Electromagnetic properties of neutrinos

The 7th International Conference on Particle Physics and Astrophysics

Alexander Studenikin
Moscow State University
a-studenik@yandex.ru

National Research Nuclear University "MEPhI"
25/10/2024

Programme # 8 of
National Centre for Physics and Mathematics
"Physics of Hydrogen Isotopes"
Supported by Russian Science Foundation under grant No. 24-12-00084

Outline

① reminder of ν electromagnetic properties

② constraints on μ_ν, d_ν, q_ν and $<r^2_\nu>$ from laboratory experiments

③ effects of electromagnetic ν interactions in astrophysics

④ astrophysical probes of electromagnetic ν

⑤ new effects in ν oscillations related to electromagnetic ν interactions

… new phenomena in ν spin (flavor) oscillations in moving and polarized mater and magnetic field of interest for astrophysical applications …

⑥ conclusions – most recent constraints on ν emp

- SATURNE tritium neutrino experiment -

first observation of *coherent elastic neutrino-atom scattering* (CEνAS) and search for ν magnetic moment - talk by Konstantin Kouzakov:
"Status and Physics Potential of SATURNE"

ν exhibits unexpected properties (puzzles)

W. Pauli, 1930

- neutral "neutron" $\Longrightarrow$ ν E.Fermi, 1933
- • probably $\mu_\nu \neq 0$!?

Pauli himself wrote to Baade:

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

H. Bethe, R. Peierls,

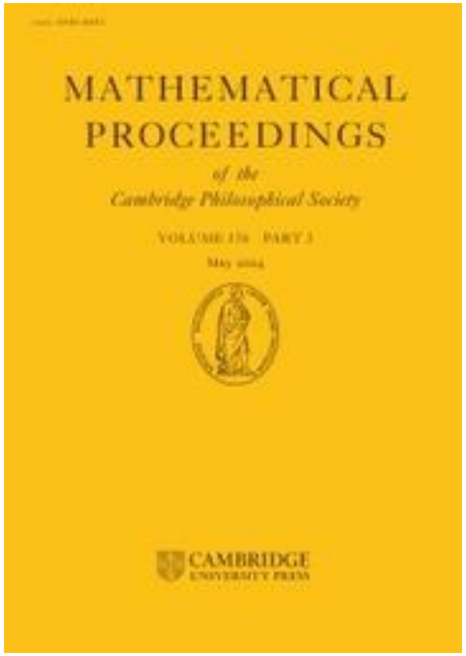
«The ‘neutrino’»

Nature 133 (1934) 532

- «There is no practically possible way of observing the neutrino» !

. . . puzzles . . .

