Electromagnetic neutrinos: New constraints and new effects in oscillations

"Particle Physics and Cosmology"
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Outline (1)

1. (short) review of ν electromagnetic properties

2. experimental constraints on μ_ν, q_ν and $\langle r_\nu^2 \rangle$

magnetic moment — millicharge — charge radius

Particle Data Group
Review of Particle Properties (2014-2018)
update of 2019

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

Neutrino electromagnetic interactions: A window to new physics

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+ upgrade: Studenikin, 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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Outline (2)

3 ν electromagnetic interactions (new effects)

– two interesting new phenomena in

ν spin (flavour) oscillations

in moving matter and B

50 years of ν oscillation formulae
Gribov & Pontecorvo (1969)

new developments in νspin and flavour oscillations

1. generation of ν spin (flavour) oscillations by interaction with transversal matter current $j_\perp$

P. Pustoshny, A. Studenikin,
"Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions"
- Phys. Rev. D98 (2018) no. 11, 113009

2. inherent interplay of ν spin and flavour oscillations in B

A. Popov, A. Studenikin,
"Neutrino eigenstates and flavour, spin and spin-flavor oscillations in a constant magnetic field"
- Eur. Phys .J. C 79 (2019) no.2, 144, arXiv: 1902.08195

1

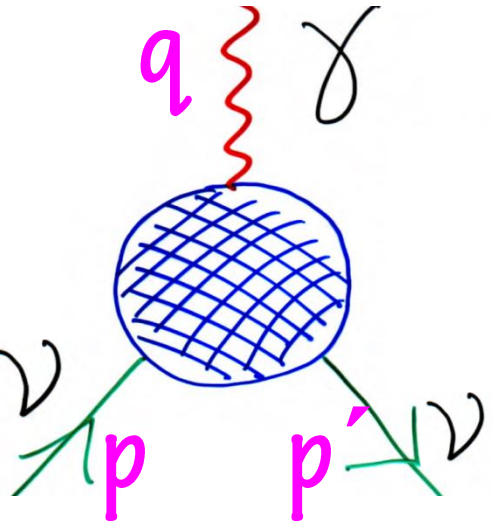
electromagnetic properties

(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

$q_\mu = p'_\mu - p_\mu,\ l_\mu = p'_\mu + p_\mu$

Lorentz covariance (1) and electromagnetic gauge invariance (2) $\Rightarrow$

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

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

$p^2 = m_i^2,\ p'^2 = m_j^2$:

… beyond SM…

and

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

form factors are matrices in mass eigenstates space.

Dirac (off-diagonal case $i \neq j$) Majorana

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

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

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

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 ???

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

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

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

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

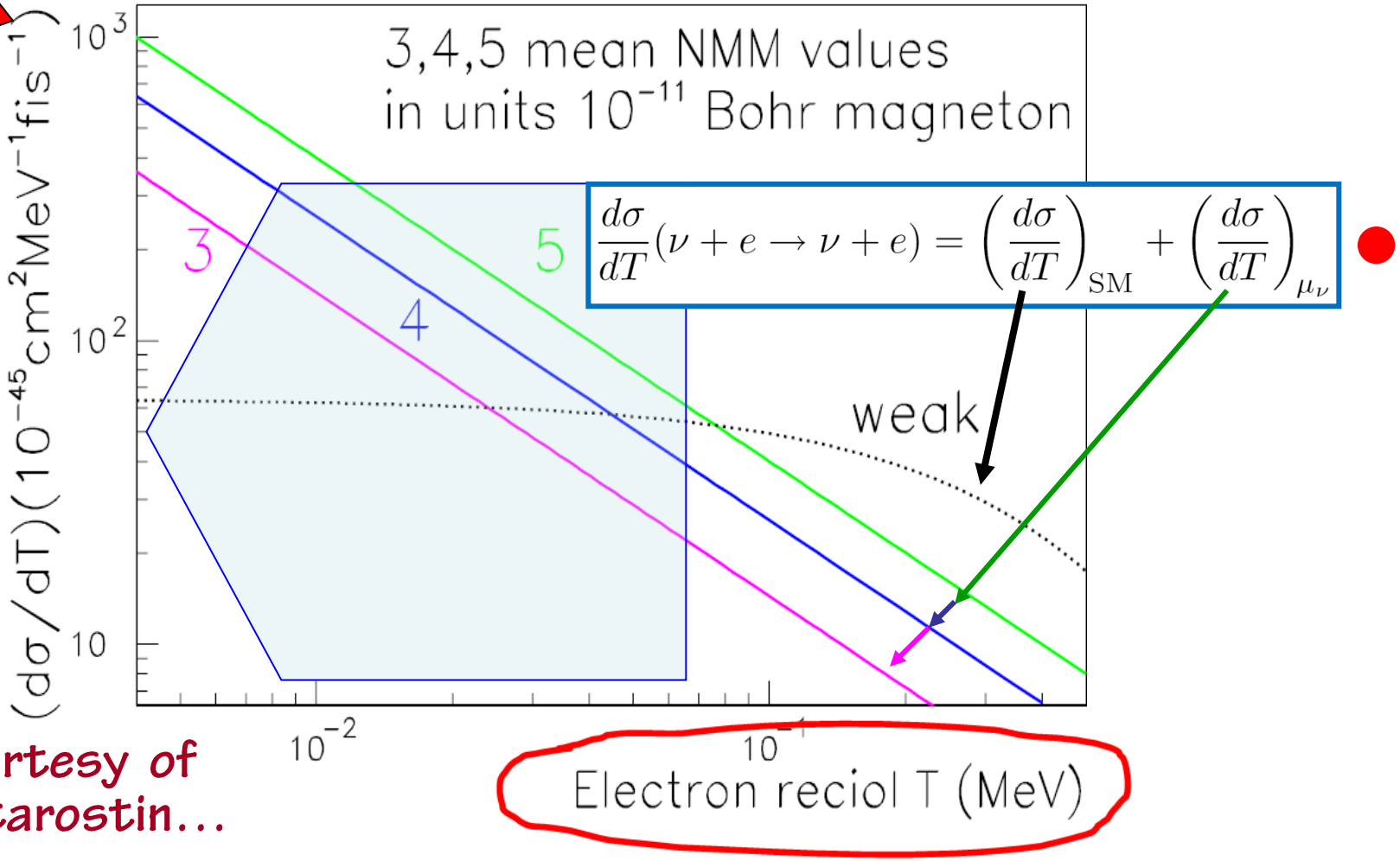
$$g_V = \begin{cases} 2\sin^2\theta_W + \frac{1}{2} & \text{for } \nu_e, \\ 2\sin^2\theta_W - \frac{1}{2} & \text{for } \nu_\mu, \nu_\tau, \end{cases} \qquad g_A = \begin{cases} \frac{1}{2} & \text{for } \nu_e, \\ -\frac{1}{2} & \text{for } \nu_\mu, \nu_\tau \end{cases}$$

for anti-neutrinos $g_A \to -g_A$

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

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…

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 ... 2019 ?

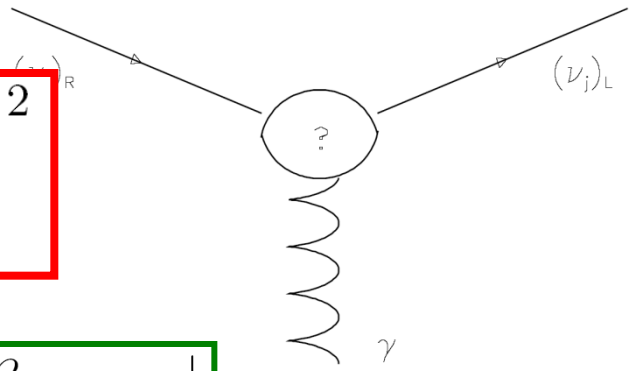
● $\mu_\nu^a \sim 0.7 \times 10^{-12} \mu_B$

unprecedentedly low threshold

$T \sim 200 \ eV$

Effective ν magnetic moment in experiments

(for neutrino produced as ν_l with energy E 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 $^8\mathrm{B}$ and $^7\mathrm{Be}$) are different.

