Magnetic moment of the neutrino

Neutrino
Oscillation Workshop

Rosa Marina
Ostuni, Italy
15/09/2018

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Moscow State University
&
JINR-Dubna
GEMMA coll.

...2018 anniversaries in ν oscillation story

1968 - $\nu_\odot$ (Davis et al) **50**

1968 - $\nu_e \leftrightarrow \nu_\mu$ theory (Gribov & Pontecorvo)

1978 - ν flavour-dependent refraction in matter (Wolfenstein) **40**

1988 - Resonance Spin-Flavour Precession in matter (Akhmedov + Lim & Marciano) **30**

1998 - ν oscillations in ν_{atm} fluxes (Super-Kamiokande) **20**

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 $j_\perp$ new oscillations !

Studenikin, Phys.Atom.Nucl. 67 (2004) 993; PoS 318 (2018) 085
Pustoshny, Studenikin, arXiv: 1808.00302

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

Neutrino electromagnetic interactions: A window to new physics

+ upgrade:

Studenikin,
“ν electromagnetic interactions: A window to new physics – II”, arXiv: 1801.18887

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(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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Staff member at
Faculty of Physics of
Moscow State University,
1966 - 1986

if $m_\nu \neq 0$

then $\nu \leftrightarrow \bar{\nu}$
in vacuum

Bruno Pontecorvo, «Inverse β processes and nonconcervation of leptonic charge», JINR Preprint P-95, Dubna, 1957 (3 pp.) :

61 years of mixing and oscillations

«Neutrinos in vacuum can transform themselves into antineutrino and vice versa. This means that neutrino and antineutrino are particle mixtures ...

So, for example, a beam of neutral leptons from a reactor which at first consists mainly of antineutrinos will change its composition and at a certain distance R from the reactor will be composed of neutrino and antineutrino in equal quantities».

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

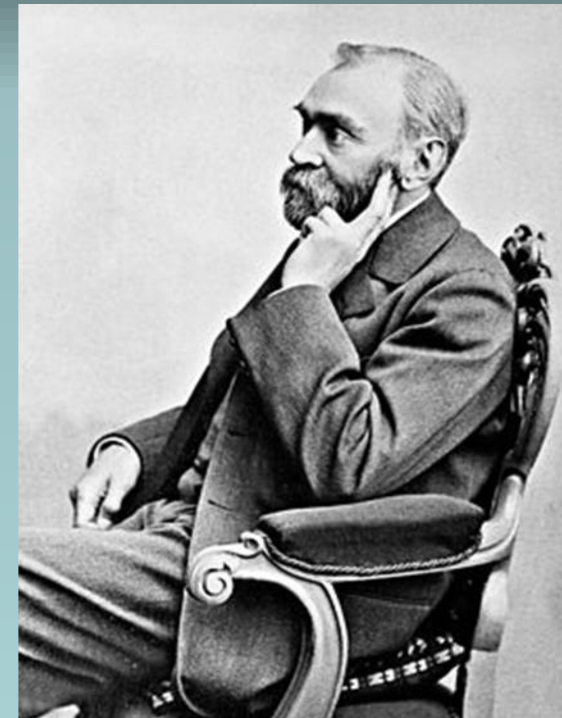
are in agreement with "ZERO"
ν EM properties

Nobel Prizes

2013

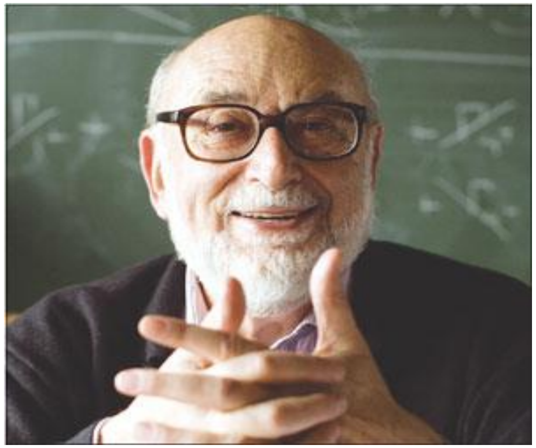
&

2015



1833 – 1896

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**

2013

- celebrates the glorious triumph of Standard Model
- highlight on ν as the only known particle with properties beyond Standard Model

2015

- importance of ν electromagnetic properties

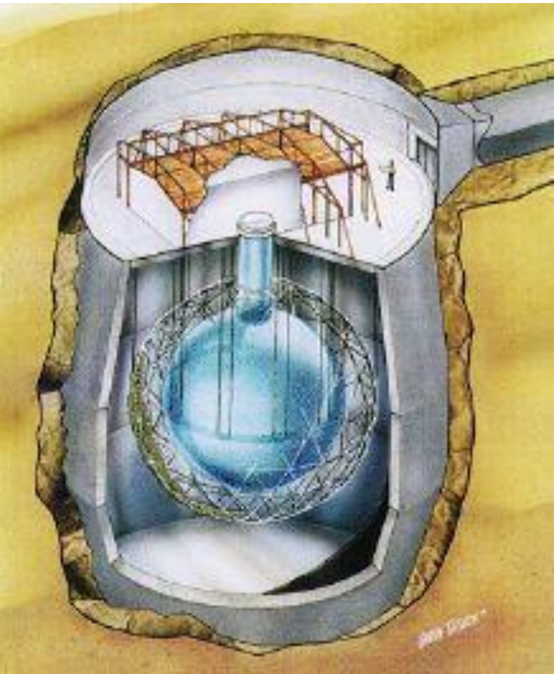
Arthur McDonald

The Nobel Prize in Physics 2015

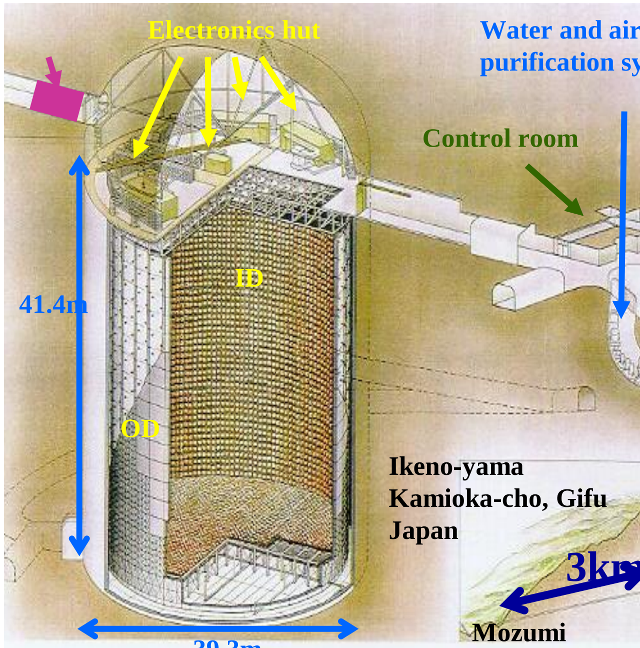
Takaaki Kajita

Sudbury Neutrino Observatory

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)

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

Lee Shrock, 1977; Fujikawa Shrock, 1980

magnetic moment

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

… much greater values are desired

for astrophysical or cosmology

visualization of μ_ν

new physics

… hopes for physics BESM …

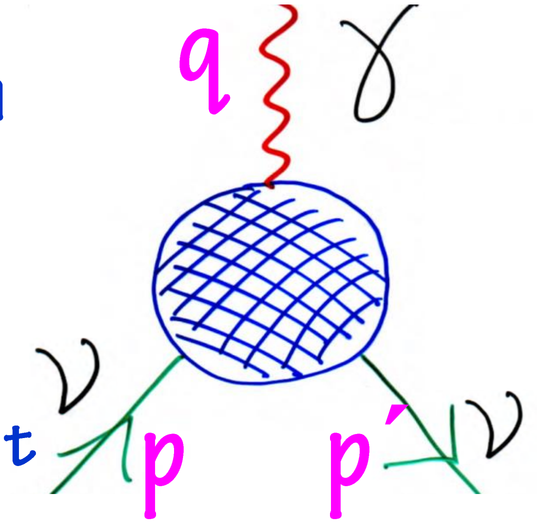
1

ν electromagnetic properties

(flash on theory)

$m_\nu \neq 0$

electromagnetic vertex function



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

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

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

where vertex function generally contains 4 form factors

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

1. electric
2. magnetic dipole
3. electric dipole
4. anapole

- Hermiticity and discrete symmetries of EM current J_μ^{EM} put constraints on form factors

Dirac ν

1) CP invariance + Hermiticity $\Longrightarrow f_E = 0$,

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 $\Longrightarrow$ 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 $\Longrightarrow$ 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