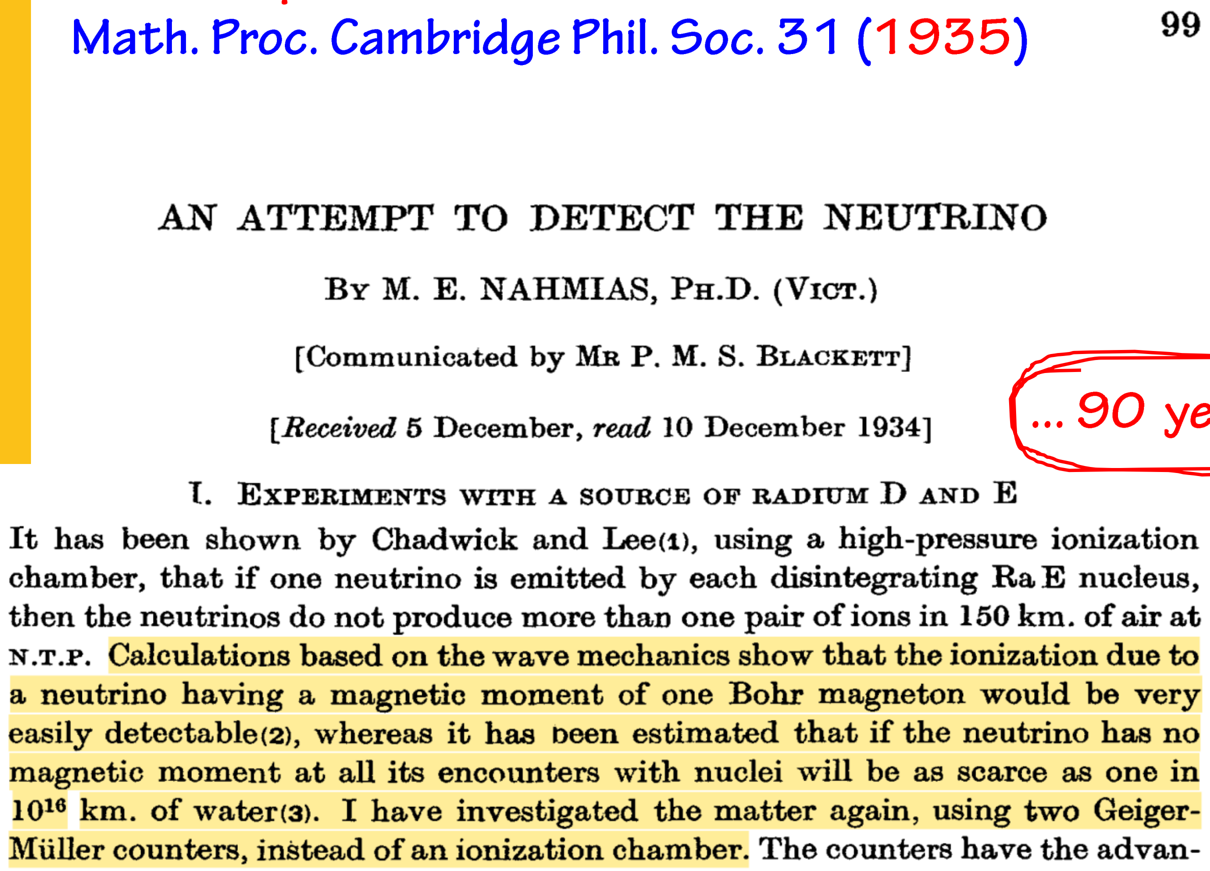
- . . . what about electromagnetic properties of ν ?


MATHEMATICAL PROCEEDINGS
of the
Cambridge Philosophical Society

CAMBRIDGE
UNIVERSITY PRESS

M.E. Nahmias,
An attempt to detect the neutrino,
Math. Proc. Cambridge Phil. Soc. 31 (1935)

... earlier years of ν ...


99

AN ATTEMPT TO DETECT THE NEUTRINO

By M. E. NAHMIAS, Ph.D. (Vict.)

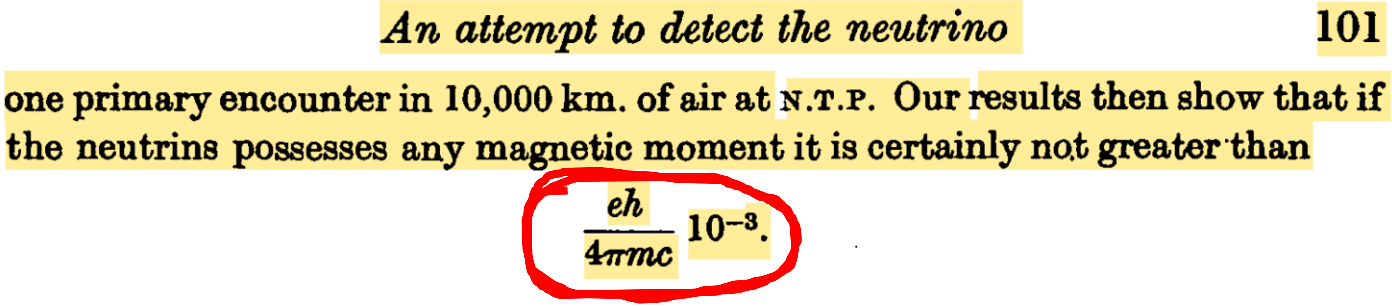
[Communicated by Mr P. M. S. Blackett]

[*Received* 5 December, *read* 10 December 1934]

... 90 years ago...