Mitglied der Helmholtz-Gemeinschaft

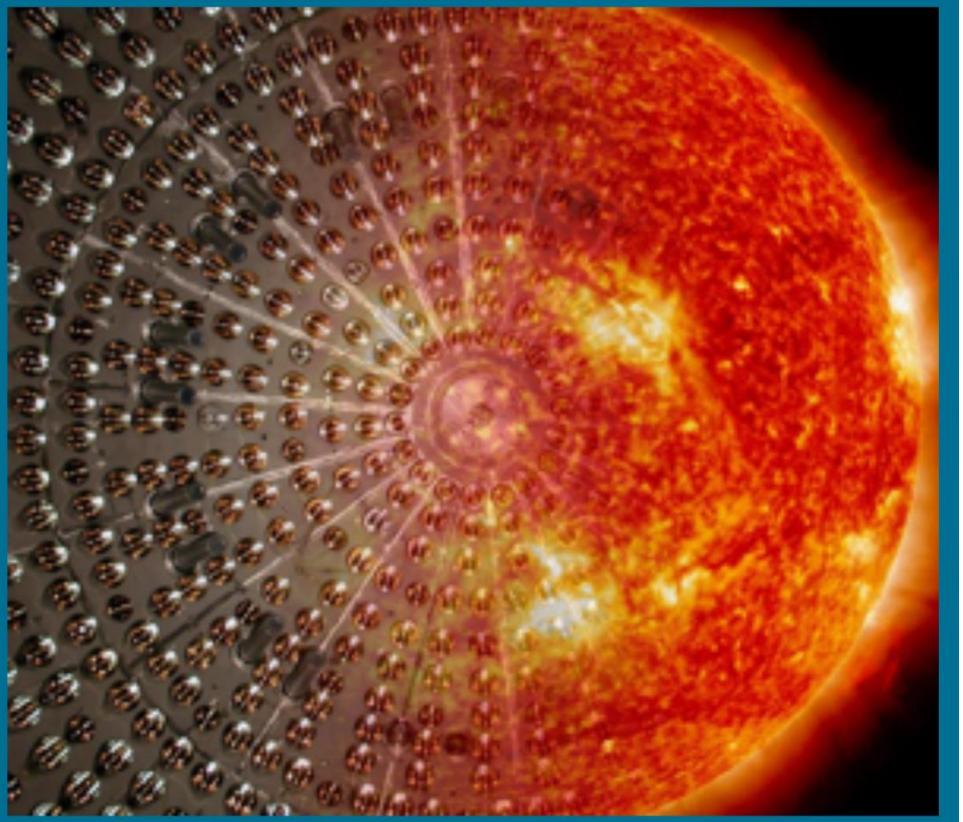
TAUP Topics in Astroparticle and Underground Physics

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

σ(e⁻-ν scattering) with NMM > 0

σ(e⁻-ν scattering) with NMM > 0

- In addition to the weak-interaction term σ_{WI}, there appears an **additional electro-magnetic term σ_{EM}, proportional to NMM**:

$$\frac{d\sigma_{EM}}{dT_e}(T_e, E_\nu) = \pi\, r_0^2\, \mu_{eff}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$$

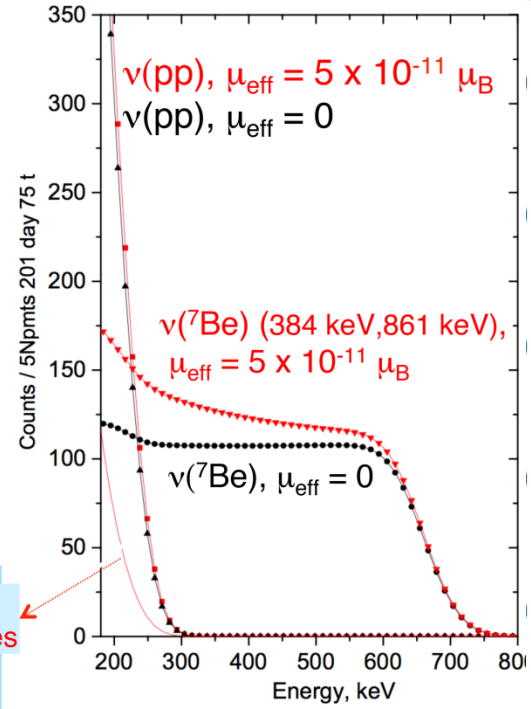
$r_0 = 1.818 \times 10^{-13}$ cm (electron radius)

- μ_{eff}: for a mixture of mass eigenstates
- 1-photon exchange + ν flips helicity (WI and EM terms do not interfere)
- For $T_e << E_\nu$: $\sigma_{TOTAL} \sim 1/T_e$, the spectrum of the scattered electron is influenced mostly at low energies.

^{7}Be-ν: strong change of the shape
MAJOR SENSITIVTY TO NMM

Difference for pp shapes

pp-ν: the change of the shape is almost equivalent to the change of only normalization
CONSTRAINING PP FLUX HELPS!



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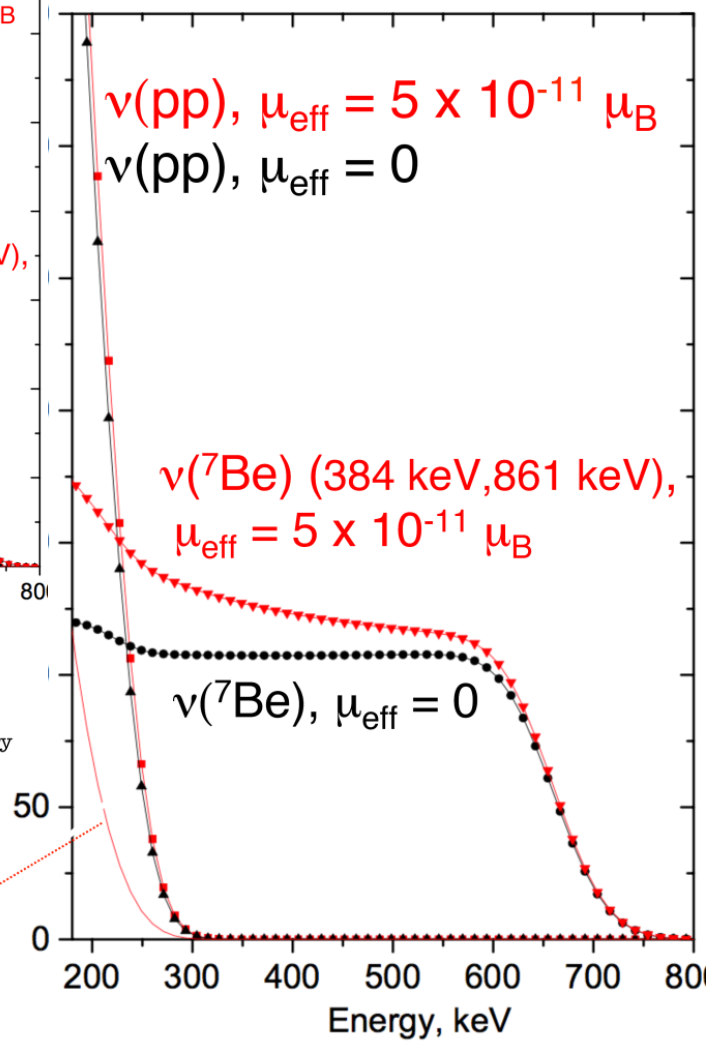


Livia Ludhova: Limiting the effective magnetic moment of solar neutrinos with the Borexino detector TAUP 2017, Sudbury

NEW

NMM results from Phase 2

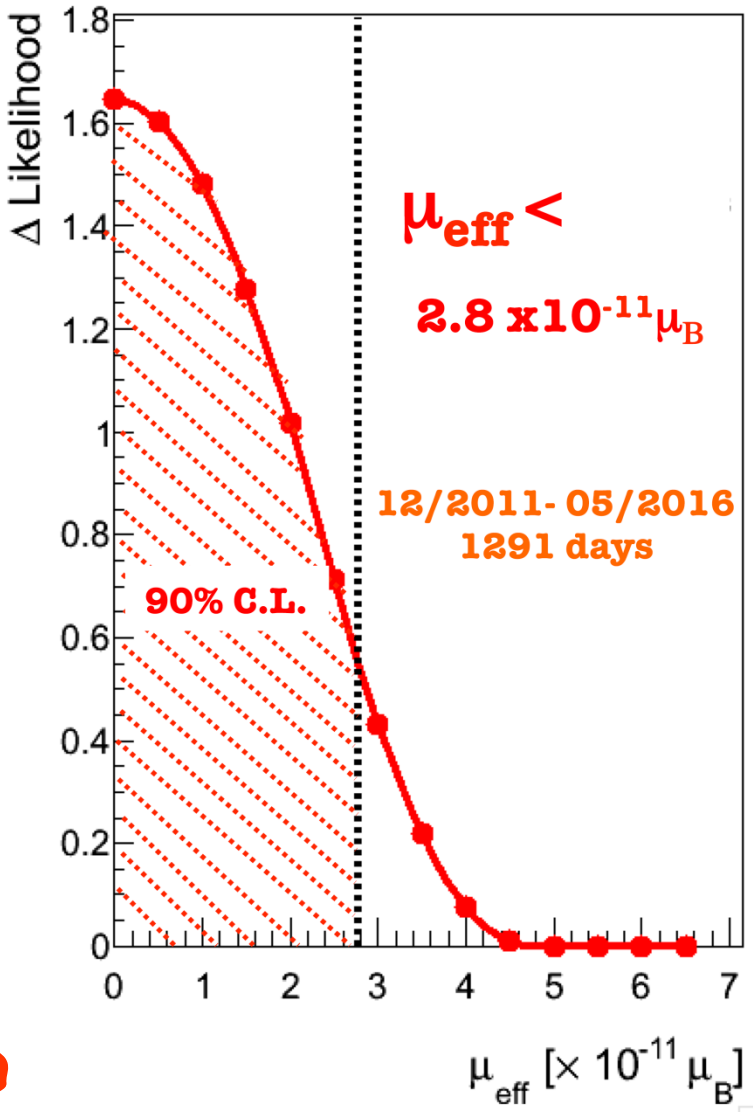
JÜLICH FORSCHUNGSZENTRUM

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



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)

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

- new 2017 Borexino PRD: $\mu_\nu^{eff} < 2.8 \cdot 10^{-11}\ \mu_B$ at 90% c.l.
- Particle Data Group, 2014-2018 and update of 2019

... 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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(Received 11 February 2017; published 14 March 2017)

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

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 dipole
3. electric dipole
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

Concluding remarks

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

- 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

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

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

!

