Neutrino electromagnetic properties and new effects in astrophysics

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Moscow State University

&

JINR -Dubna

"Particle Physics and Cosmology"

XXVI Rencontres de Blois

21/05/2014

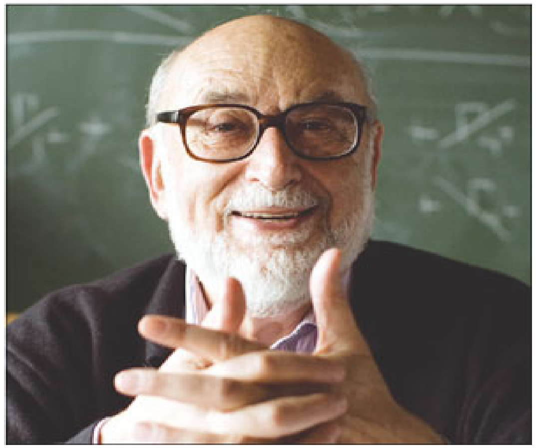
- Blois - 2014

Particle Physics and Cosmology

. . . a period of spectacular success of

Particle Physics . . .

Robert Brout



François Englert

Peter Higgs

Observation of Higgs boson confirms the symmetry breaking mechanism by

Brout-Englert-Higgs (BEH)

provides final glorious triumph of

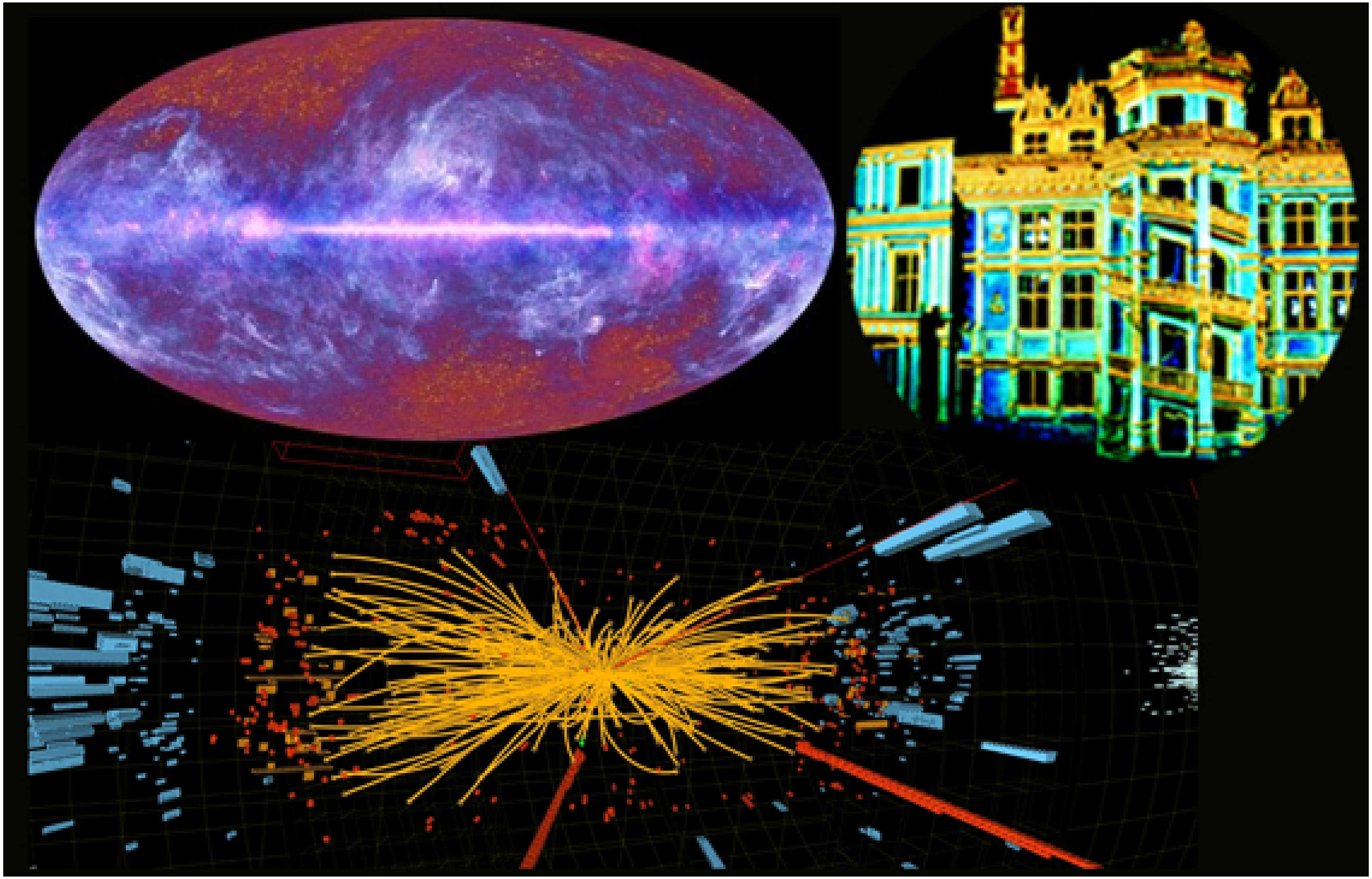
Standard Model

What

is

next ?