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

Dipole magnetic $\boxed{f_M(q^2)}$ and electric $\boxed{f_E(q^2)}$

are most well studied and theoretically understood among form factors

…because in the limit $\boxed{q^2 \to 0}$ they have nonvanishing values

$$\boxed{\mu_\nu = f_M(0)} \Leftarrow \nu \text{ magnetic moment}$$

$$\boxed{\epsilon_\nu = f_E(0)} \Leftarrow \nu \text{ electric moment ???}$$

Magnetic moment dependence

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

on neutrino mass

3.1 ν vertex function

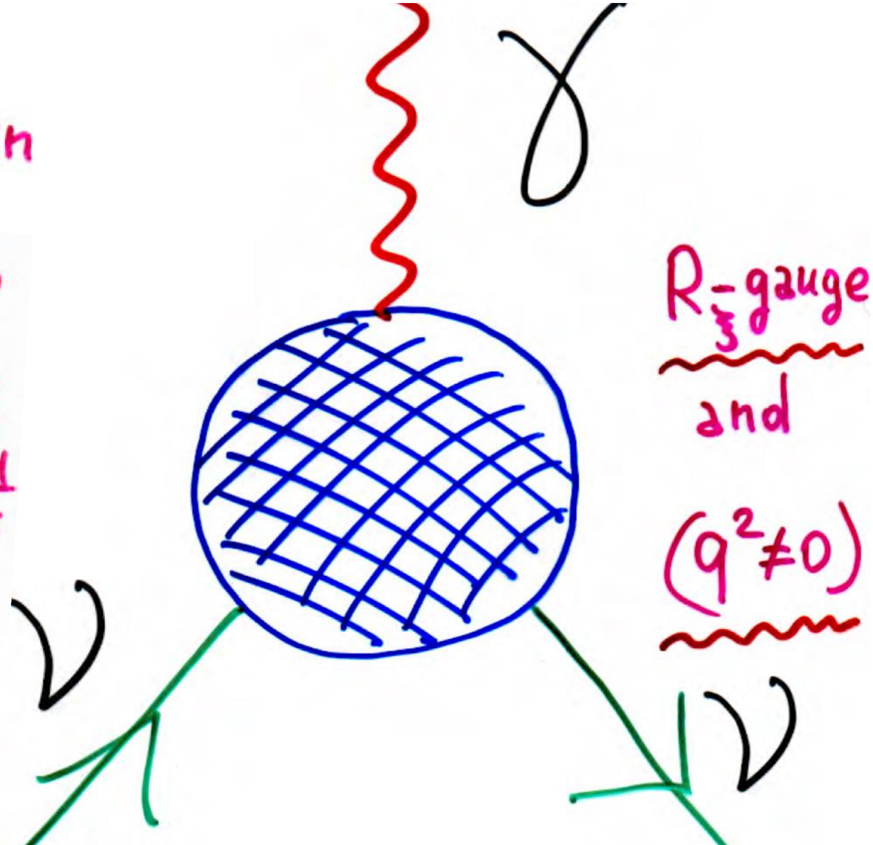
The most general study of the massive neutrino vertex function (including electric and magnetic form factors) in arbitrary R_ξ gauge in the context of the SM + SU(2)-singlet ν_R accounting for masses of particles in polarization loops

Dvornikov
Studenikin,
PRD 2004,
JETP 2004

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

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

electric moment　　　　anapole moment

$m_\nu \ll m_e \ll M_W$ light ν

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

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

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

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

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

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

$m_e \ll M_W \ll m_\nu$

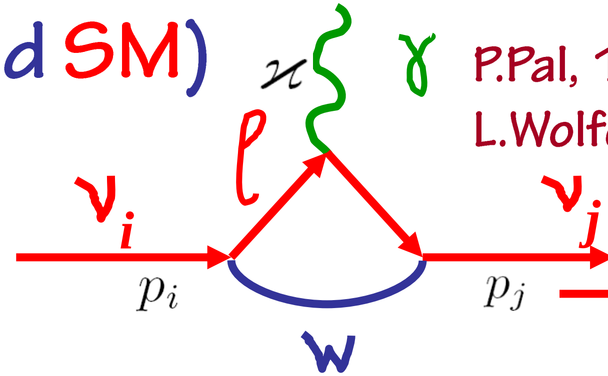
$$\boxed{\mu_\nu = \frac{eG_F m_\nu}{8\pi^2\sqrt{2}}}$$

heavy ν

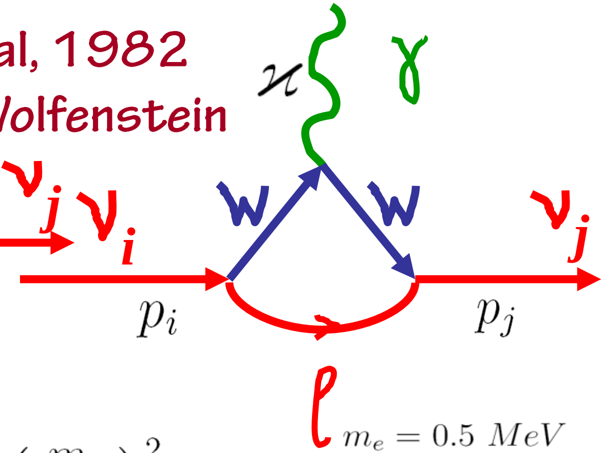
$$\sim 10^{-19}\mu_B\left(\frac{m_{\nu_e}}{1\,eV}\right)$$

... μ_ν in case of mixing ... 0

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



P.Pal, 1982
L.Wolfenstein



- Dirac neutrino

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

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

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

- $m_i, m_j \ll m_l, m_W$

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

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

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

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

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

or

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

… depending on relative CP phase of ν_i and ν_j

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

GIM cancellation

The first nonzero contribution to neutrino transition moments

$$\left.\begin{matrix}\mu_{ij} \\ \epsilon_{ij}\end{matrix}\right\} = \frac{3eG_F m_i}{32\sqrt{2}\pi^2}\left(1 \pm \frac{m_j}{m_i}\right)\left(\frac{m_\tau}{m_W}\right)^2 \sum_{l=e,\,\mu,\,\tau}\left(\frac{m_l}{m_\tau}\right)^2 U_{lj}U_{li}^*$$

$$\mu_B = \frac{e}{2m_e}$$

- $$\left.\begin{matrix}\mu_{ij} \\ \epsilon_{ij}\end{matrix}\right\} = 4 \times 10^{-23}\mu_B\left(\frac{m_i \pm m_j}{1\ eV}\right) \sum_{l=e,\,\mu,\,\tau}\left(\frac{m_l}{m_\tau}\right)^2 U_{lj}U_{li}^*$$

… neutrino radiative decay is very slow

- Dirac ν diagonal (i=j) magnetic moment

$\boxed{\epsilon_{ii}^D = 0}$ for CP-invariant interactions

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

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

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

- no GIM cancellation

Lee, Shrock, Fujikawa, 1977

- μ_{ii}^D - to leading order - independent on U_{li} and $m_{\,l=e,\,\mu,\,\tau}$
- $\boxed{\mu_e^2 = \sum_{i=1,2,3} \mid U_{ie}\mid^2 \mu_{ii}^2}$ …possibility to measure fundamental μ_{ii}^D

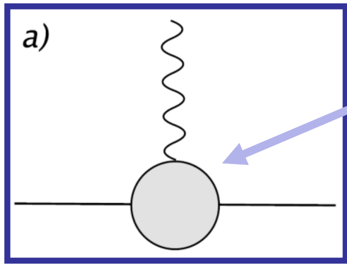
$\mu_{ii}^D = 0$ for massless ν (in the absence of right-handed charged currents)

3.3 Naïve relationship between m_ν and μ_ν

… problem to get large μ_ν and still acceptable m_ν

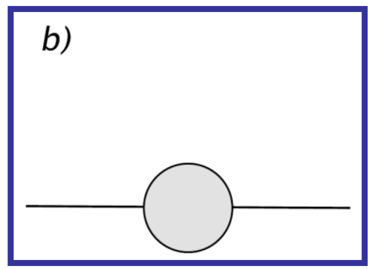
If μ_ν is generated by physics beyond the SM at energy scale Λ,

P. Vogel e.a., 2006



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

contribution to m_ν given by



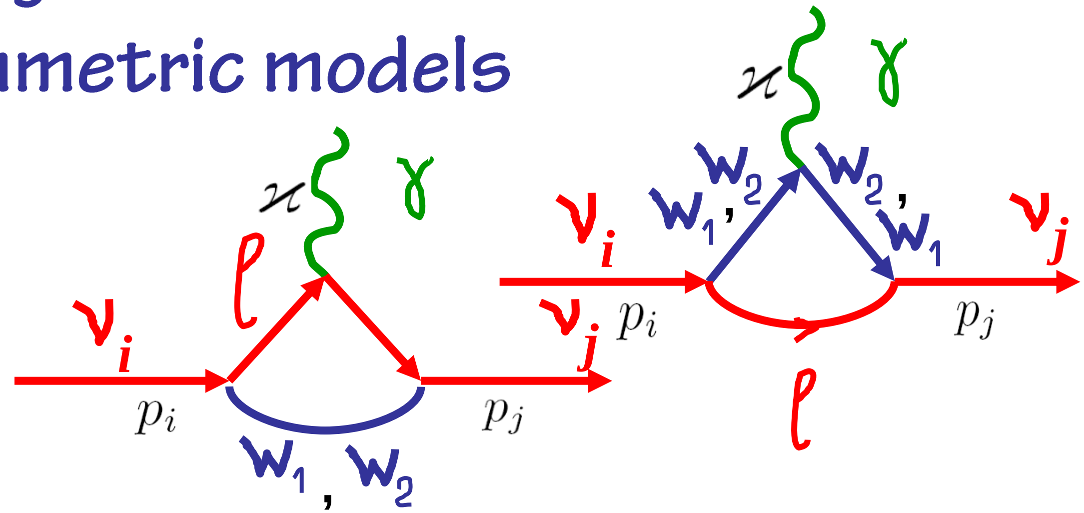
, then $\boxed{m_\nu \sim G\Lambda}$

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

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 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

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

... 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 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

considerable enhancement of μ_ν to experimentally relevant range

- model-independent constraint μ_ν

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

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

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

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:

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

where the Standard Model contribution

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

T is the electron recoil energy and

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

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

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

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

for anti-neutrinos $g_A \to -g_A$

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

3.11

ν charge radius and anapole moment

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

1. electric *2. magnetic* *dipole* *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

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

… next talk by Carlo Giunti

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 $\Rightarrow$ 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. $\Rightarrow$

? ? ? For massive ν ? ? ?

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

... comprehensive analysis of ν-e scattering ...

PHYSICAL REVIEW D **95,** 055013 (2017)

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

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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 traveling 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.