PHYSICAL REVIEW D **98,** 113010 (2018)

Editors' Suggestion

Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering

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(Received 15 October 2018; published 26 December 2018)

Coherent elastic neutrino-nucleus scattering is a powerful probe of neutrino properties, in particular of the neutrino charge radii. We present the bounds on the neutrino charge radii obtained from the analysis of the data of the COHERENT experiment. We show that the time information of the COHERENT data allows us to restrict the allowed ranges of the neutrino charge radii, especially that of ν_μ. We also obtained for the first time bounds on the neutrino transition charge radii, which are quantities beyond the standard model.

DOI: 10.1103/PhysRevD.98.113[illegible]

Ch – It – Ru collaboration

Physical Review D – Highlights 2018 – Editors' Suggestion

"Using data from the COHERENT experiment, the authors put bounds on electromagnetic ν charge radii, including the first bounds on transition charge radii. These results show promising prospects for current and upcoming ν-nucleus experiments"

$$\left(\left|\left\langle r^2_{\nu_{e\mu}}\right\rangle\right|, \left|\left\langle r^2_{\nu_{e\tau}}\right\rangle\right|, \left|\left\langle r^2_{\nu_{\mu\tau}}\right\rangle\right|\right) < (22, 38, 27) \times 10^{-32}\ \mathrm{cm}^2$$

K. Kouzakov, A. Studenikin, "Electromagnetic properties of massive neutrinos in low-energy elastic neutrino-electron scattering" Phys. Rev. D 95 (2017) 055013

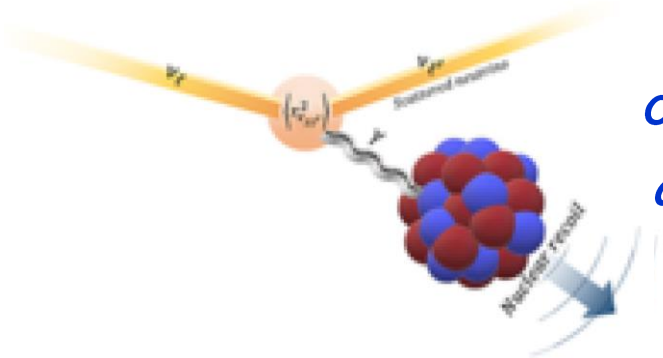
Physical Review D – Highlights 2018 – Editors' Suggestion

Editors' Suggestion

Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering (/prd/abstract/10.1103/PhysRevD.98.113010)

M. Cadeddu, C. Giunti, K. A. Kouzakov, Y. F. Li, A. I. Studenikin, and Y. Y. Zhang

Phys. Rev. D **98**, 113010 (2018) – Published 26 December 2018



coherent ν scattering due to charge radius

Using data from the COHERENT experiment, the authors put bounds on neutrino electromagnetic charge radii, including the first bounds on the transition charge radii. These results show promising prospects for current and upcoming neutrino-nucleus scattering experiments.

Show Abstract + ()

Particle Data Group,
Review of Particle Properties (2018),
update of 2019

3

Experimental limits on ν charge radius $\langle r_\nu^2 \rangle$

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

Method	Experiment	Limit (cm^2)	C.L.	Reference
Reactor $\bar{\nu}_e$-e^-	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3 \times 10^{-32}$	90%	Vidyakin *et al.* (1992)
	TEXONO	$-4.2 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 6.6 \times 10^{-32}$	90%	Deniz *et al.* (2010)[a]
Accelerator ν_e-e^-	LAMPF	$-7.12 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 10.88 \times 10^{-32}$	90%	Allen *et al.* (1993)[a]
	LSND	$-5.94 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 8.28 \times 10^{-32}$	90%	Auerbach *et al.* (2001)[a]
Accelerator ν_μ-e^-	BNL-E734	$-4.22 \times 10^{-32} < \langle r^2_{\nu_\mu}\rangle < 0.48 \times 10^{-32}$	90%	Ahrens *et al.* (1990)[a]
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2 \times 10^{-32}$	90%	Vilain *et al.* (1995)[a]

... updated by the recent constraints
(effects of physics Beyond Standard Model)

$$(|\langle r^2_{\nu_{e\mu}}\rangle|, |\langle r^2_{\nu_{e\tau}}\rangle|, |\langle r^2_{\nu_{\mu\tau}}\rangle|) < (22, 38, 27) \times 10^{-32}\ \mathrm{cm}^2$$

M.Cadeddu, C. Giunti, K.Kouzakov,
Yu-Feng Li, A. Studenikin, Y.Y.Zhang,
Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering, Phys.Rev.D 98 (2018) 113010

… if one trusts

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

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

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

- ***…General proof:***
- ***In SM :***

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

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

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

Q=0

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

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 ... unobserved effects of New Physics

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

Studenikin, Europhys. Lett. 107 (2014) 210011
Particle Data Group, 2016-2018 and update of 2019

Expected new constraints from GEMMA:

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

Constraints on q_ν

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

2019 (expected)

... unprecedentedly low threshold ...

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

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

Astrophysics bounds on μ_ν

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

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

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

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

Bounds depend on

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

Generic assumption:

- absence of other nonstandard interactions except for μ_ν

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

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

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

... 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 $\nu_R \xleftrightarrow{B} \nu_L$ in galactic B

(sterile) (active)

⇒ from absence of anomalous high-energy ν

Nötzold
1988

50 years of ν oscillation formulae
Gribov & Pontecorvo (1969)

new developments in ν spin and flavour scillations

1. generation of ν spin (flavour) oscillations by interaction with transversal matter current $j_\perp$

P. Pustoshny, A. Studenikin,
"Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions"
- Phys. Rev. D98 (2018) no. 11, 113009

2. inherent interplay of ν spin and flavour oscillations in B

A. Popov, A. Studenikin,
"Neutrino eigenstates and flavour, spin and spin-flavor oscillations in a constant magnetic field"
- Eur. Phys .J. C 79 (2019) no.2, 144, arXiv: 1902.08195

Pavel Pustoshny, A. S.
"Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions",
Phys. Rev. D98 (2018) no. 11, 113009

Artem Popov, A. S..
"Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field ",
Eur. Phys .J. C79 (2019) no.2, 144

Main steps in ν oscillations

1. $\nu_e \overset{vac}{\longleftrightarrow} \overline{\nu}_e$, B. Pontecorvo, 1957

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

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

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

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

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

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

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

$>$ 30 years !

62 years !

early history of ν oscillations

Bruno Pontecorvo

1913-1993

only in $B_\perp$ and matter at rest

2 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 $B = |\mathbf{B}_\perp| e^{i\phi(t)}$

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

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

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

- Resonance amplification of oscillations in matter:

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

Akhmedov, 1988
Lim, Marciano

… similar to MSW effect

In magnetic field

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

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

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

1

ν

Neutrino spin $\boxed{\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R}$ and

spin-flavour $\boxed{\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R}$

oscillations engendered

by transversal matter currents $j_\perp$ $(\mu_\nu B)$

P. Pustoshny, A. Studenikin,

"Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions"