26th Rencontres de Blois
Particle Physics and Cosmology



Château Royal de Blois May 18-23, 2014

Prof. Jean Trân Thanh Vân
(opening speech at the conference) :

... the primary goal
of XXVI Rencontres de Blois
is to discuss phenomena of vast
variety scales -
from extremely fine scales where
fundamentals of particle physics
should manifest themselves
to huge scales
related to phenomenology
in astrophysics and cosmology...

- ν electromagnetic properties

(1) C.Giunti, A.Studenikin :
"Electromagnetic interactions of neutrinos: a window to new physics",
arXiv: 1403.6344 , March 25, 2014

- Astrophysical consequences of ν interactions

(2) A. Studenikin , I.Tokarev:
"Millicharged neutrino with anomalous magnetic moment in rotating magnetized matter",
Nucl.Phys.B (2014)
http://dx.doi.org/10.1016/j.nuclphysb.2014.04.026

(3) I.Balantsev, A.Studenikin :
"Spin light of electron in dense neutrino fluxes",
arXiv: 1405.xxxx , May 19, 2014

ν electromagnetic properties

(short review)

$m_\nu \neq 0$

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

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

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

4. Carlo Broggini, C. Giunti, A. Studenikin :
"Electromagnetic properties of neutrinos",
in: Special issue "Neutrino Physics",
Adv. in High Energy Phys. 2012 (2012) 459526 (49 pp)

5. C. Giunti, A. Studenikin :
"Electromagnetic interactions of neutrinos:
a window to new physics",
arXiv:1403.6344 , March 25, 2014, sent to Rev.Mod.Phys.

$m_\nu \neq 0$

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

Theory (Standard Model with ν_R)

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

magnetic moment

Lee, Shrock, 1977; Fujikawa, Shrock, 1980

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

... much greater values are desired

for astrophysical or cosmology

visualization of μ_ν

... hopes for physics BSM ...

- **Astrophysical bounds**

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

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

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

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

Lee, Shrock, 1977; Fujikawa, Shrok, 1980

- **Limits from reactor ν-e scattering experiments**

A.Beda et al. (GEMMA Coll.) (2012):

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

...the present status...

to have visible $m_\nu \neq 0$

is not an easy task for

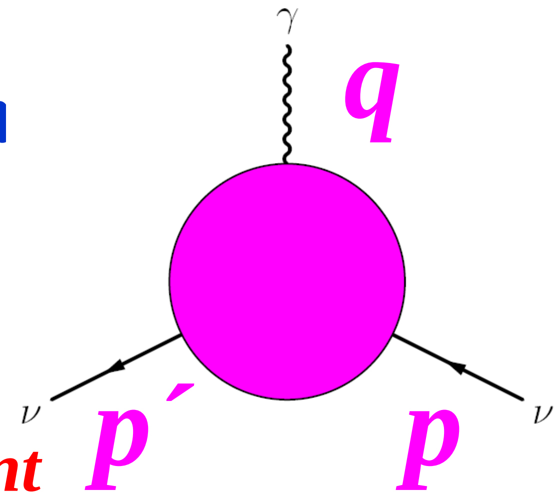
theoreticians

and experimentalists

… a bit of ν electromagnetic properties theory …

electromagnetic vertex function

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



Matrix element of electromagnetic current is a Lorentz vector

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

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

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

vectors q_μ *and* l_μ

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

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

Matrix element of electromagnetic current between neutrino states

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

where vertex function generally contains 4 *form factors*

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

1. electric

dipole

2. magnetic

3. electric

4. anapole

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

Dirac ν

1) *CP invariance + hermiticity* ⟹ $f_E = 0$,

2) *at zero momentum transfer **only** electric charge* $f_Q(0)$ *and magnetic moment* $f_M(0)$ *contribute to* $H_{int} \sim J_\mu^{EM} A^\mu$,

3) *hermiticity itself* ⟹ *three form factors are real:* $Im f_Q = Im f_M = Im f_A = 0$

Majoran ν

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

$$f_Q = f_M = f_E = 0$$

…as early as 1939, W.Pauli…

EM properties ⟹ a way to distinguish Dirac and Majorana ν

ν magnetic moment in experiments

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

Cross-section:

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

where the Standard Model contribution

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

T is the electron recoil energy and

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

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

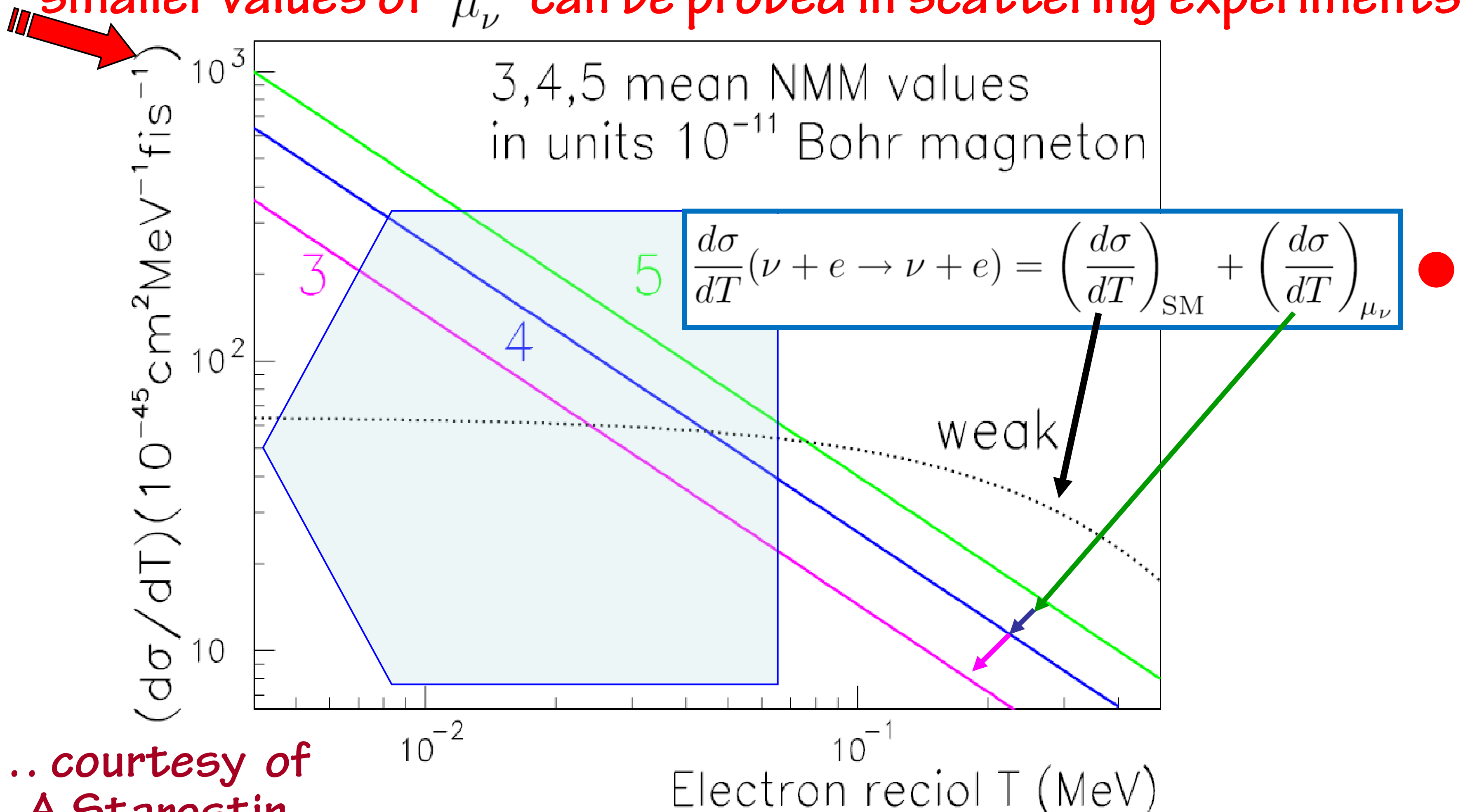
$$g_V = \begin{cases} 2\sin^2\theta_W + \frac{1}{2} & \text{for } \nu_e, \\ 2\sin^2\theta_W - \frac{1}{2} & \text{for } \nu_\mu, \nu_\tau, \end{cases} \qquad g_A = \begin{cases} \frac{1}{2} & \text{for } \nu_e, \\ -\frac{1}{2} & \text{for } \nu_\mu, \nu_\tau \end{cases}$$

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…

MUNU experiment at Bugey reactor (2005)

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

TEXONO collaboration at Kuo-Sheng power plant (2006)

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

GEMMA (2007)

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

GEMMA I 2005 - 2007

BOREXINO (2008)

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

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

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

based on first release of BOREXINO data

Montanino, Picariello, Pulido, PRD 2008

...attempts to improve bounds

GEMMA (2005-2012)