DOI: 10.1103/PhysRevD.95.055013

... all experimental constraints on charge radius should be redone

Concluding remarks

Kouzakov, Studenikin
PRD 2017, arXiv: 1703.0040

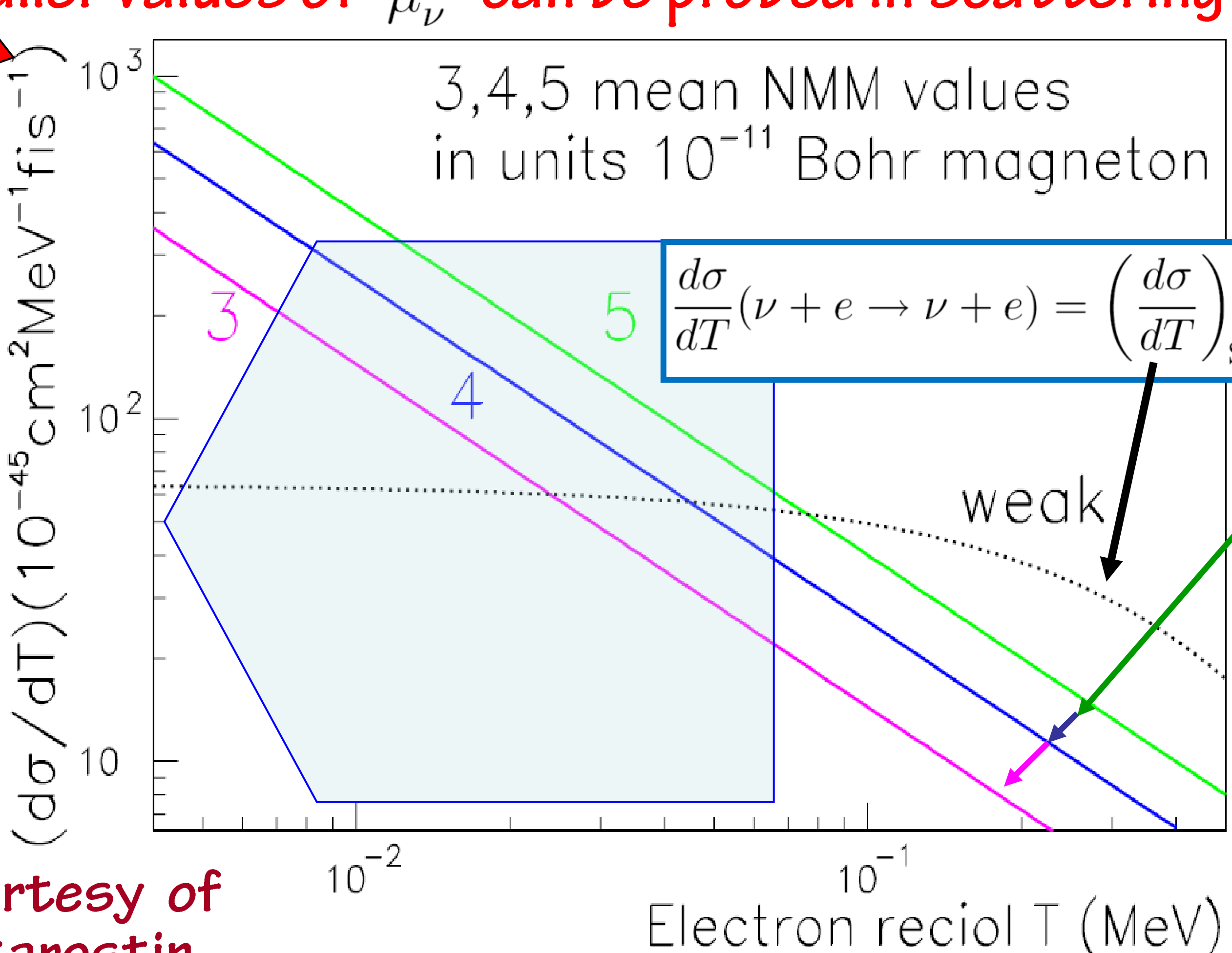
- cross section of ν-e is determined in terms of 3x3 matrices of ν electromagnetic form factors
- in short-baseline experiments one studies form factors in flavour basis
- long-baseline experiments more convenient to interpret in terms of fundamental form factors in mass basis
- ν millicharge when it is constrained in reactor short-baseline experiments (GEMMA, for instance) should be interpreted as

$$\boxed{|e_{\nu_e}| = \sqrt{|(e_\nu)_{ee}|^2 + |(e_\nu)_{\mu e}|^2 + |(e_\nu)_{\tau e}|^2}}$$

- ν charge radius in ν-e elastic scattering can't be considered as a shift $g_V \to g_V + \boxed{\frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2 \theta_W}$, there are also contributions from flavor-transition charge radii … see Carlo Giunti talk…

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

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



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

… courtesy of A.Starostin…

MUNU experiment at Bugey reactor (2005)

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

TEXONO collaboration at Kuo-Sheng power plant (2006)

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

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

GEMMA I 2005 - 2007

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

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

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

based on first release of BOREXINO data

Montanino, Picariello, Pulido, PRD 2008

... attempts to improve bounds

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

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

June 2012

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

... quite realistic prospects of the near future ... 2018-2019 ?

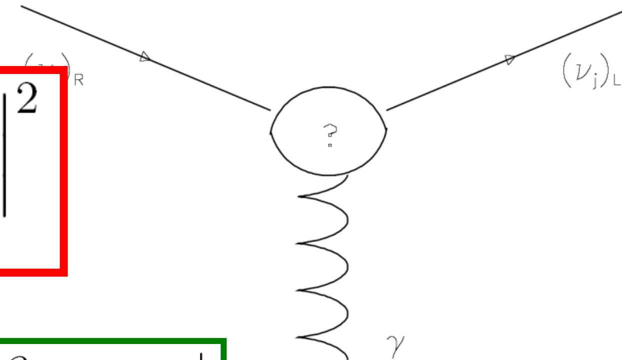
- $$\boxed{\mu_\nu^a \sim \ 0.7 \times 10^{-12} \ \mu_B}$$

unprecedentedly low threshold

$\boxed{T \sim 200 \ \ eV}$

Effective ν magnetic moment in experiments

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



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

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

Mitglied der Helmholtz-Gemeinschaft

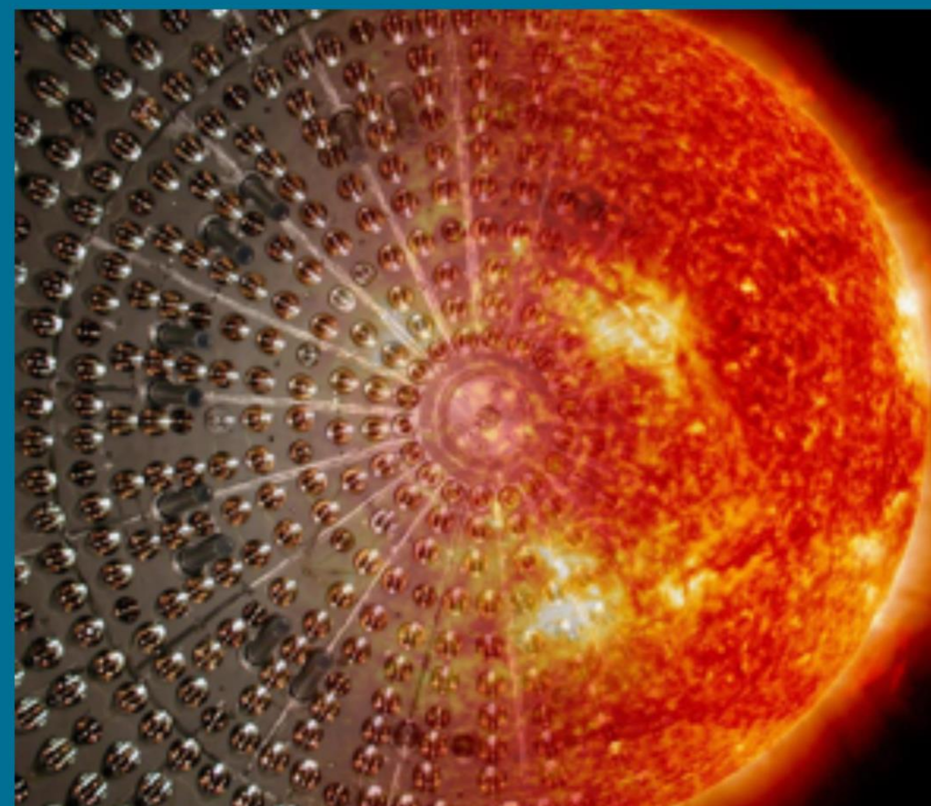
TAUP Topics in Astroparticle and Underground Physics

JÜLICH FORSCHUNGSZENTRUM

Limiting the effective magnetic moment of solar neutrinos with the Borexino detector

Livia Ludhova
on behalf of
the Borexino collaboration

IKP-2 FZ Jülich,
RWTH Aachen,
and JARA Institute, Germany



Phys. Rev. D 96 (2017) 091103
Limiting μ_ν with Borexino Phase-II solar neutrino data

