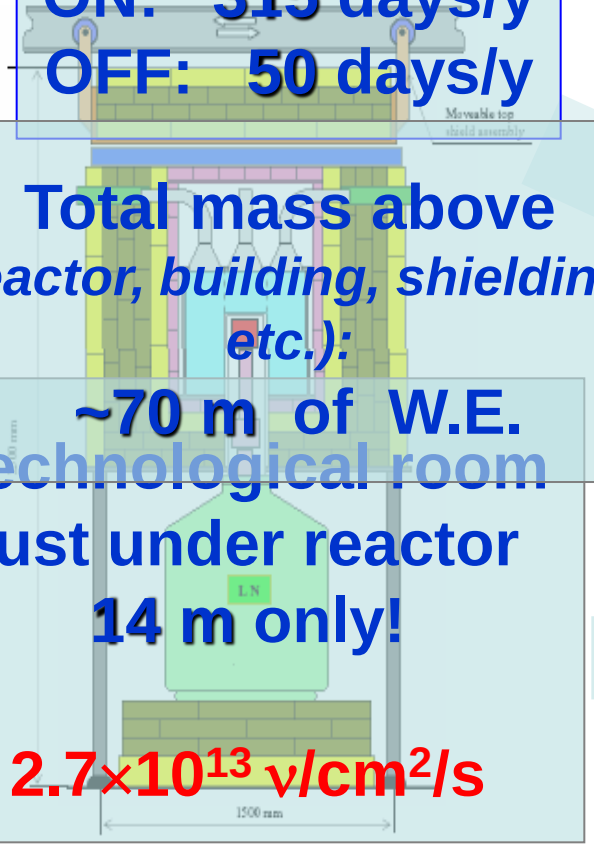
(Germanium Experiment for measurement of Magnetic Moment of Antineutrino)

[Phys. of At. Nucl.,67(2004)1948]

- Spectrometer includes a HPGe detector of 1.5 kg installed within NaI active shielding.
- HPGe + NaI are surrounded with multi-layer passive shielding : electrolytic copper, borated polyethylene and lead.



Reactor unit # 2 of the "Kalinin" Nuclear Power Plant (400 km North from Moscow)



Power: 3 GW
ON: 315 days/y
OFF: 50 days/y

Total mass above
(reactor, building, shielding, etc.):
~70 m of W.E.

Technological room just under reactor
14 m only!

2.7×10^{13} ν/cm²/s

… courtesy of D.Medvedev…

GEMMA background conditions

- γ-rays were measured with Ge detector. The main sources are: ^{137}Cs, ^{60}Co, ^{134}Cs.
- Neutron background was measured with ^{3}He counters, i.e., thermal neutrons were counted. Their flux at the facility site turned out to be 30 times lower than in the outside laboratory room.
- Charged component of the cosmic radiation (muons) was measured to be 5 times lower than outside.

Experimental sensitivity

$$\mu_\nu \propto \frac{1}{\sqrt{N_\nu}} \left(\frac{B}{mt} \right)^{\frac{1}{4}}$$

N_ν : number of signal events expected
B : background level in the ROI
m : target (=detector) mass
t : measurement time

$$N_\nu \sim \varphi_\nu \, (\sim Power / r^2)$$
$$\sim (T_{max} - T_{min} / T_{max} * T_{min})^{1/2}$$

GEMMA I

$\varphi_\nu \sim 2.7 \times 10^{13}\ \nu / cm^2 / s$
$t \sim 4$ years
$B \sim 2.5\ keV^{-1}\ kg^{-1}\ day^{-1}$
$m \sim 1.5$ kg
$T_{th} \sim 2.8$ keV

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

… courtesy of D.Medvedev…

Data Set

- I phase – 5184 h ON, 1853 h OFF

$$\mu_\nu < 5.8*10^{-11}\mu_B$$

- II phase – 6798 h ON, 1021 h OFF
- I+II – 11982 h ON, 2874 h OFF

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

- III phase – 6152 h ON, 1613 h OFF
- I+II+III – 18134 h ON, 4487 h OFF

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

***Beda A.G. et al.* // Advances in High Energy Physics. 2012. V. 2012, Article ID 350150.**

***Beda A.G. et al.* // Physics of Particles and Nuclei Letters, 2013, V. 10, №2, pp. 139–143.**

Sensitivity of future experiments

B = 0.2 1/keV/kg/day (background level in ROI)

Mass, kg	Threshold, keV	Sensitivity, $10^{-12}\mu_B$
4.5	0.4	5.8
10	0.4	4.7
20	0.4	4.0
4.5	0.3	5.6
10	0.3	4.6
20	0.3	3.9

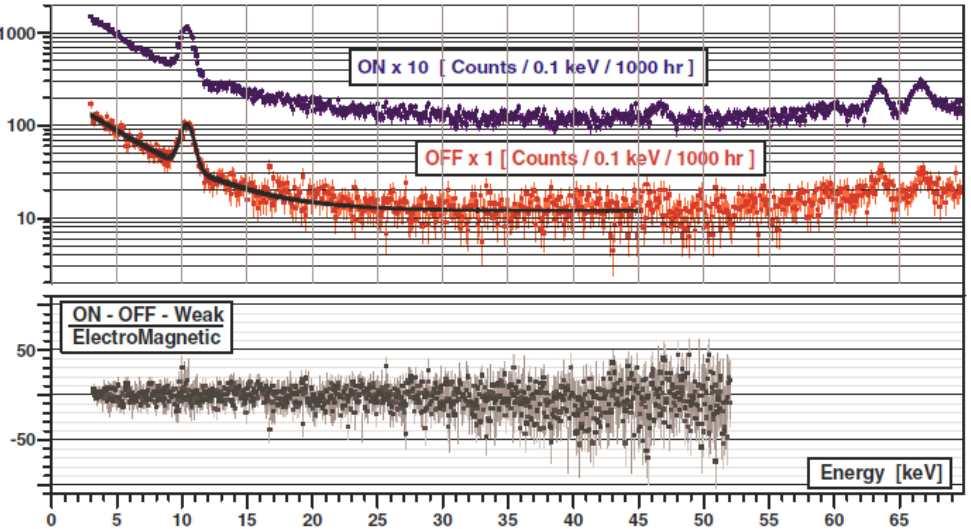
... courtesy of D.Medvedev...

… the obtained constraint on neutrino millicharge q_ν

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

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

A.Studenikin : "New bounds on neutrino electric millicharge from limits on neutrino magnetic moment", Eur.Phys.Lett. 107 (2014) 2100, arXiv:1302.1168



Difference between reactor on and off electron recoil energy spectra (with account for weak interaction contribution) normalized by theoretical electromagnetic spectra

A. Beda et al, Adv. High Energy Phys. 2012(2012) 350150

- Limit evaluated using statistical procedures is of the same order as previously discussed

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

A.Studenikin : "New bounds on neutrino electric millicharge from limits on neutrino magnetic moment", Eur.Phys.Lett. 107 (2014) 2100, arXiv:1302.1168

- V.Brudanin, D.Medvedev, A.Starostin, A.Studenikin : "New bounds on neutrino electric millicharge from GEMMA experiment on neutrino magnetic moment", arXiv: 1411.2279