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

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

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

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

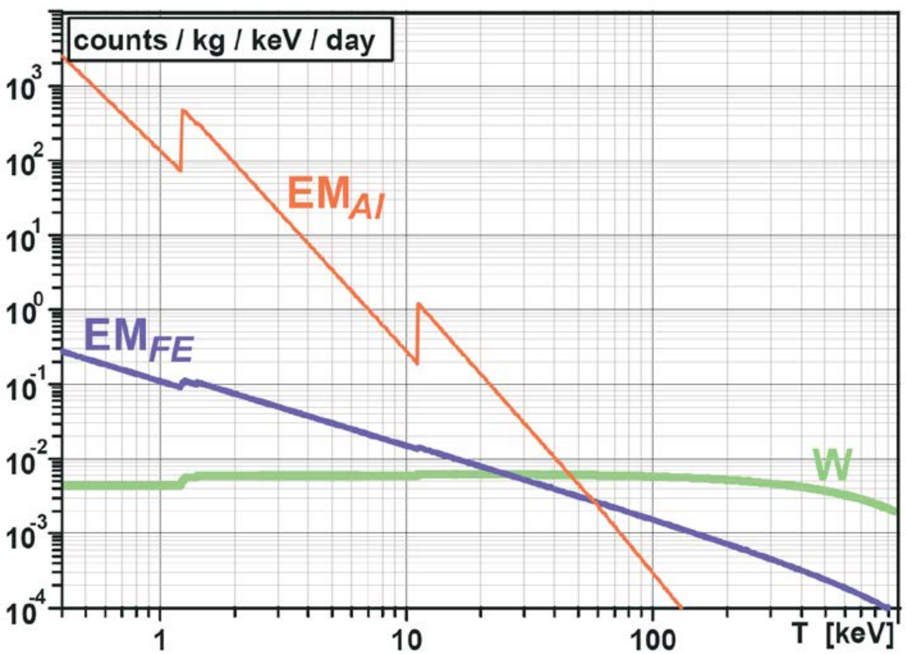
H.Wong et al. (TEXONO Coll.), PRL 105 (2010) 061801

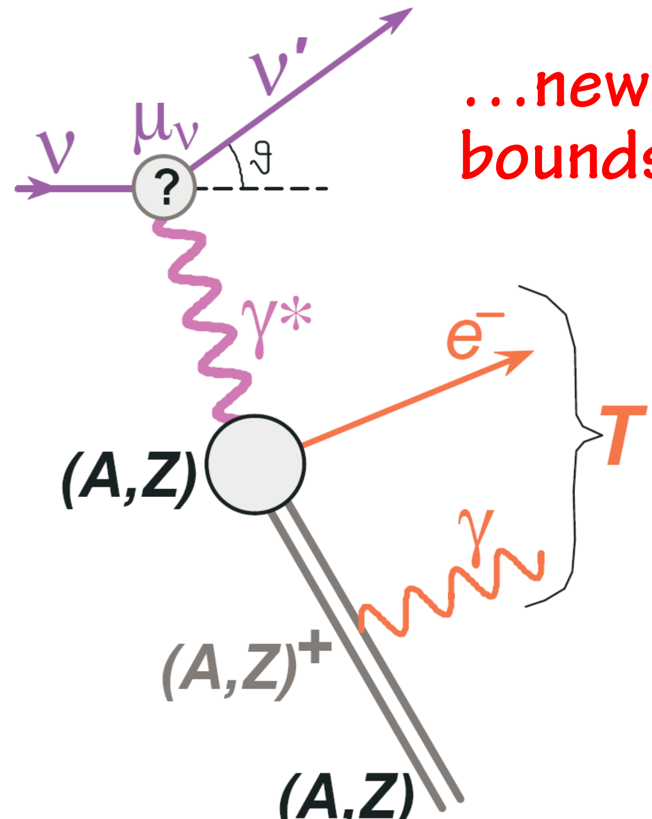
?

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

(ν scattering on bound e)

... an interesting hypothetical possibility to improve bounds...





...new bounds ...

K.Kouzakov, A.Studenikin,

- "Magnetic neutrino scattering on atomic electrons revisited" **Phys.Lett. B** 105 (2011) 061801,
- "Electromagnetic neutrino-atom collisions: The role of electron binding" **Nucl.Phys.B** (Proc.Suppl.) 217 (2011) 353

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

- "Neutrino electromagnetic properties and new bounds on neutrino magnetic moments" **J.Phys.: Conf.Ser**. 375 (2012) 042045
- "Neutrino-impact ionization of atoms in search for neutrino magnetic moment", **Phys.Rev.D** 83 (2011) 113001
- "On neutrino-atom scattering in searches for neutrino magnetic moments" **Nucl.Phys.B** (Proc.Supp.) 2011 (Proc. of Neutrino 2010 Conf.)
- "Testing neutrino magnetic moment in ionization of atoms by neutrino impact", **JETP Lett.** 93 (2011) 699

M.Voloshin,

- "Neutrino scattering on atomic electrons in search for neutrino magnetic moment" **Phys.Rev.Lett.** 105 (2010) 201801

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

...free electron approximation ...