NMM results from Phase 2

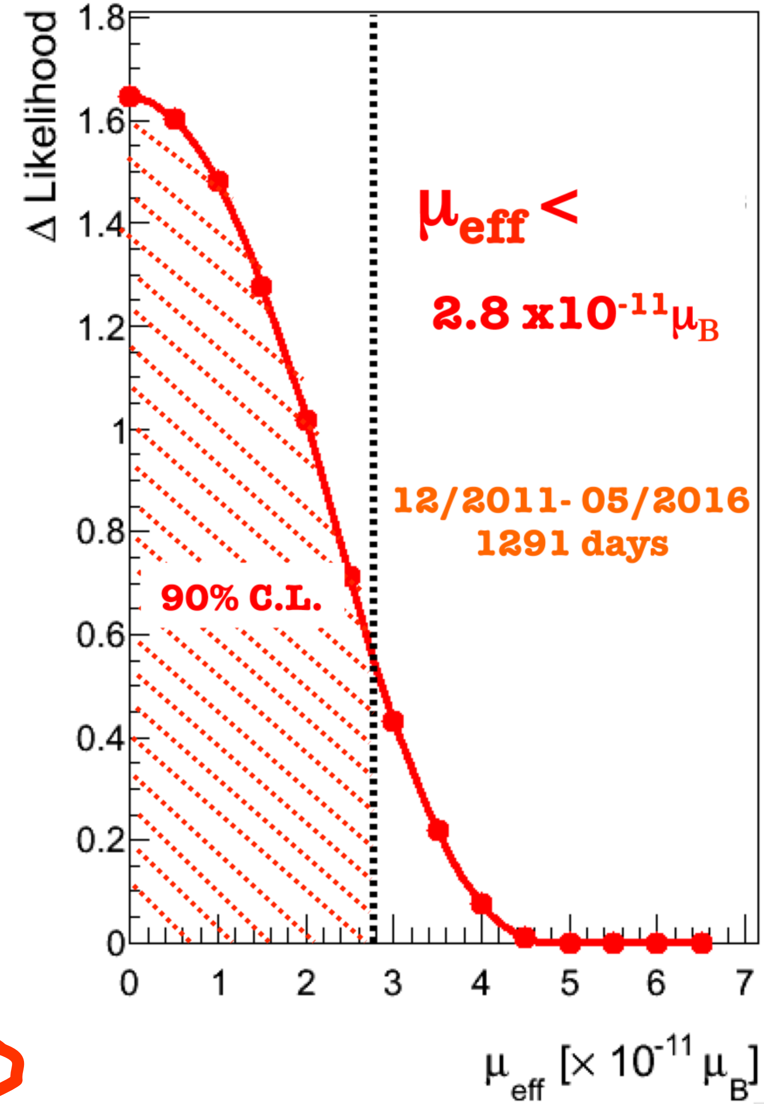
NEW

Data selection:
Fiducial volume: R < 3.021 m, |z| < 1.67 m
Muon, ^{214}Bi-^{214}Po, and noise suppression
Free fit parameters: **solar-ν** (pp, ^{7}Be) and **backgrounds** (^{85}Kr, ^{210}Po, ^{210}Bi, ^{11}C, external bgr.), **response parameters** (light yield, ^{210}Po position and width, ^{11}C edge (2 x 511 keV), 2 energy resolution parameters)
Constrained parameters: ^{14}C, pile up
Fixed parameters: pep-, CNO-, ^{8}B-ν rates
Systematics: treatment of pile-up, energy estimators, pep and CNO constraints with LZ and HZ SSM

Without radiochemical constraint
$\mu_{eff} < 4.0 \times 10^{-11} \mu_B$ (90% C.L.)

With radiochemical constraint
$\mu_{eff} < 2.6 \times 10^{-11} \mu_B$ (90% C.L.)
adding systematics
$\mu_{eff} < 2.8 \times 10^{-11} \mu_B$ **(90% C.L.)**

Profiling μ_{eff} with σ_{EM} for pp & ^{7}Be



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	$\mu_S(E_\nu \gtrsim 5\,\mathrm{MeV}) < 1.1 \times 10^{-10}\,\mu_B$	90%	Liu *et al.* (2004)
	Borexino	$\mu_S(E_\nu \lesssim 1\,\mathrm{MeV}) < 5.4 \times 10^{-11}\,\mu_B$	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)

- *…General proof:*

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

- *In SM :* $\boxed{Q = I_3 + \frac{Y}{2}}$

- *In SM (without ν_R) triangle anomalies cancellation constraints* ⇒ *certain relations among particle hypercharges Y, that is enough to fix all Y so that they, and consequently Q, are quantized*

$\boxed{Q=0}$

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

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

- *… However, strict requirements for* ***Q*** *quantization may disappear in extensions of standard $SU(2)_L \times U(1)_Y$ EW model if ν_R with* ***Y ≠ 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

two not seen contributions:

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

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

ν-e cross-section

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

Bounds on q_ν from

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

… unobservable effects of New Physics

Studenikin, Eurphys. Lett. 107 (2014) 21001

Particle Data Group, 2016

Constraints on q_ν

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

Expected new constraints from GEMMA:

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

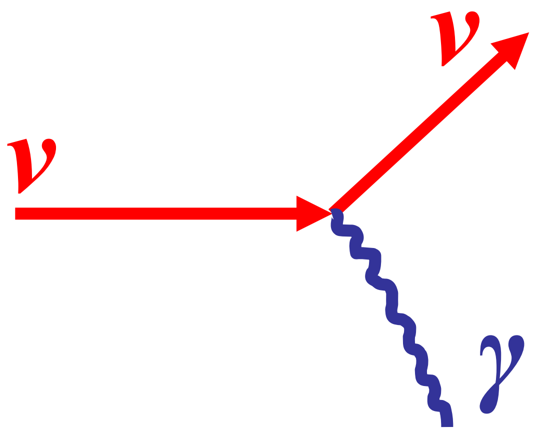
$\boxed{\text{2018/19 (expected)}}$

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

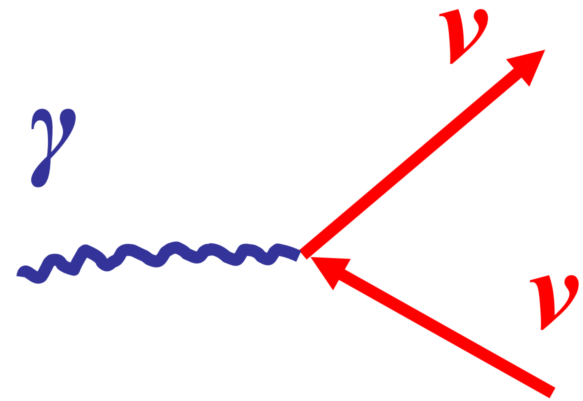
… unprecedentedly low threshold …

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

3 ν electromagnetic interactions

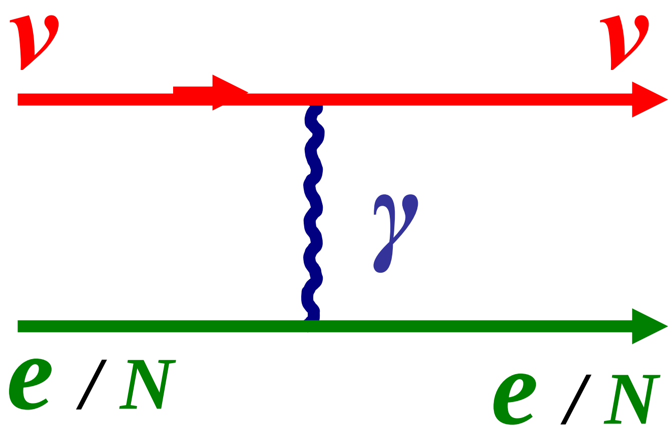


ν decay, Cherenkov radiation

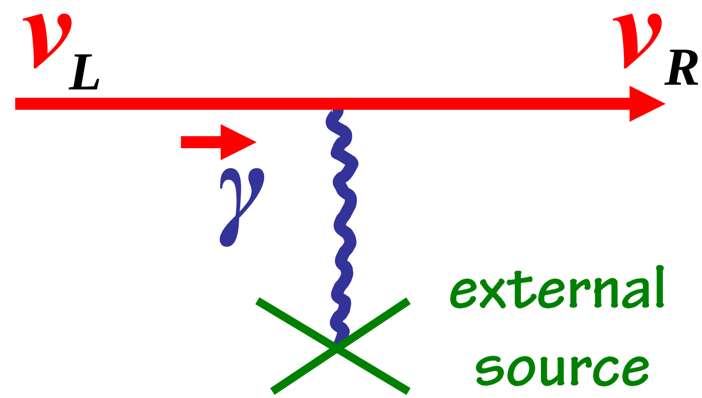


γ decay in plasma

!!!



Scattering

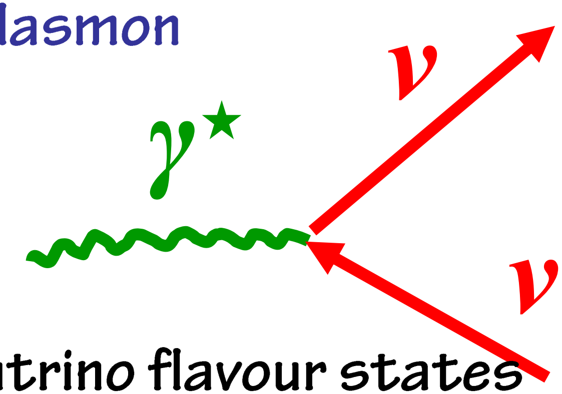


Spin precession

2 Astrophysical bound on μ_ν

G.Raffelt, PRL 1990

comes from cooling of red gaint stars by plasmon decay $\gamma^\star \longrightarrow \nu\nu$



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

neutrino flavour states

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

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

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

= 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

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

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

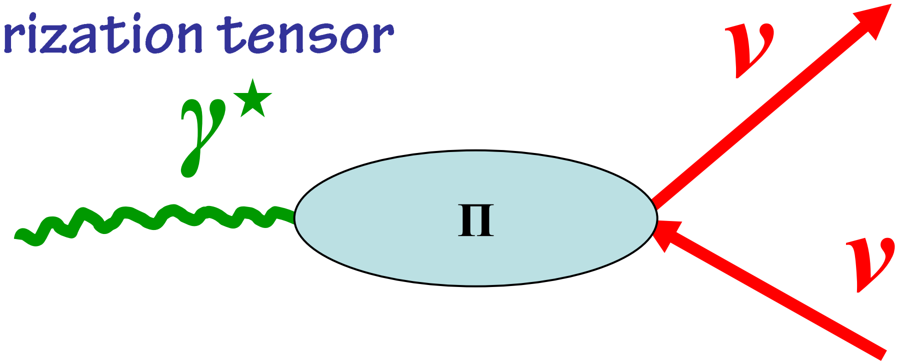
distribution function of plasmons

Astrophysical bound on μ_ν

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

Energy-loss rate per unit volume

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



more fast star cooling

In order not to delay helium ignition ($\lesssim 5\%$ in Q)

… best astrophysical limit on ν magnetic moment…

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

G.Raffelt, PRL 1990

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

Astrophysics bounds on μ_ν

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

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

Astrophysics bounds on μ_ν

... examples...