I. Experiments with a source of radium D and E

It has been shown by Chadwick and Lee(1), using a high-pressure ionization chamber, that if one neutrino is emitted by each disintegrating Ra E nucleus, then the neutrinos do not produce more than one pair of ions in 150 km. of air at N.T.P. Calculations based on the wave mechanics show that the ionization due to a neutrino having a magnetic moment of one Bohr magneton would be very easily detectable(2), whereas it has been estimated that if the neutrino has no magnetic moment at all its encounters with nuclei will be as scarce as one in 10^{16} km. of water(3). I have investigated the matter again, using two Geiger-Müller counters, instead of an ionization chamber. The counters have the advan-


An attempt to detect the neutrino 101

one primary encounter in 10,000 km. of air at N.T.P. Our results then show that if the neutrins possesses any magnetic moment it is certainly not greater than

$$\frac{eh}{4\pi mc}10^{-3}.$$

70 years ago ...

- C. L. Cowan, F. Reines and F. B. Harrison,
  Upper limit on the neutrino magnetic moment,
  Phys. Rev. 96 (1954) 1294

ν electromagnetic properties

and possibility of measuring μ_ν

raised before experimental discovery of ν

⇒

… problem and puzzle …

ν electromagnetic properties

up to now nothing has been seen

… in spite of reasonable efforts …

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

… However, in course of recent development of knowledge on ν mixing and oscillations,

… Why ν electromagnetic properties are important ?

…Why ν em properties

to new physics ?

●

… How does it all relate to ν oscillations ?

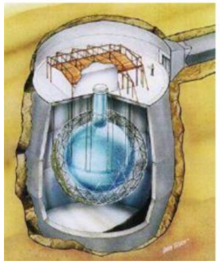
$\Longrightarrow$ $m_\nu \neq 0$ ●

magnetic moment $\mu_\nu \neq 0$ ●

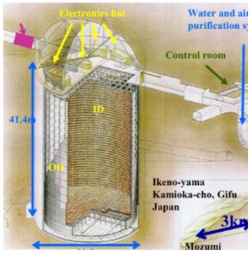
Arthur McDonald

The Nobel Prize in Physics 2015

Takaaki Kajita



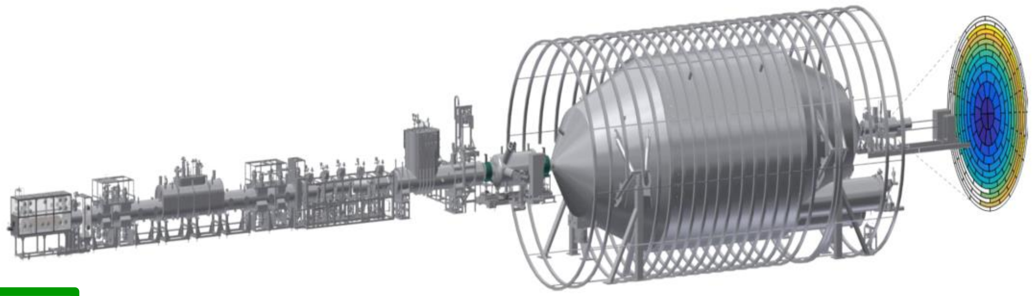
«for the discovery of neutrino oscillations, which shows that neutrinos have mass»



in Standard Model

● $m_\nu = 0$!!!