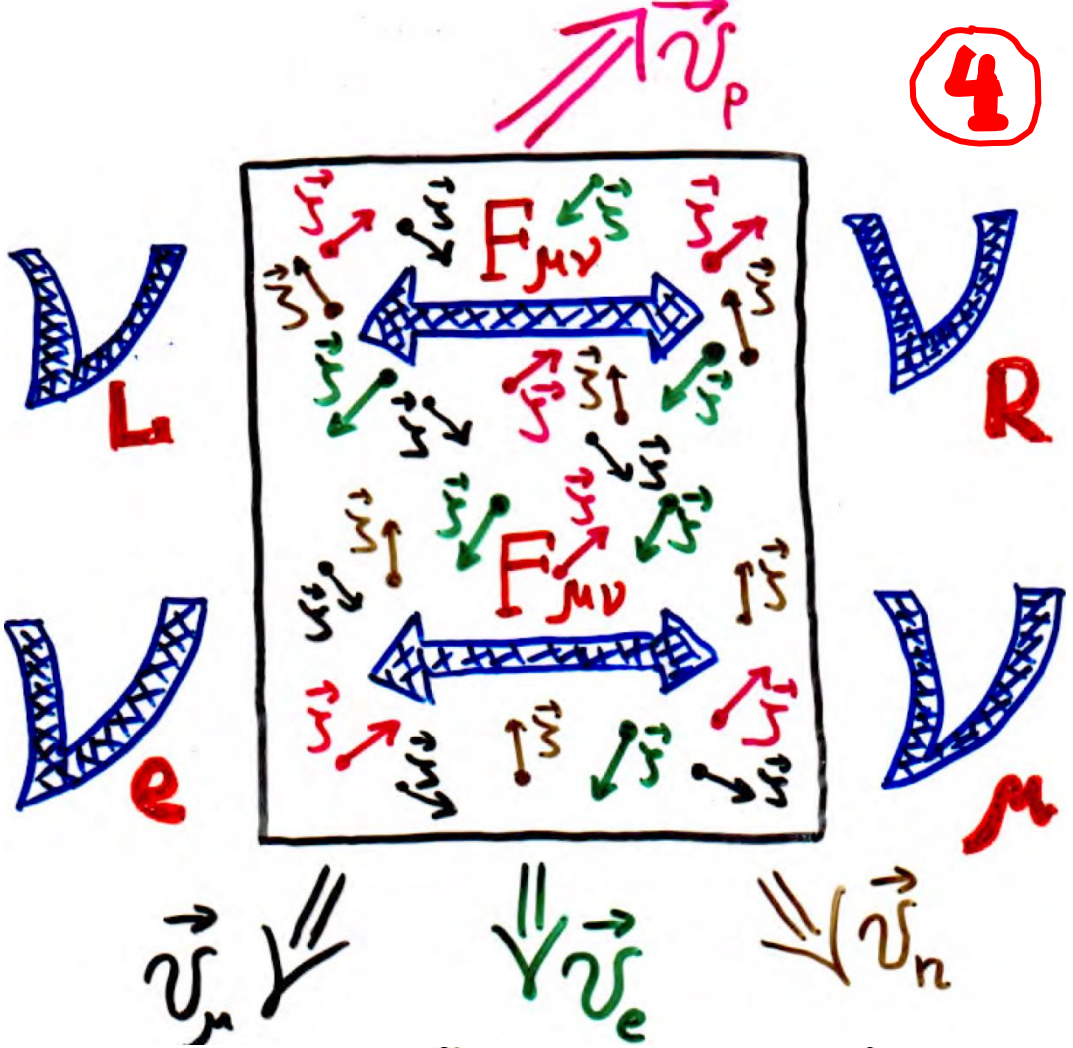
Phys. Rev. D98 (2018) no. 11, 113009

- 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, μ, 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

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

interaction of neutrino with an electromagnetic field

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

(in rest frame of neutrino)

interaction of neutrino with matter

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

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

matter density

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

$\parallel$ $\perp$

ν spin procession 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.
Original Russian Text Copyright © 2004 by Studenikin.

ELEMENTARY PARTICLES AND FIELDS
Theory

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

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.
© 2004 MAIK "Nauka/Interperiodica".

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

Consider spin / spin-flavour

$$\nu_{eL} \to \nu_{eR}, \quad \nu_{eL} \to \nu_{\mu R}$$

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

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

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

A.Studenikin, "Neutrinos in electromagnetic fields and moving media", Phys. Atom. Nucl. 67 (2004)

• transversal current $j_\perp$

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

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

matter density

∥ ⊥

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

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

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.

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

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

- J. Serreau and C. Volpe, "Neutrino-antineutrino correlations in dense anisotropic media", Phys .Rev. D90 (2014) 125040

- V. Ciriglianoa, 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 ...

.

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

... quantum treatment ...

- ν spin evolution effective Hamiltonian in moving matter ? transversal and longitudinal currents $\vec{j}_\perp + \vec{j}_{\parallel}$
- two flavor ν with two helicities: $\nu_f = (\nu_e^+, \nu_e^-, \nu_\mu^+, \nu_\mu^-)^T$

ν interaction with matter composed of neutrons: $n = \frac{n_0}{\sqrt{1-v^2}}$ neutron number density in laboratory reference frame

$\mathbf{v} = (v_1, v_2, v_3)$ velocity of matter

- $$L_{\rm int} = -f^\mu \sum_l \bar{\nu}_l(x)\gamma_\mu \frac{1+\gamma_5}{2}\nu_l(x) = -f^\mu \sum_i \bar{\nu}_i(x)\gamma_\mu \frac{1+\gamma_5}{2}\nu_i(x) \qquad l = e,\ or\ \mu,\quad i = 1,\ 2$$

$$f^\mu = -\frac{G_F}{2\sqrt{2}} j_n^\mu$$

- $$j_n^\mu = n(1, \mathbf{v})$$

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

ν flavour and mass states

P. Pustoshny, A. Studenikin,
Phys. Rev. D98 (2018) no. 11, 113009

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

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

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

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

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

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

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

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

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

two helicity states $s,s' = \pm$

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

- longitudinal currents $\vec{j}_\parallel$ do not change ν helicity
- transversal currents $\vec{j}_\perp$ do change ν helicity

Studenikin, PoS (2017) NOW2016_070, arXiv:1610.06563

J.Phys.Conf.Ser. 888 (2017) 012221

ν (2 flavours x 2 helicities) evolution equation

$$i\frac{d}{dt}\nu_f^s = \left(H_0 + \Delta H_0^{SM} + \Delta H_{j_{||}+j_\perp}^{SM} + \Delta H_{B_{||}+B_\perp}^{SM} + \Delta H_0^{NSI} + \Delta H_{j_{||}+j_\perp}^{NSI}\right)\nu_f^s$$

vacuum

matter at rest

moving matter

Standard Model

B

matter at rest

moving matter

Non-Standard Interactions

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

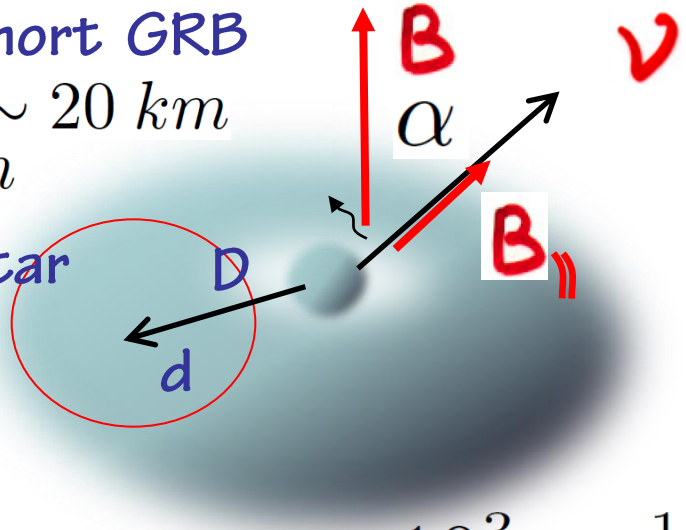
P. Pustoshny, A. Studenikin, Phys. Rev. D98 (2018) no. 11, 113009

$$\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$$

a model of short GRB

$D \sim 20\ km$

$d \sim 20\ km$



- Consider ν escaping central neutron star with inclination angle α from accretion disk: $B_\parallel = B \sin\alpha \sim \frac{1}{2} B$

- Toroidal bulk of rotating dense matter with $\omega = 10^3\ s^{-1}$

- transversal velocity of matter

$v_\perp = \omega D = 0.067$ and $\gamma_n = 1.002$

- Perego et al, Mon.Not.Roy.Astron.Soc. 443 (2014) 3134

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

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

- Grigoriev, Lokhov, Studenikin, Ternov, JCAP 1711 (2017) 024

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

$$\boldsymbol{B}_{||} \boldsymbol{\beta} = -1$$

resonance condition

$$\left| \frac{\mu_{11} B_{||}}{\widetilde{G} n_0 \gamma_n} - \gamma_\nu \right| \leq 1$$

Resonance amplification of spin-flavor oscillations (in the absence of $j_{\parallel}$)

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

$\vec{B} = \vec{B}_\perp + \vec{B}_\parallel \to 0$

Criterion – oscillations are important:

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

$$E_{eff} = \left|\mu_{e\mu} B_\perp + \left(\frac{\eta}{\gamma}\right)_{e\mu} \widetilde{G} n v_\perp\right| \geq \left|\Delta M - \frac{1}{2}\left(\frac{\mu_{11}}{\gamma_{11}} + \frac{\mu_{22}}{\gamma_{22}}\right) B_\parallel - \widetilde{G} n (1 - \boldsymbol{v}\boldsymbol{\beta})\right|$$

neglecting $\vec{B} = \vec{B}_\perp + \vec{B}_\parallel \to 0$:

$$L_{eff} = \frac{\pi}{\left(\frac{\eta}{\gamma}\right)_{e\mu} \widetilde{G} n v_\perp} \qquad \left(\frac{\eta}{\gamma}\right)_{e\mu} \approx \frac{\sin 2\theta}{\gamma_\nu}$$