1) SN 1987A provides energy-loss limit on μ_ν (also d and transition moments)

...in magnetic moment scattering (change of helicity) $\nu_L \Rightarrow \nu_R$

proto-neutron star formed in core-collapse SN can cool faster

$$\boxed{\mu_\nu^D \sim 10^{-12}\mu_B}$$

... inconsistent with SN1987A observed cooling time

Barbieri, Mahapatra
Lattimer, Cooperstein
1988

2) ν_R from inner SN core have larger energy than ν_L emitted from neutrino sphere
then $\nu_R \overset{B}{\longleftrightarrow} \nu_L$ in galactic B

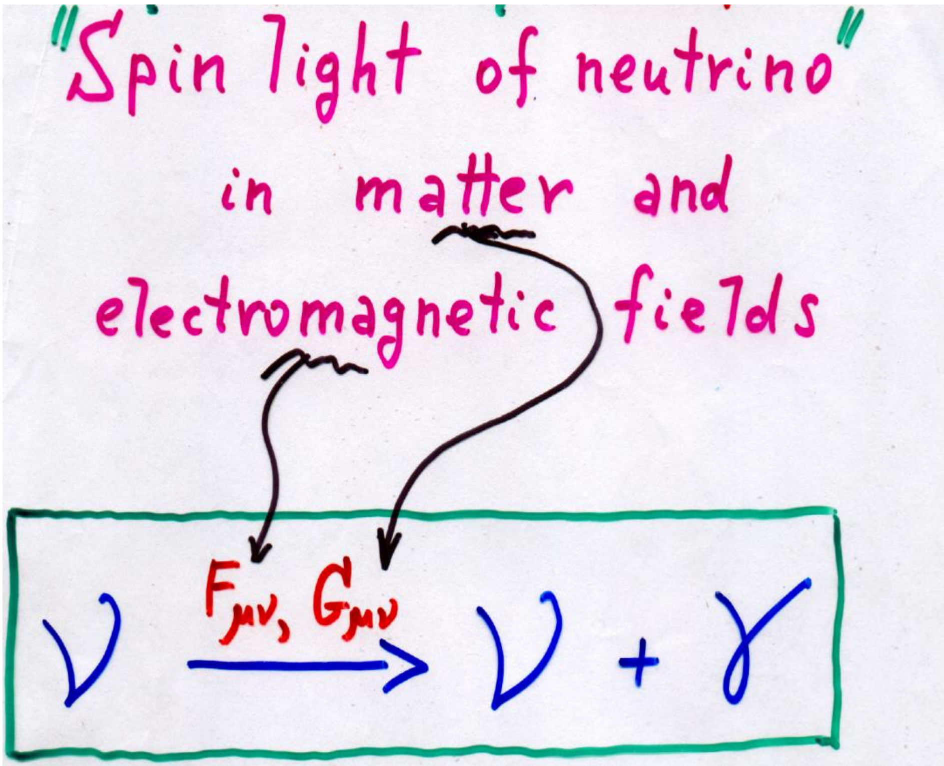
(sterile) (active)

from absence of anomalous high-energy ν

Nötzold
1988

• New mechanism of electromagnetic radiation

$SL\nu$



μ_ν

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

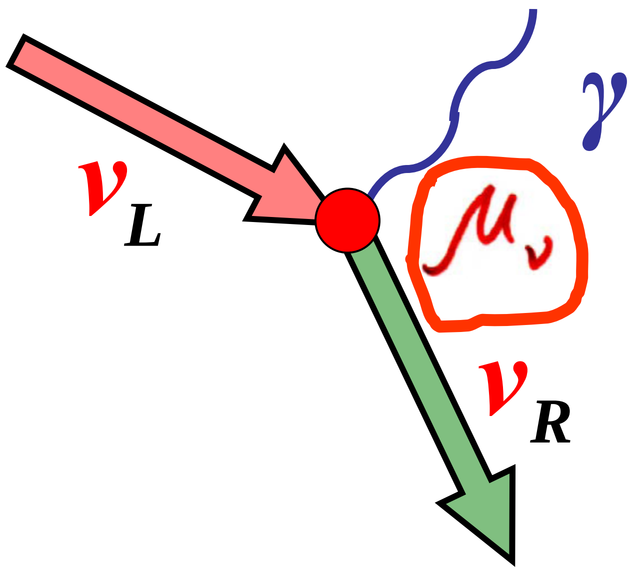
Studenikin, A.Ternov,
Phys.Lett. B 608 (2005) 107

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
J. Cosm. Astropart. Phys. 11 (2017) 024

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

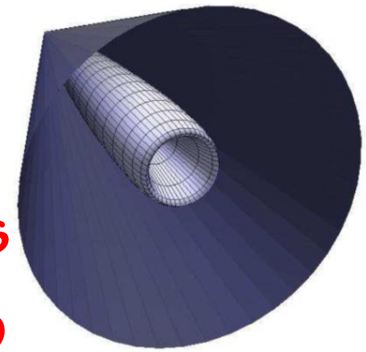


Figure 1: 3D representation of the radiation power distribution.

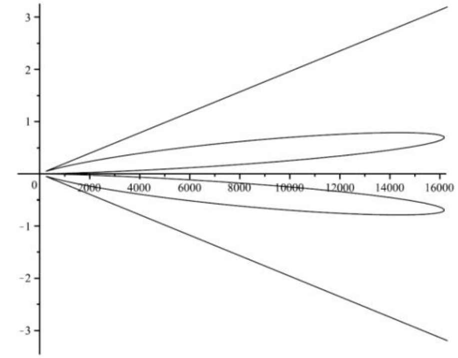


Figure 2: The two-dimensional cut along the symmetry axis. Relative units are used.

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

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Accepted October 31, 2017
Published November 16, 2017

JCAP11(2017)024

• ... astrophysical bound on millicharge q_ν from

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

2

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

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

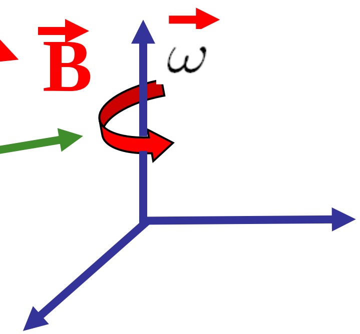
external magnetic field

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

matter potential

rotating matter

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



rotation angular frequency

In quasi-classical approach

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

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

due to effective Lorentz force

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

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

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

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

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

- ν Star Turning mechanism (ν ST)

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

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

- $|\Delta\omega| < \omega_0$! ...to avoid contradiction of ν ST impact with observational data on pulsars ...

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

- ... best astrophysical bound ...

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

ν evolution equation

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

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

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

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

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

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

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

- Resonance amplification of oscillations in matter:

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

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 — $\nu_L \overset{B}{\longleftrightarrow} \nu_R$ — Cisneros, 1971

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

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

...for recent analysis see J.Pulido, 2006, 2009; A.Balantekin, C.Volpe, 2005

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

$\nu_\odot$

- ⊛ Supernova $\nu_L \overset{B}{\longleftrightarrow} \nu_R$
  - 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 (???)

ν spin and flavor oscillations in arbitrary magnetic fields $\vec{B} = \vec{B}_\perp + \vec{B}_\parallel$

4

- A. Studenikin, "Neutrino electromagnetic properties: three new effects in neutrino spin oscillations"
  EPJ Web Conf. 125 (2016) 04018,
  arXiv:1705.05944

- A. Grigoriev
  R. Fabbricatore
  A. Studenikin
  "Neutrino spin-flavour oscillations derived from the mass basis"
  J. Phys.: Conf. Ser. 718 (2016) 062058 TAUP 2015 (2016)
  arXiv:1604.01245

- A. Dmitriev
  R. Fabbricatore
  A. Studenikin
  "Neutrino electromagnetic properties: new approach to oscillations in arbitrary magnetic field"
  arxXiv: 1506.05311

Two ν mass states with two helicities in $\vec{B} = \vec{B}_\perp + \vec{B}_\parallel$