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

Experimental limits for different effective neutrino magnetic moments

Method		Experiment	Limit	CL	Reference
		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)
Reactor $\bar{\nu}_e$-e^-	●	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, arXiv: 1403.6344

… 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

- *…General proof:*

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

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

- *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*

- *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**

Experimental limits for different effective neutrino millicharges

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)

C.Giunti, A.Studenikin, arXiv: 1403.6344

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

A.S., arXiv: 1302.1168, 18 March, 2014

ν-e cross-section

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

two not seen contributions:

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

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

Bounds on q_ν from

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

... no observable effects of New Physics

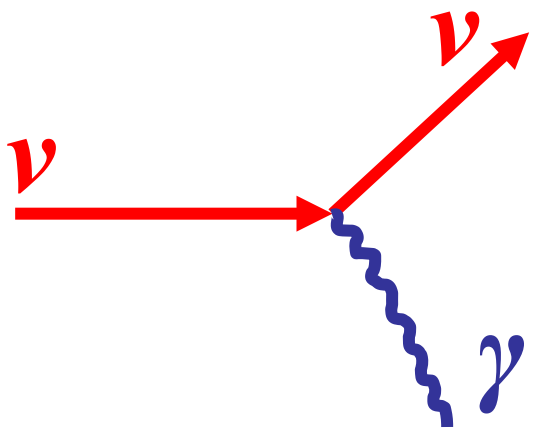
Constraints on μ_ν from GEMMA: Constraints on q_ν

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

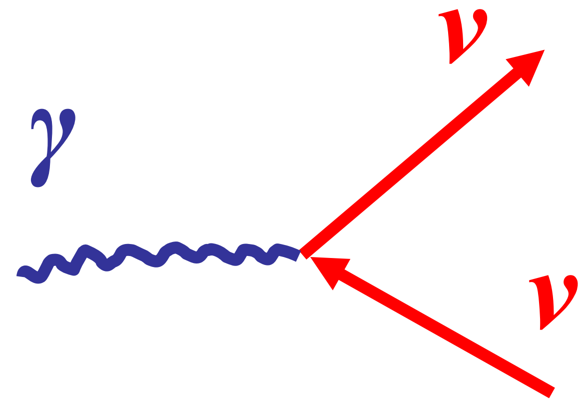
2015 (expected) $\mu_\nu^a \sim 1.5 \times 10^{-11}\mu_B$ ($T = 1.5\ keV$) $\quad | q_\nu |< 3.7 \times 10^{-13} e_0$

2018 (expected) $\mu_\nu^a \sim 0.9 \times 10^{-12}\mu_B$ $\quad T = 350\ eV$ $\quad |q_\nu| < 1.8 \times 10^{-13} e_0$