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

$\Delta m^2 = 7.37 \times 10^{-5}\ eV^2$

$\sin^2\theta = 0.297$

$p_0^\nu = 10^6\ eV$

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

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

$$n_0 \sim \frac{\Delta M}{\widetilde{G}} = 10^{12}\ eV^3 \approx 10^{26}\ cm^{-3}$$

$$L_{eff} = \frac{\pi}{(\frac{\eta}{\gamma})_{e\mu} \widetilde{G} n v_\perp} \approx 5 \times 10^{11}\ km$$

$L_{eff} \approx 10\ km$ (within short GRB) if $n_0 \approx 5 \times 10^{36}\ cm^{-3}$

2

"Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field"

$$\boxed{\nu_e^L \leftrightarrow \nu_\mu^L} \qquad \boxed{\nu_e^L \leftrightarrow \nu_e^R} \qquad \boxed{\nu_e^L \leftrightarrow \nu_\mu^R}$$

A.Popov, A.Studenikin,

Eur. Phys .J. C79 (2019) 144,

arXiv: 1902.08195

Consider two flavour ν with two helicities as superposition of helicity mass states $\nu_i^{L(R)}$

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

however, $\nu_i^{L(R)}$ are not stationary states in magnetic field $\mathbf{B} = (B_\perp, 0, B_\parallel)$

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

$\Leftarrow$ $\nu_i^{-(+)}$ stationary states in B

- Dirac equation $(\gamma_\mu p^\mu - m_i - \mu_i \boldsymbol{\Sigma B})\nu_i^s(p) = 0$ in a constant B

$\hat{H}_i \nu_i^s = E \nu_i^s$ $\quad \hat{H}_i = \gamma_0 \boldsymbol{\gamma p} + \mu_i \gamma_0 \boldsymbol{\Sigma B} + m_i \gamma_0 \quad (s = \pm 1)$ $\quad \mu_{ij} (i \neq j) = 0$ ●

ν spin operator that commutes with $\hat{H}_i$:

"bra-ket" products

- $\hat{S}_i = \frac{1}{N}\left[\boldsymbol{\Sigma B} - \frac{i}{m_i}\gamma_0\gamma_5[\boldsymbol{\Sigma} \times \boldsymbol{p}]\boldsymbol{B}\right]$ $\quad \hat{S}_i \left|\nu_i^s\right\rangle = s \left|\nu_i^s\right\rangle, s = \pm 1$ $\quad \left\langle \nu_i^s \middle| \nu_k^{s'} \right\rangle = \delta_{ik}\delta_{ss'}$ ●

$$\frac{1}{N} = \frac{m_i}{\sqrt{m_i^2 \mathbf{B}^2 + \mathbf{p}^2 B_\perp^2}}$$

- ν energy spectrum

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

Probabilities of ν oscillations (flavour, spin and spin-flavour)

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

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 on magnetic frequencies

$\omega_{vac} = \frac{\Delta m^2}{4p}$ $\quad \omega_B = \mu B_\perp$

A.Popov, A.S., Eur. Phys .J. C79 (2019) 144

- 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

no spin oscillations

- A.Popov, A.S., Eur. Phys . J. C79 (2019) 144

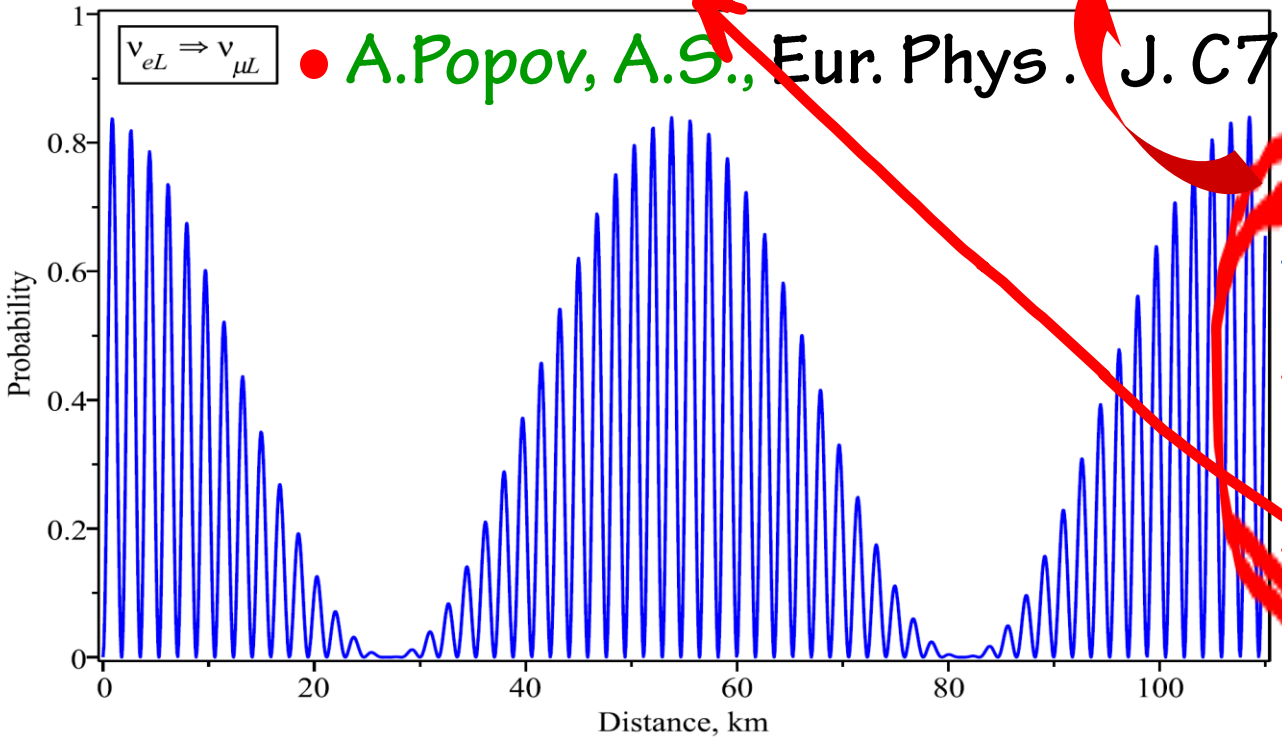


Fig. 1 The probability of the neutrino flavour oscillations $\nu_e^L \to \nu_\mu^L$ in the transversal magnetic field

- $B_\perp = 10^{16}\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20}\mu_B$.

... amplitude of flavour oscillations on vacuum frequency $\omega_{vac} = \frac{\Delta m^2}{4p}$ is modulated by magnetic frequency $\omega_B = \mu B_\perp$

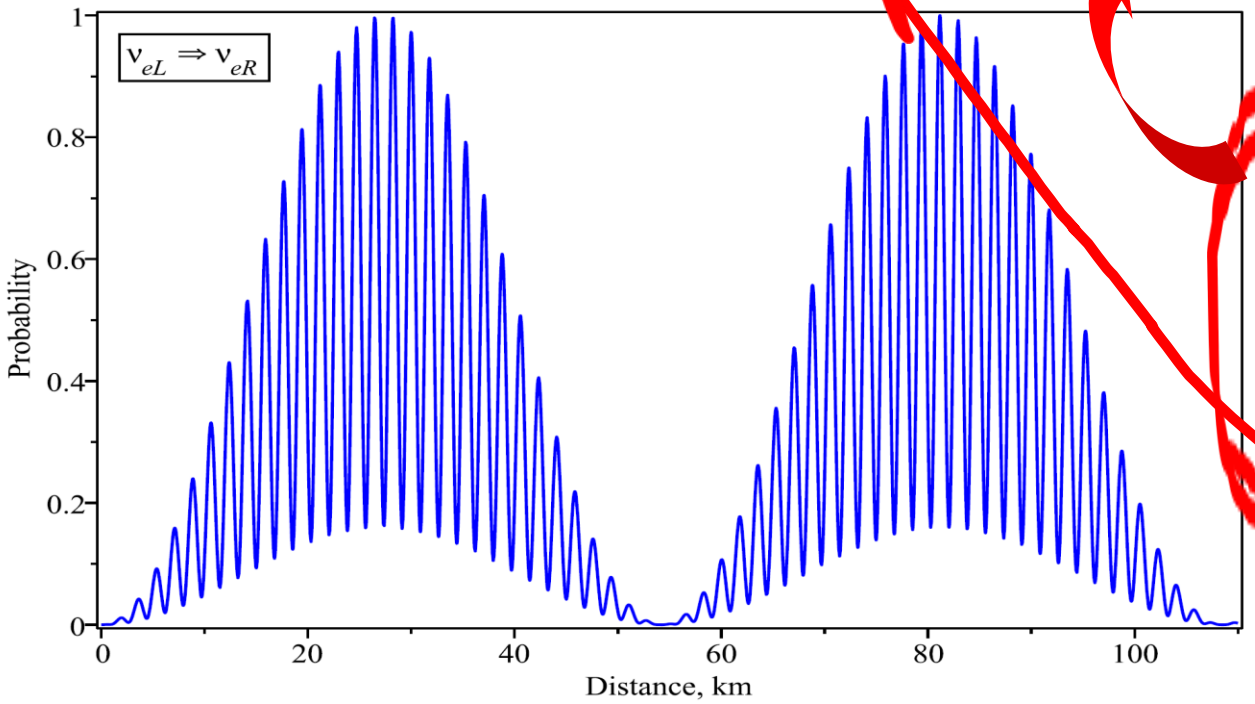
Chotorlishvili, Kouzakov, Kurashvili, Studenikin, Spin-flavor oscillations of ultrahigh-energy cosmic neutrinos in interstellar space: The role of neutrino magnetic moments, Phys. Rev. D96 (2017) 103017