Probabilities of ν oscillations

Popov, Studenikin
arXiv: 1803.05755

Chotorlishvili, Kouzakov, Kurashvili, Studenikin,
Phys. Rev. D96 (2017) 103017

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

flavour

$$\mu_\pm = \frac{1}{2}(\mu_1 \pm \mu_2)$$

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

spin

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

spin-flavour

… interplay of oscillations on vacuum and magnetic frequencies

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

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

- Popov, AS, arXiv: 1803.05755

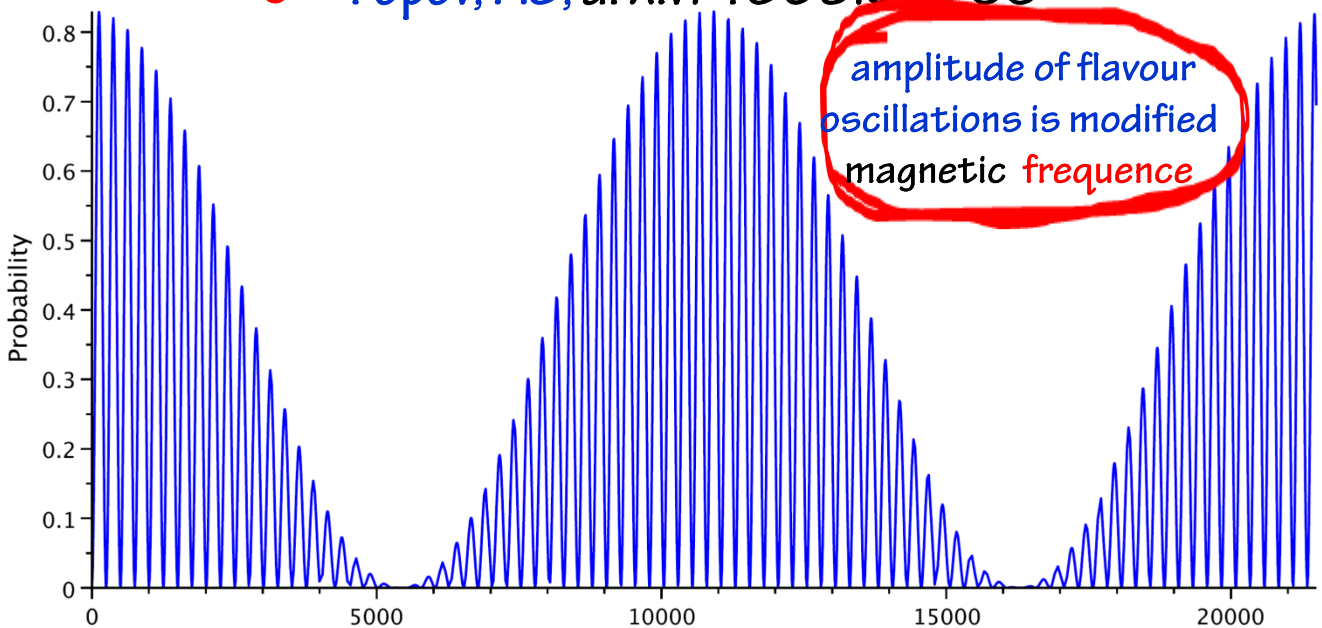


Figure 1: The probability of the neutrino flavour oscillations $\nu_e^L \to \nu_\mu^L$ in the transversal magnetic field $B_\perp = 10^8\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-12}\mu_B$.

Chotorlishvili, Kouzakov, Kurashvili, Studenikin,

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

... new phenomena in ν oscillations

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

Studenikin (2004)

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

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

Neutrino in Electromagnetic Fields and Moving Media

A. I. Studenikin*
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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.

- Electromagnetic properties of neutrinos: three new phenomena in neutrino spin oscillations, Europhys. J. Web of Conf. 125 (2016) 04018

- From neutrino electromagnetic interactions to spin oscillations in transversal matter currents, PoS NOW2016 (2017) 070

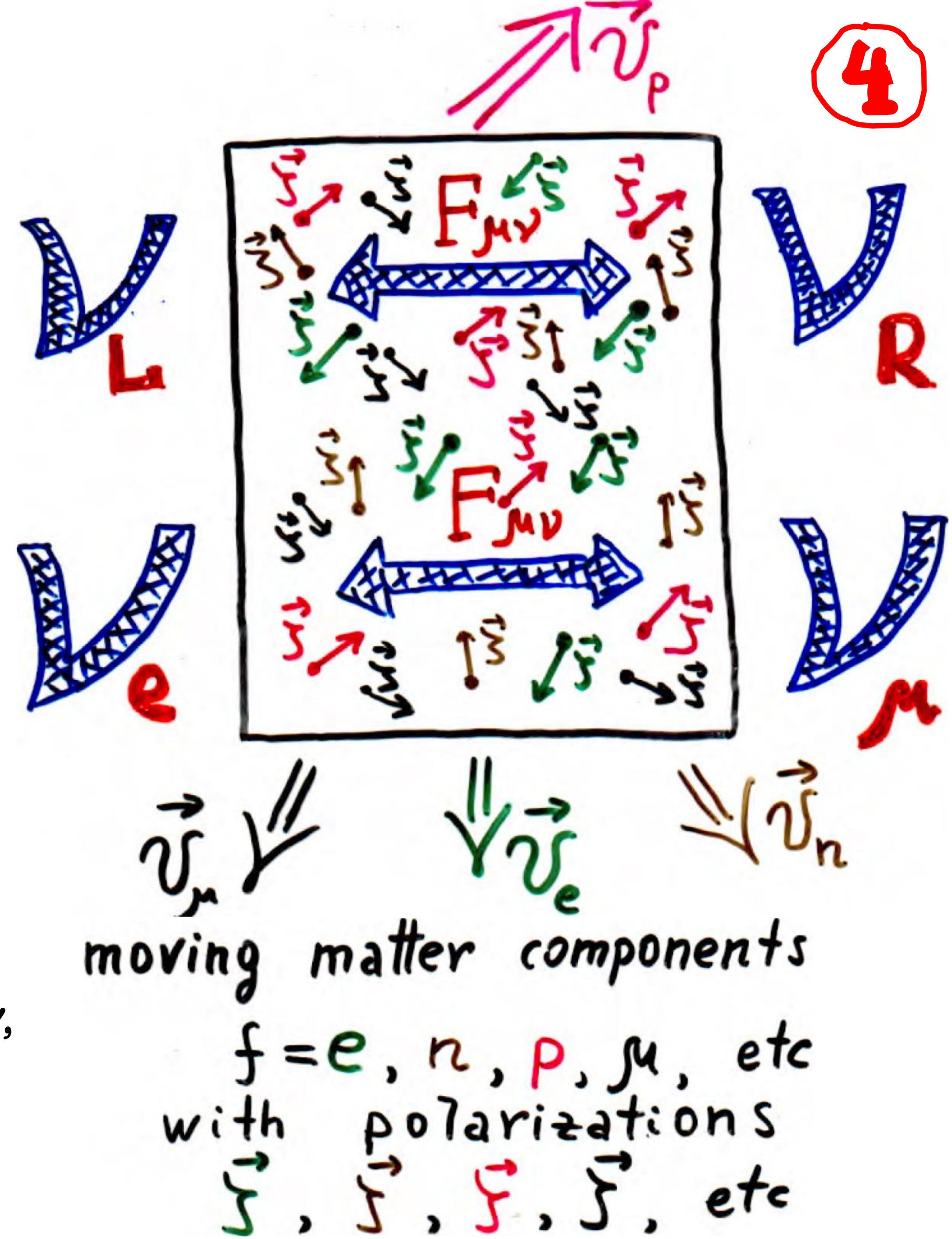
- Neutrino spin and spin-flavour oscillations in transversally moving or polarized matter, J. Phys. Conf. Ser. 888 (2017) 012221

- 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



ν spin evolution in presence of general external fields

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

General types non-derivative interaction with external fields

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

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

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

Relativistic equation (quasiclassical) for ν spin vector:

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

- ***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**

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

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" J.Phys.Conf.Ser. 718 (2016) 062076

interaction of neutrino with matter

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

transversal matter current

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

matter density

$\parallel$

$\perp$

where

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

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.

Two flavour ν with two helicities in moving matter

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

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

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

Contribution of matter currents

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

$$\Delta_{kl}^{ss'} = \langle \nu_k^s | \Delta H^{SM} | \nu_l^{s'} \rangle \quad k,l = e,\mu \qquad s,s' = \pm$$

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

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

$$\gamma_{\alpha\alpha'}{}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} + \gamma_{\alpha'}^{-1}\right) \qquad \widetilde{\gamma}_{\alpha\alpha'}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} - \gamma_{\alpha'}^{-1}\right)$$

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

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

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

two helicity states

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

- longitudinal currents $j_{\parallel}$ do not change ν helicity
- transversal currents $j_{\perp}$ do change ν helicity

Studenikin 2004

Studenikin, New phenomenon of ν spin oscillations in transversal matter currents, PoS 318 (2018) 085

Resonant amplification of ν

spin $\nu_e^L \Leftarrow (j_\perp, B_\perp) \Rightarrow \nu_e^R$ and

spin-flavour $\nu_e^L \Leftarrow (j_\perp, B_\perp) \Rightarrow \nu_\mu^R$

oscillations in transversal matter currents $j_\perp$

with SM interactions and NSI in presence of magnetic field
$\left[\begin{array}{l} \vec{j}_\perp + \vec{j}_\parallel \\ \vec{B} = \vec{B}_\perp + \vec{B}_\parallel \end{array}\right.$

- Studenikin, New phenomenon of neutrino spin oscillations in transversal matter currents, PoS 318 (2018) 085, 283 (2017) 070
    - Pustoshny, Studenikin, Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions, arXiv:1808.00302

ν (2 flavours x 2 helicities) evolution equation

$$i\frac{d}{dt}\nu_f^s = \Big(\underbrace{H_0}_{\text{vacuum}} + \underbrace{\underbrace{\Delta H_0^{SM}}_{\text{matter at rest}} + \underbrace{\Delta H_{j_{||}+j_\perp}^{SM}}_{\text{moving matter}}}_{\text{Standard Model}} + \underbrace{\Delta H_{B_{||}+B_\perp}^{SM}}_{B} + \underbrace{\underbrace{\Delta H_0^{NSI}}_{\text{matter at rest}} + \underbrace{\Delta H_{j_{||}+j_\perp}^{NSI}}_{\text{moving matter}}}_{\text{Non-Standard Interactions}}\Big)\nu_f^s$$

Resonant amplification of ν oscillations:

- $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$ by longitudinal matter current $j_{||}$
- $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$ by longitudinal $B_{||}$
- $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R$ by matter-at-rest effect
- $\nu_e^L \Leftarrow (j_\perp^{NSI}) \Rightarrow \nu_\mu^R$ by matter-at-rest effect