Karlsruhe Institute of Technology



$\boxed{m_\nu \leq 0.45\ eV}$ $\Longleftarrow$ new KATRIN limit arrive: 2406.13516, 19 Jun 2024

Direct neutrino-mass measurement based on 259 days of KATRIN data

-

XXXI International Conference on Neutrino Physics and Astrophysics

Milano (Italy) - June 16-22, 2024

Alexey Lokhov
on behalf of the
KATRIN collaboration

Karlsruhe Institute
of Technology,
Germany

- ... PhD 2013 at Department of Theoretical Physics, MSU

Meeting of the MSU ν group
Faculty of Physics, Moscow State University
January 2019

In the easiest generalization of SM

$$\boxed{\mu^D_{ii} = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19}\left(\frac{m_i}{1\ \mathrm{eV}}\right)\mu_B}$$

Fujikawa, Shrock,
Phys.Rev.Lett. 45
(1980) 963

if $\boxed{m_\nu \leq 0.45\ eV}$ ⇐ new KATRIN limit arXiv: 2406.13516, 19 Jun 2024

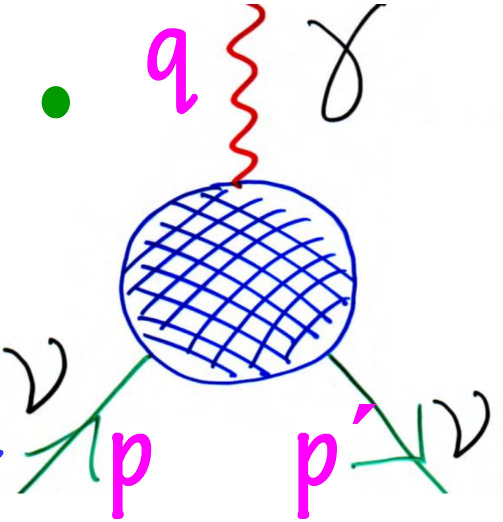
then $\boxed{\mu^D_{ii} \sim 1.8 \times 10^{-19}\ \mu_B}$!

many orders of magnitude smaller than present experimental limits:

- $\mu_\nu \sim 10^{-11}\mu_B$ reactor ν limits GEMMA 2012
- $\mu_\nu \sim 10^{-11} \div 10^{-12}\mu_B$ Astrophysical (ν_{solar}, ν_{SN}, DM) limits
  Borexino 2017 - XENONnT 2023, LUX-ZEPLIN 2023
- μ_ν is no less extravagant than possibility of $q_\nu \neq 0$
  - limitations imposed by general principles of any theory are very strict
  - $\boxed{q_\nu \leq 3 \times 10^{-21} e}$ from neutrality of hydrogen atom
- slightly weaker constraints are imposed by astrophysics $\boxed{q_\nu \leq 1.3 \times 10^{-19}\ e_0}$
  Studenikin, Tokarev, NPB, 2014

. . . a bit of ν electromagnetic properties theory . . .

ν electromagnetic vertex function



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

Matrix element of electromagnetic current is a Lorentz vector

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

- matrices $\hat{1}, \quad \gamma_5, \quad \gamma_\mu, \quad \gamma_5\gamma_\mu, \quad \sigma_{\mu\nu},$
- tensors $g_{\mu\nu}, \quad \epsilon_{\mu\nu\sigma\gamma}$
- vectors q_μ and l_μ

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

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

Matrix element of electromagnetic current between neutrino states

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

where vertex function generally contains 4 form factors

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

1. electric

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: $Imf_Q = Imf_M = Imf_A = 0$

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 ⟹ a way to distinguish Dirac and Majorana ν

In general case matrix element of $J_\mu^{\rm EM}$ can be considered between different initial $\psi_i(p)$ and final $\psi_j(p')$ states of different masses

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

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

… beyond ν SM…

and

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

! form factors are matrices in ν mass eigenstates space •

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

1) Hermiticity itself does not apply restrictions on form factors,

2) CP invariance + Hermiticity

$f_Q(q^2), \; f_M(q^2), \; f_E(q^2), \; f_A(q^2)$

are relatively real (no relative phases) .