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

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

spin

no flavour oscillations



... amplitude of spin oscillations on magnetic frequency $\omega_B = \mu B_\perp$ is modulated by vacuum frequency $\omega_{vac} = \frac{\Delta m^2}{4p}$

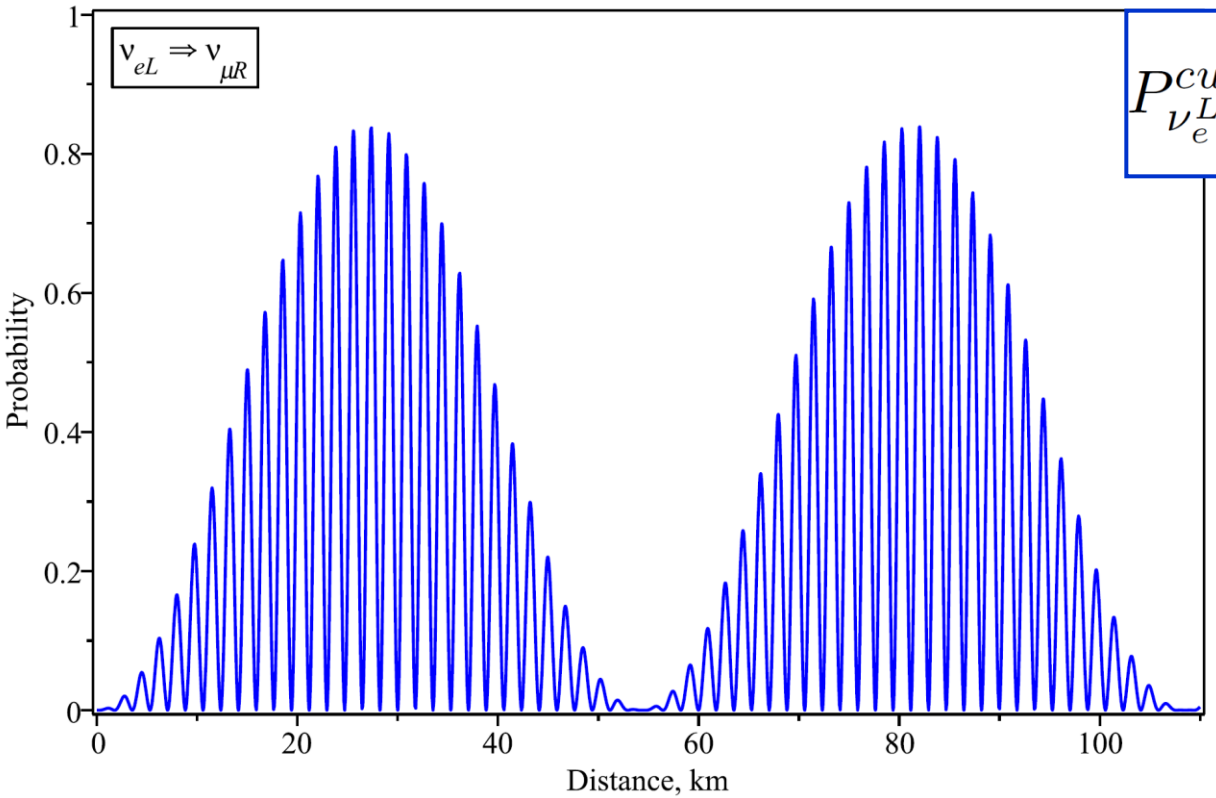
A.Popov, A.S., Eur. Phys. J. C 79 (2019) 144

Fig. 2 The probability of the neutrino spin oscillations $\nu_e^L \to \nu_e^R$ in the transversal magnetic field $B_\perp = 10^{16}\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20}\mu_B$.

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

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

spin-flavour



$$P^{cust}_{\nu_e^L \to \nu_\mu^L} = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4p} t$$

$$P^{cust}_{\nu_e^L \to \nu_e^R} = \sin^2(\mu B_\perp t)$$

... interplay of oscillations
on vacuum $\omega_{vac} = \frac{\Delta m^2}{4p}$
and
on magnetic $\omega_B = \mu B_\perp$
frequencies

Fig. 3 The probability of the neutrino spin flavour oscillations $\nu_e^L \to \nu_\mu^R$ in the transversal magnetic field $B_\perp = 10^{16}\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

... in literature:

- $P_{\nu_e^L \nu_\mu^R} = \sin^2(\mu_{e\mu} B_\perp t) = 0$

$\mu_{e\mu} = \frac{1}{2}(\mu_2 - \mu_1) \sin 2\theta$

$\mu_1 = \mu_2, \quad \mu_{ij} = 0, \ i \neq j$

- For completeness: ν survival $\nu_e^L \leftrightarrow \nu_e^L$ probability

... depends on μ_ν and B

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

$\sum$ of all probabilities (as it should be...):

$$P_{\nu_e^L \to \nu_\mu^L} + P_{\nu_e^L \to \nu_e^R} + P_{\nu_e^L \to \nu_\mu^R} + P_{\nu_e^L \to \nu_e^L} = 1$$

A.Popov, A.S., Eur. Phys .J. C79 (2019) 144

Conclusions

1 2 3

1 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 $g_V \to g_V + \frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2 \theta_W$, there are also contributions from flavor-transition charge radii – new analysis (re-analysis) of data is needed

2

μ_ν interactions could have important effects in astrophysical and cosmological environments

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

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

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

3 ν electromagnetic interactions (new effects)

two new aspects of ν spin, spin-flavour and flavour oscillations

1 generation of ν spin and spin-flavour oscillations by ν interaction with transversal matter current $j_\perp$

P. Pustoshny, A. Studenikin, Phys.Rev. D98 (2018) 113009

2 consistent treatment of ν spin, flavour and spin-flavour oscillations in B

A.Popov, A. Studenikin, Eur. Phys .J. C 79 (2019) 144

new effects in ν oscillations in analysis of supernovae ν fluxes (for JUNO ?)