Pustoshny, Studenikin, arXiv:1808.00302

ν spin oscillations: $\nu_e^L \Leftarrow (j_\perp, B_\perp) \Rightarrow \nu_e^R$

evolution equation $B_{||}$ $j_{||}$ $B_\perp$ $j_\perp$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e^L\\ \nu_e^R\end{pmatrix} = \begin{pmatrix}(\frac{\mu}{\gamma})_{ee}B_{||} + \eta_{ee}\widetilde{G}n(1-\boldsymbol{v\beta}) & \mu_{ee}B_\perp + (\frac{\eta}{\gamma})_{ee}\widetilde{G}nv_\perp \\ \mu_{ee}B_\perp + (\frac{\eta}{\gamma})_{ee}\widetilde{G}nv_\perp & -(\frac{\mu}{\gamma})_{ee}B_{||} - \eta_{ee}\widetilde{G}n(1-\boldsymbol{v\beta})\end{pmatrix}\begin{pmatrix}\nu_e^L\\ \nu_e^R\end{pmatrix}$$

here $\mu_{11,12,22}$ are magnetic moments for mass ν

$$\mu_{ee} = \mu_{11}\cos^2\theta + \mu_{22}\sin^2\theta + \mu_{12}\sin 2\theta$$

$$\left(\frac{\mu}{\gamma}\right)_{ee} = \frac{\mu_{11}}{\gamma_{11}}\cos^2\theta + \frac{\mu_{22}}{\gamma_{22}}\sin^2\theta + \frac{\mu_{12}}{\gamma_{12}}\sin 2\theta$$

$$\eta_{ee} = \mu_{ee}{}_{|\mu_{11}=\mu_{22}=1,\quad \mu_{12}=0} = 1$$

ν oscillations probability

$$P_{\nu_e^L \to \nu_e^R}(x) = \sin^2 2\theta_{\text{eff}} \sin^2 \frac{\pi x}{L_{\text{eff}}},$$

oscillation length

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

oscillation amplitude

$$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}$$

- oscillations are important when oscillation probability is not small

criterion based on demand

$$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2} \geq \frac{1}{2}$$

$$\boxed{E_{eff} \geq \Delta_{eff}}$$

- Resonant amplification of $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$ by longitudinal matter current $\mathbf{j}_{||}$

$$\boxed{E_{eff} = \left|\left(\frac{\eta}{\gamma}\right)_{ee} \tilde{G} n \boldsymbol{v}_\perp\right|, \quad \Delta_{eff} = \left|\tilde{G} n (1 - \boldsymbol{v}\boldsymbol{\beta})\boldsymbol{\beta}\right|}$$

$$E_{eff} \geq \Delta_{eff} \Rightarrow \left(\frac{\eta}{\gamma}\right)_{ee} v_\perp \geq (1 - \boldsymbol{v}\boldsymbol{\beta})$$

for
$$\begin{cases} p_0^\nu = 10\ MeV \\ \gamma_\nu = 10^8 \\ m_1,\ m_2 \sim 0.1\ eV \end{cases}$$

and in case $\Delta m = m_2 - m_1 \ll m_1,\ m_2 \Rightarrow \frac{1}{\gamma_\nu} = \frac{1}{\gamma_{11}} \sim \frac{1}{\gamma_{22}}$

$$\frac{v_\perp}{\gamma_\nu} \geq (1 - \boldsymbol{v}\boldsymbol{\beta})$$

finally

$$\boxed{\frac{1}{\gamma_\nu} \geq \frac{1}{\gamma_n^2}}$$

- utra-relativistic background matter

$$\gamma_n \geq \gamma_\nu{}^{1/2} \sim 10^4$$

$$L_{eff} = \frac{2\pi}{(\frac{\eta}{\gamma})_{ee} \tilde{G} n v_\perp}$$???

- Resonant amplification of $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$ by longitudinal $B_{||}$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e^L\\ \nu_e^R\end{pmatrix} = \begin{pmatrix} (\frac{\mu}{\gamma})_{ee}B_{||} + \eta_{ee}\widetilde{G}n(1-\boldsymbol{v\beta}) & \cancel{\mu_e B_\perp} + (\frac{\eta}{\gamma})_{ee}\widetilde{G}nv_\perp \\ \cancel{\mu_e B_\perp} + (\frac{\eta}{\gamma})_{ee}\widetilde{G}nv_\perp & -(\frac{\mu}{\gamma})_{ee}B_{||} - \eta_{ee}\widetilde{G}n(1-\boldsymbol{v\beta}) \end{pmatrix}\begin{pmatrix}\nu_e^L\\ \nu_e^R\end{pmatrix}$$

probability of oscillations

$$P_{\nu_e^L \to \nu_e^R}(x) = \sin^2 2\theta_{\text{eff}} \sin^2 \frac{\pi x}{L_{\text{eff}}}, \qquad \sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}$$

- ν spin oscillations due to $\boxed{E_{eff} = \left(\frac{\eta}{\gamma}\right)_{ee}\widetilde{G}nv_\perp}$ $\sim$ $j_\perp$

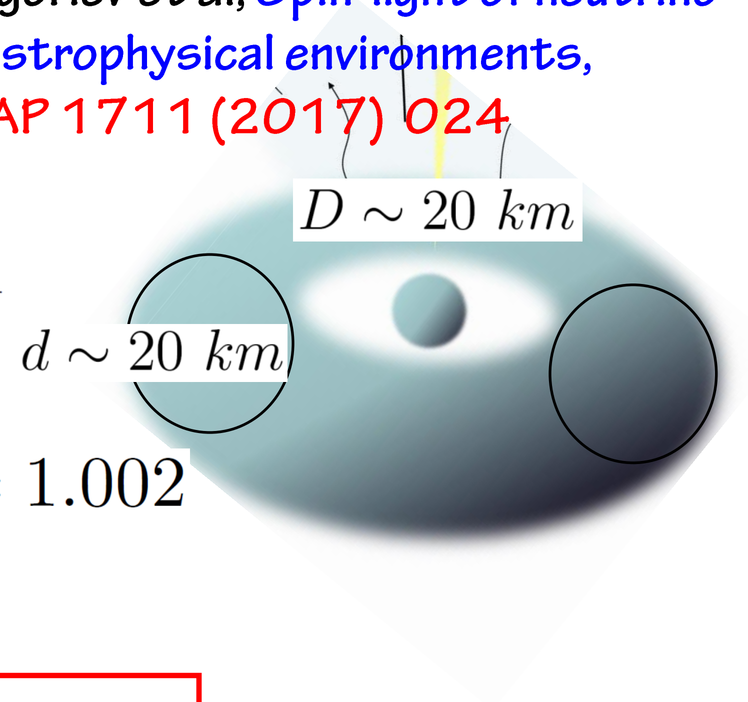
  with resonance suppression of Δ_{eff} due to $B_{||}$

- $\boxed{\Delta_{eff} = \left|\left(\frac{\mu}{\gamma}\right)_{ee}\boldsymbol{B}_{||} + \eta_{ee}\widetilde{G}n\boldsymbol{\beta}\right|}$ in case $\boldsymbol{B}_{||}\boldsymbol{\beta} = -1$

- An environment considered can be realized by models of short gamma-ray bursts

- Perego et al, Neutrino-driven winds from neutron star merger remnants MNRAS 443 (2014) 3134
- Grigoriev et al, Spin-light of neutrino in astrophysical environments, JCAP 1711 (2017) 024

Consider ν_e escaping central NS with inclination $\sin\alpha \sim \frac{1}{2}$ from accretion disk $\Longrightarrow$ ν_e propagation through toroidal rotating $\omega = 10^3 \ s^{-1}$ bulk of magnetized dense matter:



$$B_{||} \sim \frac{1}{2}B \, , \quad v_\perp = \omega D = 0.067 \, , \, \gamma_n = 1.002$$

... in case $\cancel{\mu_{ee} \boldsymbol{B}_\perp}$ $\Longrightarrow$

$$\boxed{E_{eff} = \left(\frac{\eta}{\gamma}\right)_{ee} \tilde{G} n v_\perp = \frac{\cos^2\theta}{\gamma_{11}} \tilde{G} n v_\perp \approx \tilde{G} n_0 \frac{\gamma_n}{\gamma_\nu}}$$

$$\boxed{\Delta_{eff} = \left| \left(\frac{\mu}{\gamma}\right)_{ee} \boldsymbol{B}_{||} + \eta_{ee} \tilde{G} n \boldsymbol{\beta} \right|} \boxed{\approx \left| \frac{\mu_{11}}{\gamma}_{\nu} B_{||} - \tilde{G} n_0 \gamma_n \right|}$$

- Resonant amplification of $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R$
  by longitudinal $B_{||}$

1) $\mu_{11} \sim 3 \times 10^{-11} \mu_B$ and $\gamma_\nu = 2 \times 10^7$
and low matter density $n_0 \sim 10^{23}\ cm^{-3}$
critical strength of $B_{||}$

$$\boxed{B_{||}^{cr} \sim 8 \times 10^{-3} B_0} \qquad \boxed{B_0 = \frac{m_e^2}{e_0} = 4.41 \times 10^{13}\ Gauss}$$

2) for higher densities $n_0 \sim 10^{32}\ cm^{-3}$

$$\boxed{B_{||}^{cr} \sim 10^{20}\ Gauss}$$

- Resonant amplification of spin-flavour oscillations $\nu_e^L \Leftarrow (j_\perp, B_\perp) \Rightarrow \nu_\mu^R$ by matter-at-rest effect

evolution equation

$$i\frac{d}{dt}\begin{pmatrix}\nu_e^L\\ \nu_\mu^R\end{pmatrix} = \begin{pmatrix} -\Delta M + (\frac{\mu}{\gamma})_{ee}B_{||} + \tilde{G}n(1-\boldsymbol{v\beta}) & \mu_{e\mu}B_\perp + (\frac{\eta}{\gamma})_{e\mu}\tilde{G}nv_\perp \\ \mu_{e\mu}B_\perp + (\frac{\eta}{\gamma})_{e\mu}\tilde{G}nv_\perp & \Delta M - (\frac{\mu}{\gamma})_{\mu\mu}B_{||} - \tilde{G}n(1-\boldsymbol{v\beta}) \end{pmatrix}\begin{pmatrix}\nu_e^L\\ \nu_\mu^R\end{pmatrix}$$

where $\Delta M = \dfrac{\Delta m^2 \cos 2\theta}{4p_0^\nu}$ is the mass term

... probability of oscillations

$$P_{\nu_e^L\to\nu_\mu^R}(x) = \sin^2 2\theta_{\text{eff}} \sin^2 \frac{\pi x}{L_{\text{eff}}}, \qquad \sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2},$$

and

$$\boxed{E_{eff} = \left|\cancel{\mu_{e\mu}B_\perp} + \left(\frac{\eta}{\gamma}\right)_{e\mu}\tilde{G}nv_\perp\right|,}$$

$$\boxed{\Delta_{eff} = \left|\Delta M - \frac{1}{2}\left(\frac{\mu_{11}}{\gamma_{11}} + \frac{\mu_{22}}{\gamma_{22}}\right)\cancel{B_{||}} - \tilde{G}n(1-\boldsymbol{v\beta})\right|}$$

... consider the case when B is negligible ...