… quite different EM properties …

1) CP invariance + hermiticity

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

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

… importance of μ_ν studies…

If diagonal $\mu_\nu \neq 0$

were confirmed

! then ν^{Dirac}

! … for ν^{Majorana}
non-diagonal = transitional
$\mu_\nu \neq 0$

… progress
in experimental
studies of μ_ν ⇒

. . . a bit more on ν electromagnetic properties theory

(em properties in gauge models)

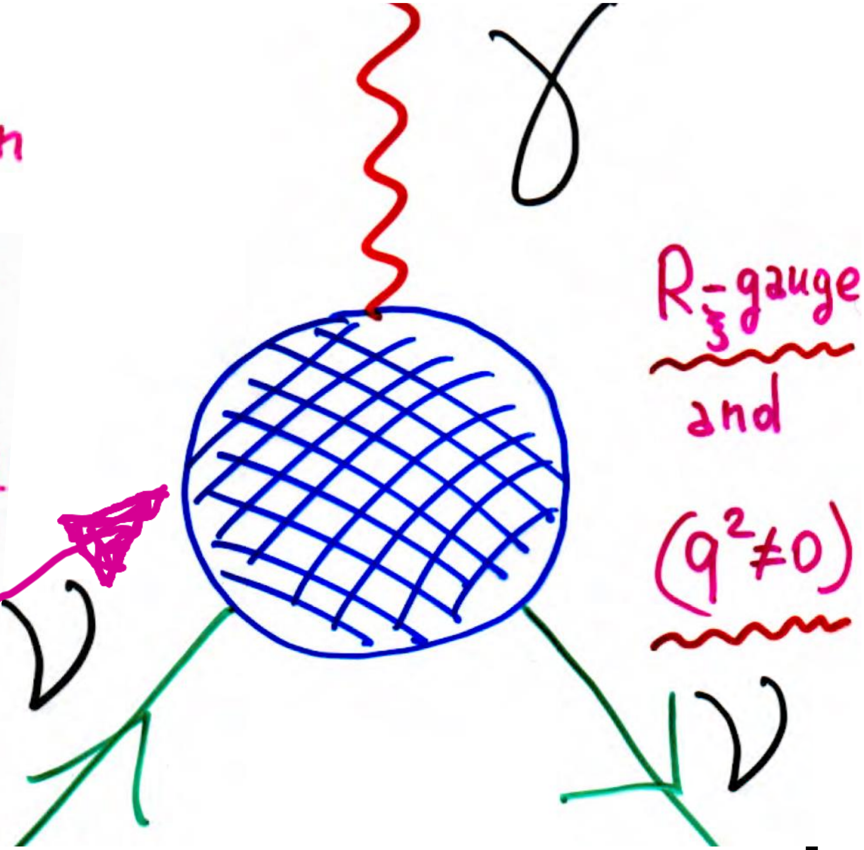
ν em vertex function

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

!

M. Dvornikov, A. Studenikin

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



R_ξ-gauge
and
$(q^2 \neq 0)$

$$\Delta_\mu(q) = \overset{\text{charge}}{f_Q(q^2)}\gamma_\mu + \overset{\text{magnetic moment}}{f_M(q^2)}\, i\sigma_{\mu\nu}q^\nu - \underset{\text{electric moment}}{f_E(q^2)}\, i\sigma_{\mu\nu}q^\nu\gamma_5 - \underset{\text{anapole moment}}{f_A(q^2)}(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

Direct calculations of complete set of one-loop contributions to ν vertex function in minimally extended SM

(for a massive Dirac neutrino)

M.Dvornikov, A.Studenikin
PRD, 2004

… in case CP conservation

- $\Lambda_\mu(q) \Longrightarrow f_Q(q^2),\ f_M(q^2),\ \cancel{f_E(q^2)},\ f_A(q^2)$