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Thank you

Back up slides

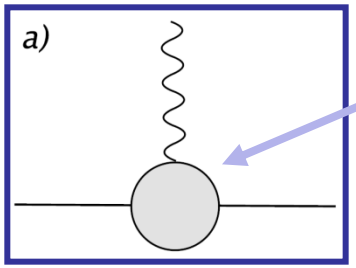
Large magnetic moment μ_ν

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

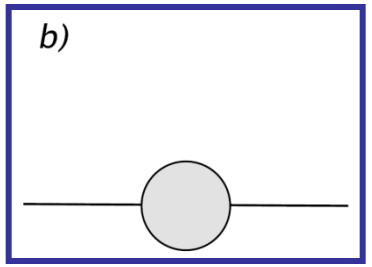


then

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

…combination of constants and loop factors…

contribution to m_ν given by



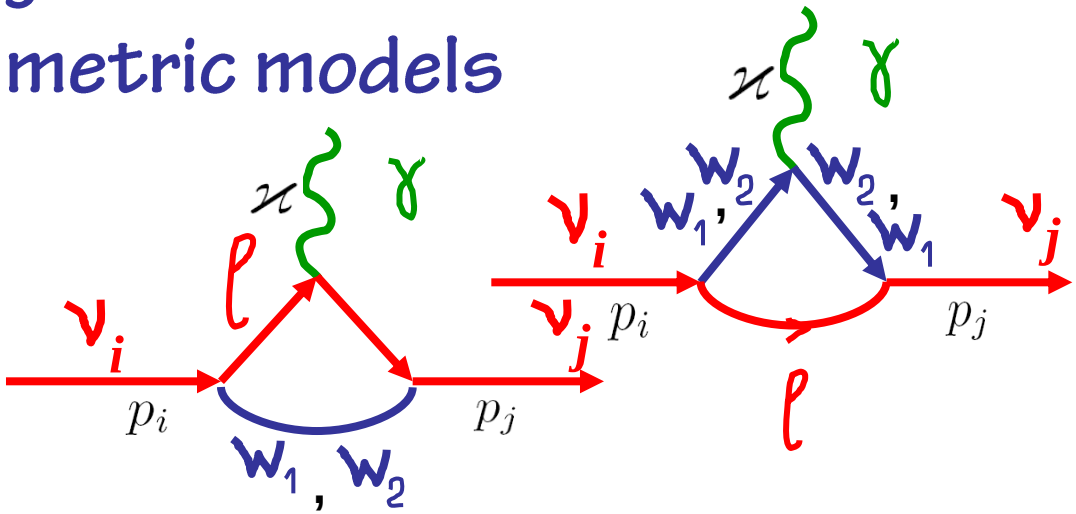
, then $m_\nu \sim G\Lambda$

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

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 mass states

$$W_1 = W_L \cos\xi - W_R \sin\xi$$
$$W_2 = W_L \sin\xi + W_R \cos\xi$$

with mixing angle ξ of gauge bosons $W_{L,R}$ with pure $(V \pm A)$ couplings

Kim, 1976; Marciano, Sanda, 1977;
Beg, Marciano, Ruderman, 1978

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

… charged lepton mass …

… neutrino mass …

Large magnetic moment

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

- 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

Astrophysical bound on q_ν

- … 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

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

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

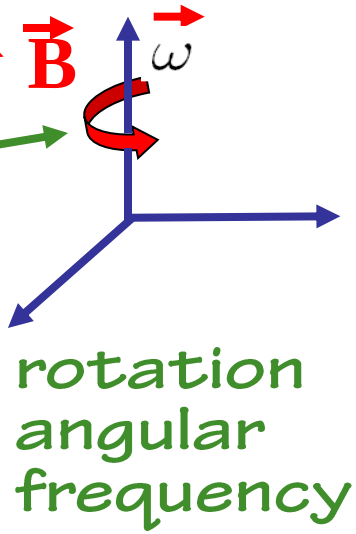
external magnetic field

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

matter potential

rotating matter

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



rotation angular frequency

ν energy is quantized in rotating matter

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

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

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

$N = 0, 1, 2, ...$
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):

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

In quasi-classical approach

ν quantum states in rotating matter

ν 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

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

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

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

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

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

... we predict :

E ~ 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 ?

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

• 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

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

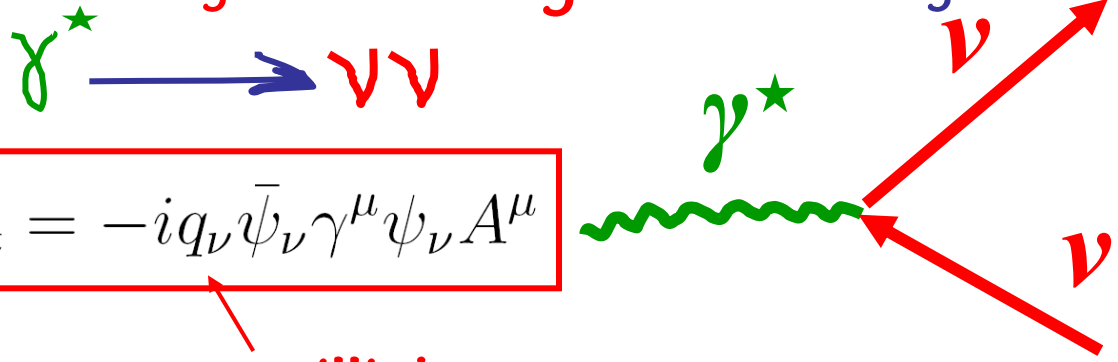
• $|\triangle\omega| < \omega_0$! ...to avoid contradiction of νST impact with observational data on pulsars ...

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

● ... best astrophysical bound ...

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

- Constraints on neutrino millicharge from red gaints cooling



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

Interaction Lagrangian

millicharge

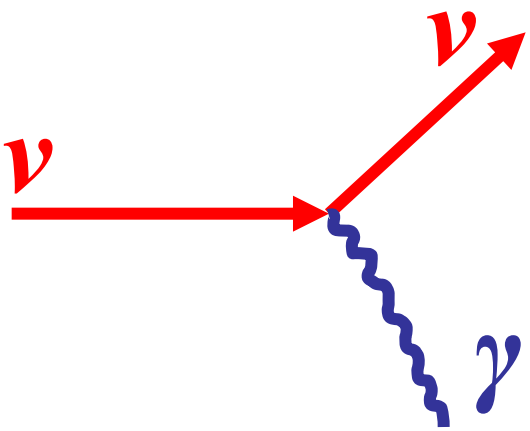
Decay rate

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

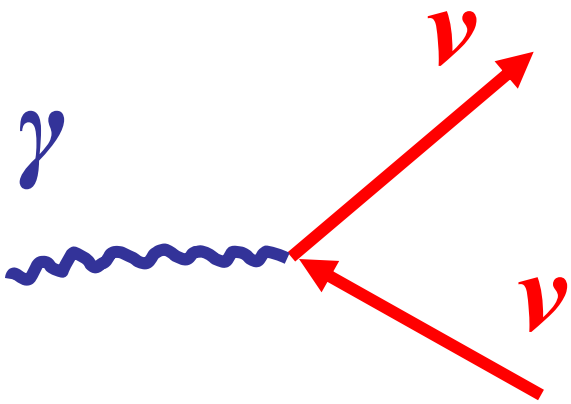
- $q_\nu \leq 2 \times 10^{-14} e$ …to avoid helium ignition in low-mass red gaints — Halt, Raffelt, Weiss, PRL1994
- $q_\nu \leq 3 \times 10^{-17} e$ … absence of anomalous energy-dependent dispersion of SN1987A ν signal, most model independent
- … from "charge neutrality" of neutron… $q_\nu \leq 3 \times 10^{-21} e$

Astrophysical bound on μ_ν

3 ν electromagnetic interactions

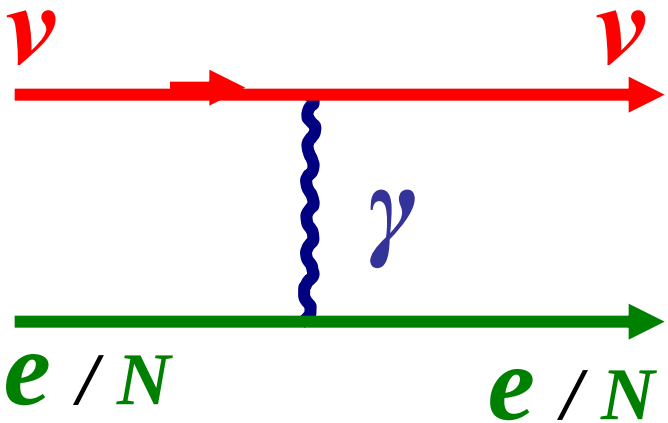


ν decay, Cherenkov radiation

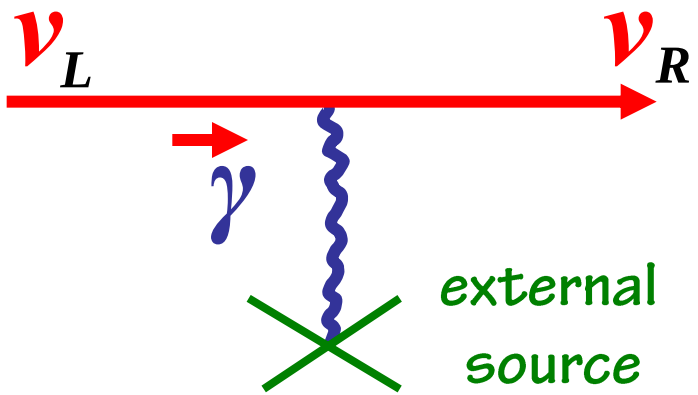


γ decay in plasma

!!!