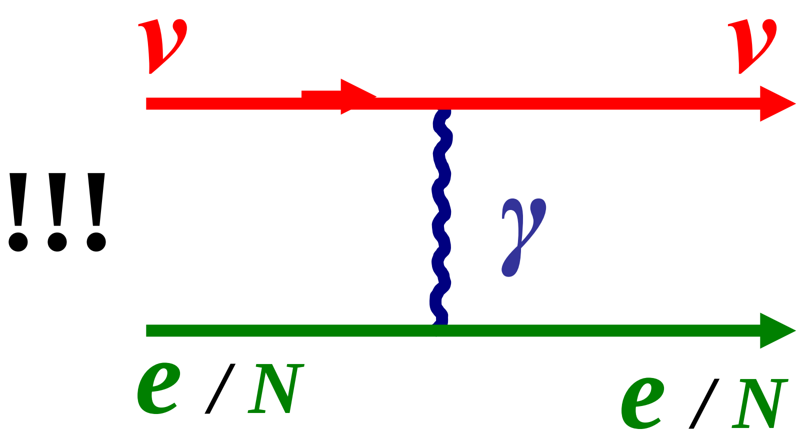
ν electromagnetic interactions



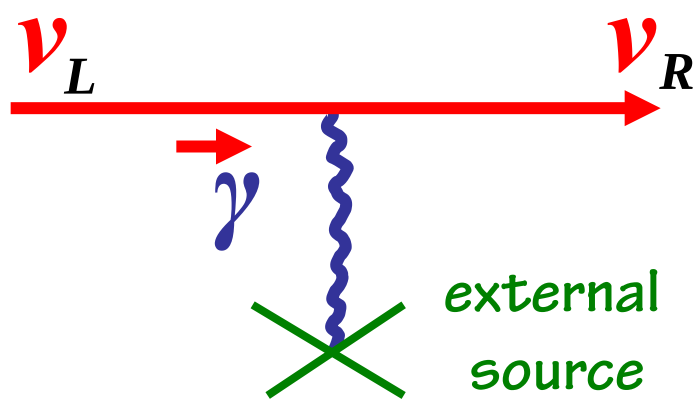
ν decay, Cherenkov radiation



γ decay in plasma



Scattering

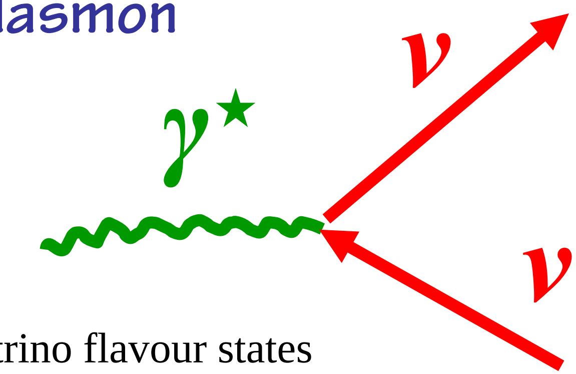


Spin precession

Astrophysical bound on μ_ν

G.Raffelt, PRL 1990

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



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

neutrino flavour states

Matrix element

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

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

Decay rate

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

= 0 in vacuum $\omega = k$

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

Energy-loss rate per unit volume

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

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

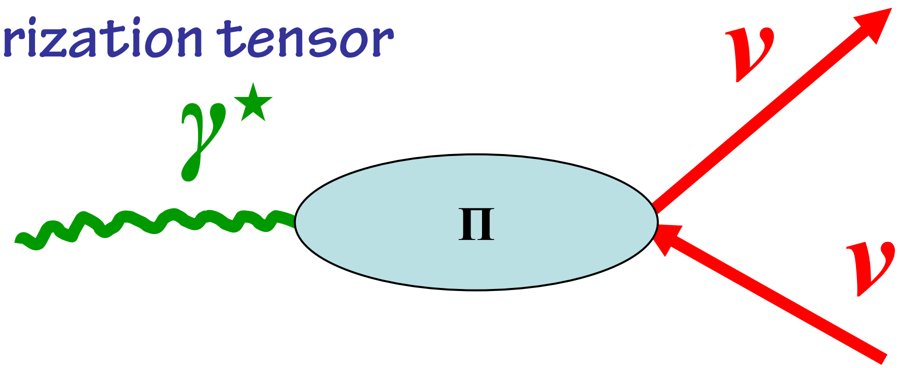
distribution function of plasmons

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)