... resonance condition $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R$

$E_{eff} \geq \Delta_{eff}$ $\Rightarrow$

$$\tilde{G} = \frac{G_F}{2\sqrt{2}} = 0.4 \times 10^{-23} \ \ eV^{-2}$$

$$\boxed{\left|\left(\frac{\eta}{\gamma}\right)_{e\mu} \tilde{G} n v_\perp\right| \geq \left|\Delta M - \tilde{G} n (1 - \boldsymbol{v\beta})\right|.}$$

$$\left(\frac{\eta}{\gamma}\right)_{e\mu} \approx \frac{\sin 2\theta}{\gamma_\nu}$$

... case $v_{||} = 0$ resonance is realized when $\boxed{\tilde{G} n \sim \Delta M}$

For environment realized by models of short gamma-ray bursts and $p_0^\nu = 10^6 \ eV$

$$\left.\begin{array}{r} \Delta m^2 = 7.37 \times 10^{-5} \ eV^2 \\ \sin^2\theta = 0.297 \end{array}\right\} \nu_\odot$$

$$\Delta M = 0.75 \times 10^{-11} eV$$

... resonance density of matter

1) $n_0 \sim \dfrac{\Delta M}{\tilde{G}} = 10^{12} \ eV^3 \approx 10^{26} \, cm^{-3}$ $\Rightarrow$ $L_{eff} = \dfrac{2\pi}{(\frac{\eta}{\gamma})_{e\mu} \tilde{G} n v_\perp} \approx 10^{12} \ km$

2) $n_0 \approx 10^{37} \, cm^{-3}$ $\Rightarrow$ $L_{eff} \approx 10 \ km$

- **Resonant amplification of ν spin-flavour oscillations**

$\nu_e^L \Leftarrow (j_\perp^{NSI}) \Rightarrow \nu_\mu^R$ by matter-at-rest effect in case of NSI

$$i\frac{d}{dt}\nu_f^s = \Big(\underbrace{H_0}_{\text{vacuum}} + \underbrace{\underbrace{\Delta H_0^{SM}}_{\text{matter at rest}} + \underbrace{\Delta H_{j_{||}+j_\perp}^{SM}}_{\text{moving matter}}}_{\text{Standard Model}} + \underbrace{\Delta H_{B_{||}+B_\perp}^{SM}}_{B} + \underbrace{\underbrace{\Delta H_0^{NSI}}_{\text{matter at rest}} + \underbrace{\Delta H_{j_{||}+j_\perp}^{NSI}}_{\text{moving matter}}}_{\text{Non-Standard Interactions}}\Big)\nu_f^s$$

matter potential in flavour basis contains off-diagonal terms – flavaour changing neutral currents

$$-L_{NSI}^{eff} = \varepsilon_{\alpha\beta}^{fP} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f}\gamma^\rho P f), \qquad L, R = (1 \pm \gamma^5)/2$$

$$-L_{NSI}^{eff} = -f^\mu \sum_{\alpha,\beta} (\varepsilon_{\alpha\beta}^{uL} + 2\varepsilon_{\alpha\beta}^{dL}) \bar{\nu}_\alpha(x) \gamma_\mu \frac{1+\gamma_5}{2} \nu_\beta(x)$$

O. Miranda , H. Nunokawa, New J. Phys. 17 (2015) 095002

... evolution equation $\nu_e^L \Leftarrow (j_\perp^{NSI}) \Rightarrow \nu_\mu^R$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e^L\\ \nu_\mu^R\end{pmatrix} = \begin{pmatrix} -\Delta M + (\frac{\mu}{\gamma})_{ee}B_{||} + 2\widetilde{F}_{ee}n(1-\boldsymbol{v\beta}) & \mu_{e\mu}B_\perp + (\frac{\eta}{\gamma})_{e\mu}\widetilde{F}_{e\mu}nv_\perp \\ \mu_{e\mu}B_\perp + (\frac{\eta}{\gamma})_{e\mu}\widetilde{F}_{e\mu}nv_\perp & \Delta M - (\frac{\mu}{\gamma})_{\mu\mu}B_{||} \end{pmatrix}\begin{pmatrix}\nu_e^L\\ \nu_\mu^R\end{pmatrix}$$

$$\widetilde{F}_{ee} = \widetilde{G}(1+\tilde{\varepsilon}_{ee}) \qquad \widetilde{F}_{e\mu} = \widetilde{G}(1+\tilde{\varepsilon}_{e\mu})$$

For environment realized by models of short gamma-ray bursts and $p_0^\nu = 10^6\ eV$

$$\left.\begin{array}{r}\Delta m^2 = 7.37\times 10^{-5}\ eV^2\\ \sin^2\theta = 0.297\end{array}\right\} \nu_\odot$$

$$\boxed{n_0 \sim \frac{\Delta M}{\widetilde{G}(1+\tilde{\epsilon}_{ee})}}$$

density of matter for resonance $\nu_e^L \Leftarrow (j_\perp^{NSI}) \Rightarrow \nu_\mu^R$

Miranda , Nunokawa
New J. Phys. 17 (2015) 095002
(from reactor neutrino)

$$\left.\begin{array}{r}\varepsilon_{ee}^{uL} = \varepsilon_{ee}^{dL} = 0.3\\ \varepsilon_{\mu\mu}^{uL} = \varepsilon_{\mu\mu}^{dL} = 0.005\\ \varepsilon_{e\mu}^{uL} = \varepsilon_{e\mu}^{dL} = 0.023\end{array}\right\} \boxed{\tilde{\varepsilon}_{ee} = 0.6}$$

$$\boxed{n_0 \approx 0.63\times 10^{26}\ cm^{-3}}$$

...thus

AS

- new possibility for ν spin oscillations (2004)
  there is no need for μ_ν and $B_\perp$

- the effect is due to weak interactions of ν
  with transversal matter current $j_\perp$

- quantum description of phenomena has been evaluated

- existence of the effect has been confirmed
  Raffelt et al (2015) ...

Pustoshny, AS 2018

- resonance amplification of spin $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$
  and spin-flavour $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R$ oscillations

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

… 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

Conclusions

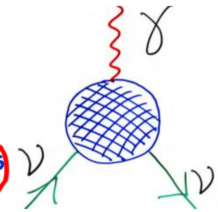
Electromagnetic Properties of ν

(effects of magnetic moments)

MSU Alexander Studenikin JINR

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

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



① νEP theory - ν vertex function

matrices in ν mass eigenstates space

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

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

- electric charge
- magnetic moment
- electric moment
- anapole moment

⇐

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

Hermiticity and discrete symmetries of EM current $\langle\nu(p')|J_\mu^{EM}|\nu(p)\rangle = \bar{u}(p')\Lambda_\mu(q)u(p)$ put constraints on form factors

②

$$\mu_{jj}^D = \frac{3e_0 G_F m_j}{8\sqrt{2}\pi^2} \approx 3.2\times10^{-19}\mu_B\left(\frac{m_j}{1\ \mathrm{eV}}\right)$$

Fujikawa & Shrock, 1980

- 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

$$\mu_\nu^{eff} < \begin{matrix} 2.9 \\ 2.8 \\ \sim 0.1 \end{matrix} \times 10^{-11}\mu_B$$

GEMMA Coll. 2012

Borexino Coll. 2017

Astrophysics, Raffelt ea 1988

Arcoa Dias ea 2015

$$q_{\nu_e} <\sim \begin{matrix} 10^{-12} \\ 10^{-19} \\ 10^{-21} \end{matrix}\ e_0$$

reactor ν scattering AS '14, Chen ea '14

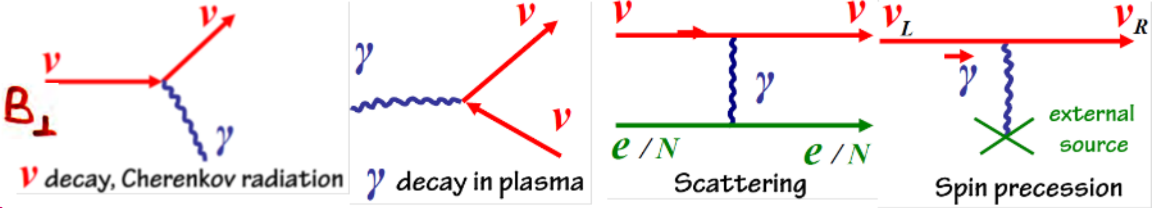
AS '14 (astrophysics)

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, Smirnov, Pulido, Dvornikov, Grigoriev, Lobanov, Lokhov, Kouzakov, Ternov, Studenikin et al



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

Kouzakov & AS, PRD 96 (2017)

$$L_B = \pi/\mu_\nu B$$

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

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

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

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

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**

Grigoriev, Lokhov, Studenikin, Ternov

new mechanism of EM radiation by ν
JCAP 1711 (2017) no. 11, 024
"SL ν in astrophysical environments"

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

ν electromagnetic properties: future prospects

- new constraints on μ_ν (and q_ν) from GEMMA and Borexino

- charge radius in ν - e elastic scattering can't be considered as a shift $g_V \rightarrow g_V + \boxed{\frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2 \theta_W}$, there are also contributions from flavor-transition charge radii –
new analysis (re-analysis) of data is needed

- need for inclusion of ν em interactions in analysis of supernovae ν fluxes

Thank you