Scattering

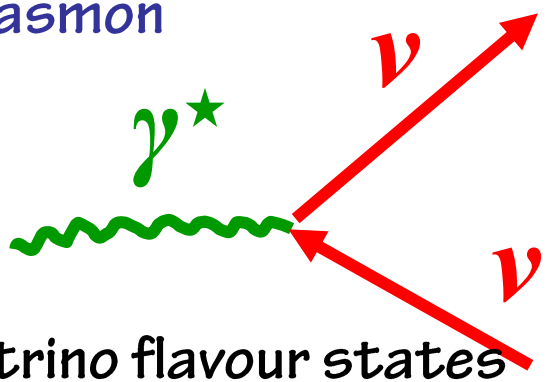


Spin precession

2 Astrophysical bound on μ_ν

G.Raffelt, PRL 1990

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



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

neutrino flavour states

Matrix element

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

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

Decay rate

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

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

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

Energy-loss rate per unit volume

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

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

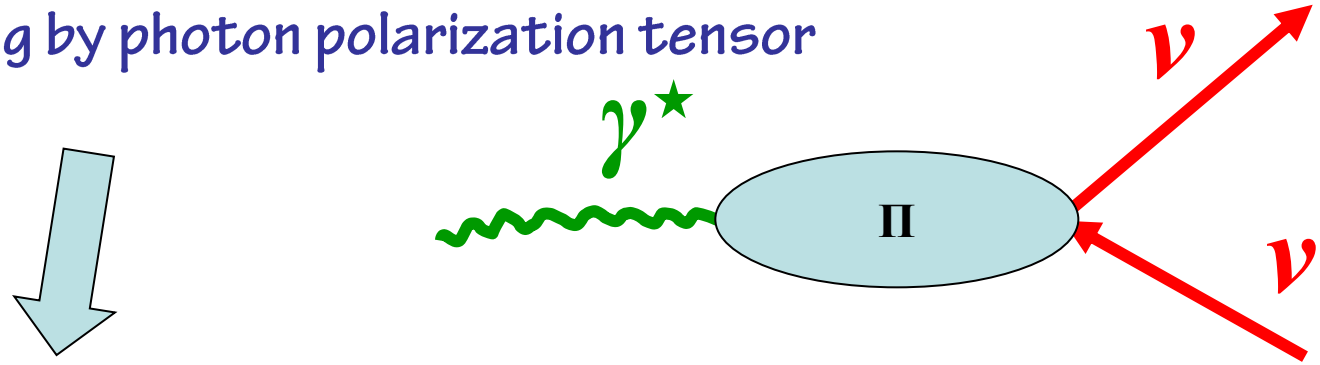
distribution function of plasmons

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)

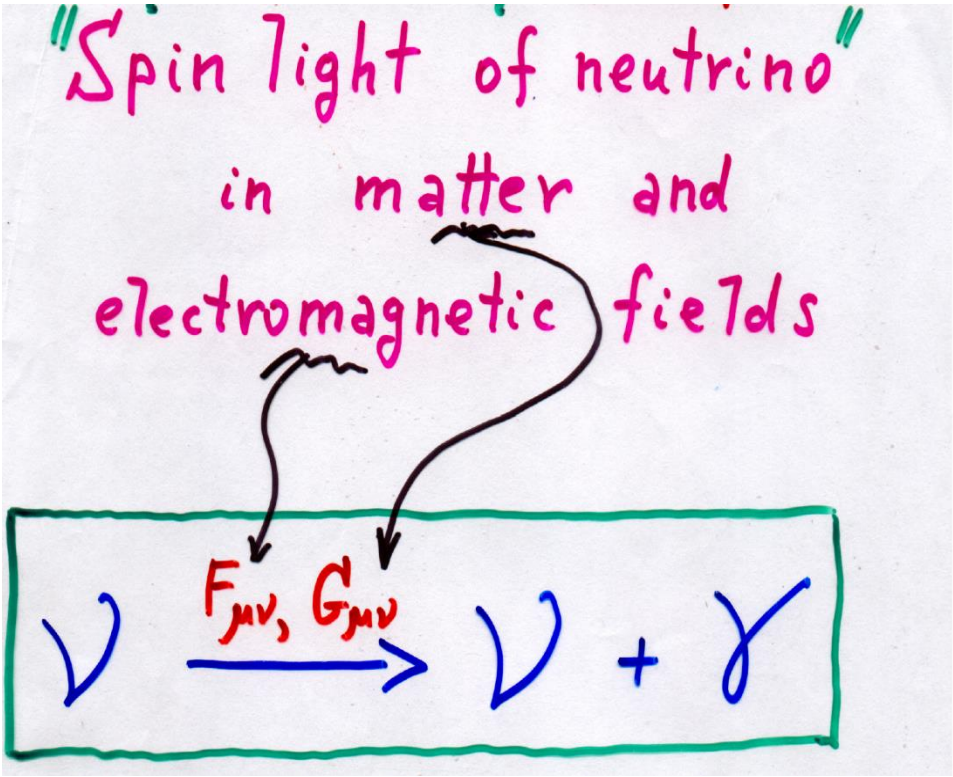
… best astrophysical limit on ν magnetic moment…

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

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



μ_ν

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

Lobanov, Studenikin,
Phys.Lett. B 515 (2001) 94
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Studenikin, A.Ternov,
Phys.Lett. B 608 (2005) 107

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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

Осцилляции нейтрино

флейворные $\nu_e \leftrightarrow \nu_\mu$

спиновые $\nu_L \leftrightarrow \nu_R$

flavour oscillations spin

$$P_{\nu_e \nu_\mu}(x) = \sin^2 2\theta \cdot \sin^2 \frac{\Delta m^2}{4E} x$$

$$\Delta m^2 = m_2^2 - m_1^2$$

$$P_{\nu_L \nu_R} = \sin^2 \beta \cdot \sin^2 \Omega x$$

$$\Omega = \left((\mu B)^2 + \left(\frac{\Delta_{LR}}{4E} \right)^2 \right)^{1/2}$$

$$\sin^2 \beta = \frac{(\mu B)^2}{(\mu B)^2 + (\Delta_{LR}/4E)^2}$$

resonance amplification of ν oscillation probabilities amplitudes

P. Pustoshny, A. S.
Phys. Rev. D98 (2018) no. 11, 113009

E. Akhmedov
C.-S. Lim, W. Marciano

(1988)

{Neutrino spin $\nu_L \overset{B_\perp}{\leftrightarrow} \nu_R$ oscillations

(mixing due to $\frac{\Delta m^2_\nu}{2E_\nu} \sin 2\theta_{vac} \to 2\mu B_\perp$)

$$P(\nu_L \leftrightarrow \nu_R) = \sin^2 2\theta_{eff} \sin^2 \frac{\pi x}{L_{eff}} ,$$

$$\sin^2 2\theta_{eff} = \frac{(2\mu B_\perp)^2}{(2\mu B_\perp)^2 + \Omega^2} ,$$

$$* \quad \Omega = \frac{\Delta m^2_\nu}{2E_\nu} A(\theta_{vac}) - \sqrt{2} G_F n_{eff} ,$$

$$L_{eff} = \frac{2\pi}{\sqrt{\Omega^2 + (2\mu B_\perp)^2}}$$

particle number density

$\Omega^2 \to 0$: resonance in $\nu_L \leftrightarrow \nu_R$ neutrino spin oscillations

Spin and spin-flavour oscillations for $\nu_\odot$ and ν_{SN}

Bruno Pontecorvo,
«Mesonium and anti-mesonium»,
Sov.Phys.JETP 6 (1957) 429
Zh.Eksp.Teor.Fiz. 33 (1957) 549-551:

«It was assumed above that there exists a conservation law for the neutrino charge, according to which a neutrino cannot change into an antineutrino in any approximation. This law has not yet been established; evidently it has been merely shown that the neutrino and antineutrino are not identical particles.

if $m_\nu \neq 0$
then
$\nu \leftrightarrow \bar{\nu}$
In vacuum

If the two-component neutrino theory should turn out to be incorrect … and if the conservation law of neutrino charge would not apply, then in principle neutrino – antineutrino transitions could take place in vacuo»

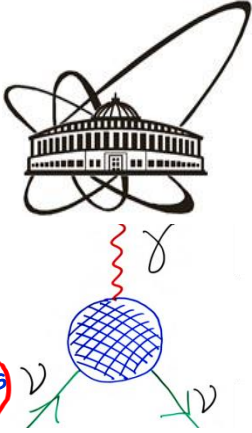
Electromagnetic Properties of ν

(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

$$\Lambda^{if}_{\mu}(q) = f^{if}_{Q}(q^2)\gamma_\mu + f^{if}_{M}(q^2)i\sigma_{\mu\nu}q^\nu + f^{if}_{E}(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f^{if}_{A}(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5,$$

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

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

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

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 ν EMP 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

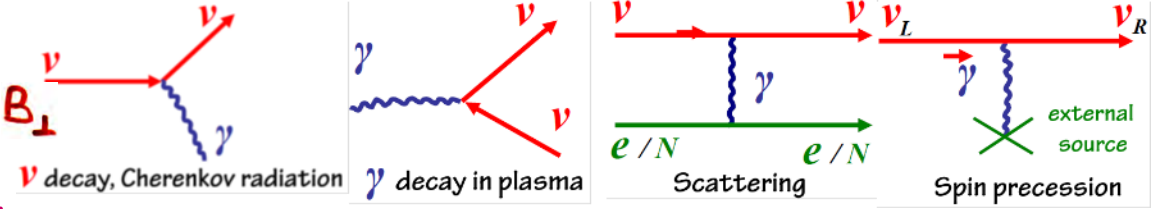
AS '14, Chen ea '14

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)**

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

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

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

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

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

Popov & AS, Eur. Phys .J. C 79 (2019) no.2, 144
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, Phys. Rev. D98 (2018) 113009
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"