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

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

… best astrophysical limit on ν magnetic moment…

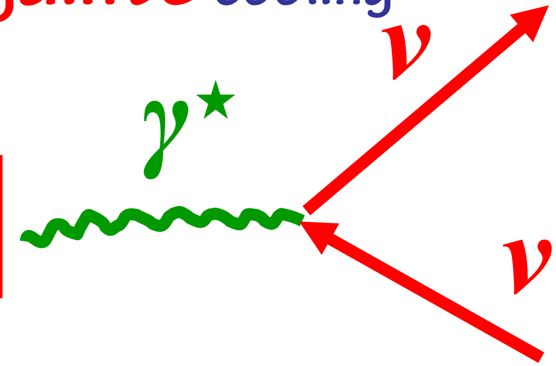
G.Raffelt, PRL 1990

3.10

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

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

$\gamma^\star \rightarrow \nu\nu$



Interaction Lagrangian

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

millicharge

Decay rate

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

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

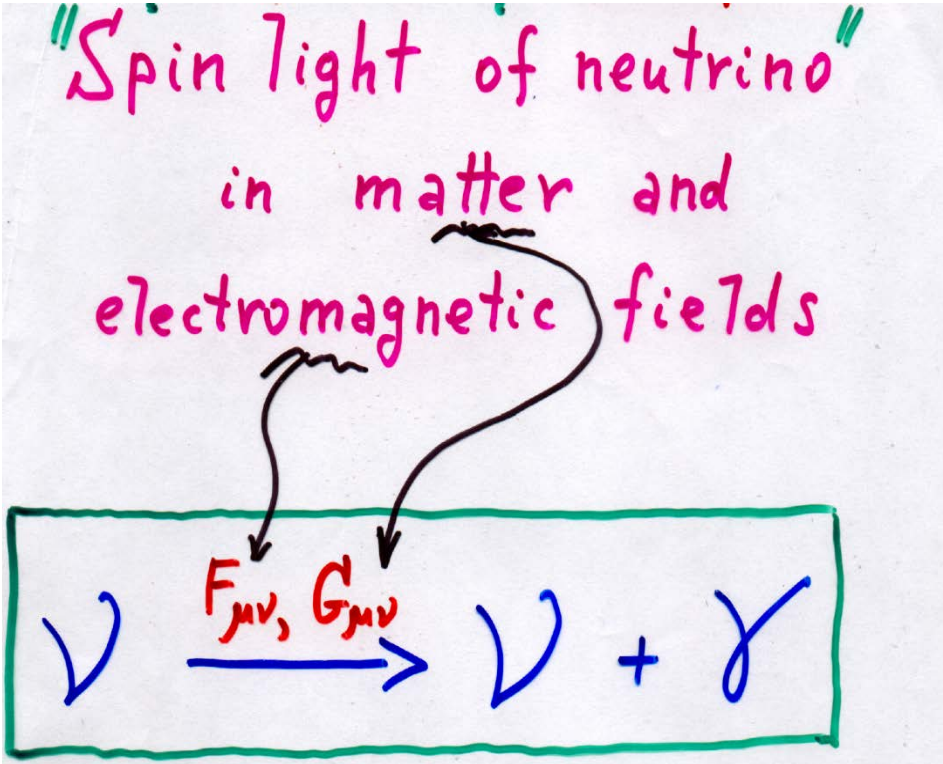
Halt, Raffelt, Weiss, PRL1994

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

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

• New mechanism of electromagnetic radiation

$SL\nu$



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

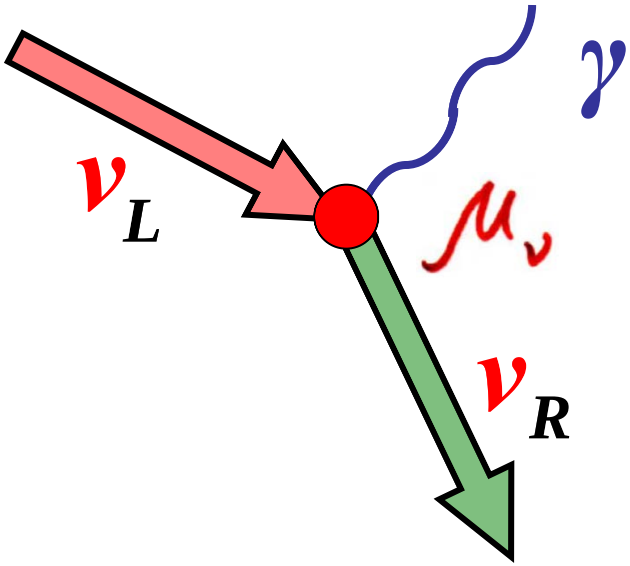
Studenikin, A.Ternov,
Phys.Lett. B 608 (2005) 107

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

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

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

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 …

ν in extreme environments

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

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

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

...«method of exact solutions»

- ν quantum states in dense magnetized matter

… new effect of …

Spin Light of ν in matter

$SL\nu$

⇒

ν energy quantization in rotating matter

… phenomenological consequences in astrophysics (pulsars)

ν in matter treated within
«method of exact solutions»
(Dirac equation with matter potential for ν)

ν energy quantization in rotating magnetized media

Grigoriev, Savochkin, Studenikin, Russ.Phys.J. 50 (2007) 845
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Studenikin, Tokarev, Nucl.Phys.B (2014)

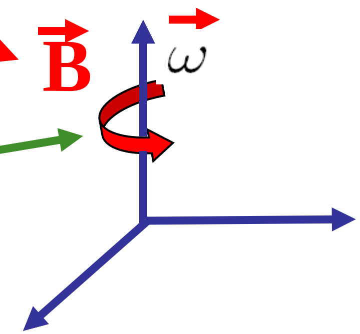
Millicharged ν in rotating magnetized matter

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

Modified Dirac equation for ν wave function

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

external magnetic field



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

matter potential *rotating matter*

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

rotation angular frequency

✓ energy is quantized in rotating matter

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

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

$N = 0, 1, 2, ...$ integer number

matter rotation frequency

scalar potential of electric field

✓ 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

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

Studenikin, J.Phys. A (2008)

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

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

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... we predict :

$E \sim 1\ eV$

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

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

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

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

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

. . . we predict :

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Nucl.Phys.B (2014)

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

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

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

Millicharged ν as star rotation engine

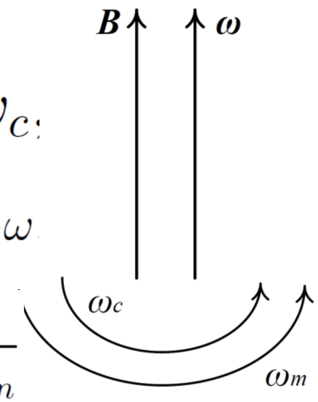
- Single ν generates feedback force with projection on rotation plane

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

$$\Omega = \omega_m + \omega_c,$$

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

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

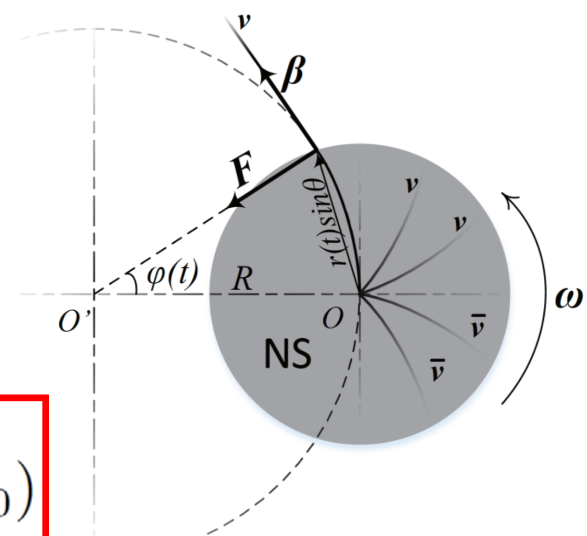


single ν torque

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

total N_ν torque

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



- Shift of star angular velocity

$$|\Delta\omega| = \frac{5N_\nu}{6M_S}(q_0 B + 2G n_n \omega_0)$$

$$\Delta\omega = \omega - \omega_0$$

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- ν Star Turning mechanism (νST)

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

- New astrophysical constraint on ν millicharge

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

- $|\Delta\omega| < \omega_0$!

...to avoid contradiction of νST impact with observational data on pulsars ...

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

... best astrophysical bound ...

Spin light of electron in dense neutrino fluxes

SLe_ν

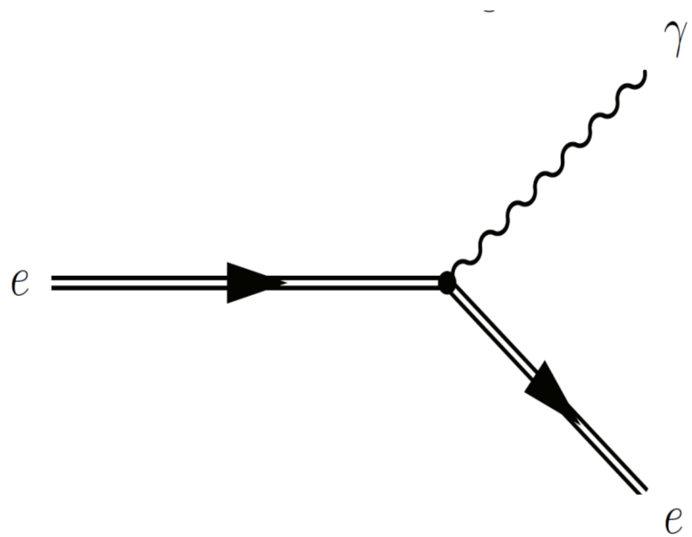
I.Balantsev,
A.Studenikin,
(2014)

Dirac eq for e in dense relativistic flux of ν

$$\left(\gamma_\mu p^\mu + \gamma_\mu \frac{c+\delta_e\gamma^5}{2} f^\mu - m\right)\Psi(x) = 0$$

$$c = \delta_e - 12\sin^2\theta_W$$

$$\delta_e = \frac{n_\mu + n_\tau - n_e}{n}$$

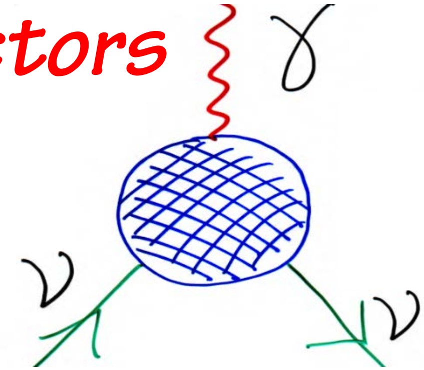


$$f^\mu = G(n,0,0,n)$$

background matter (ν flux) potential

Conclusion

ν e.m. vertex function → 4 form factors



charge dipole magnetic and electric

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

- **EM properties → a way to distinguish Dirac and Majorana ν**

- Standard Model with ν_R $(m_\nu \neq 0)$: $\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e} \sim 3 \cdot 10^{-19} \mu_B \left(\frac{m_{\nu_e}}{1eV}\right)$

- In extensions of SM → enhancement of ν magnetic moment, even electrically millicharged ν

- Limits from reactor ν-e scattering experiments (2012):

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

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

- Limits from astrophysics, star cooling (1990):

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

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