- Electric charge $f_Q(0) = 0$ and is gauge-independent

- Magnetic moment $f_M(0)$ finite and gauge-independent

- Gauge and q×q dependence … $\Longrightarrow$

Magnetic moment dependence

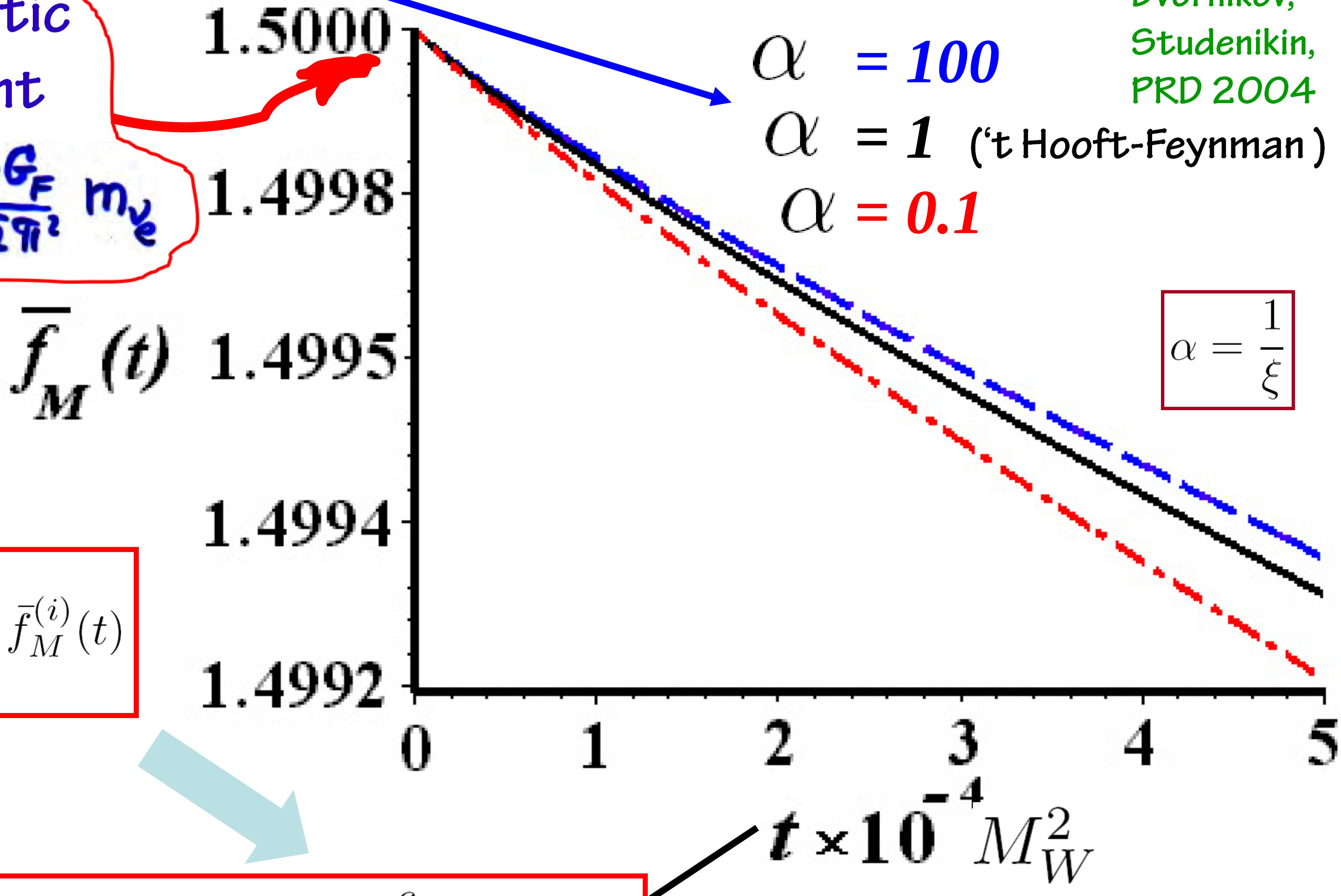
- $\mu_\nu = \mu_\nu(\underline{m_\nu})$?

on neutrino mass

Gauge and q×q dependence ...

ν magnetic moment

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



$\alpha = 100$

$\alpha = 1$ ('t Hooft-Feynman)

$\alpha = 0.1$

Dvornikov, Studenikin, PRD 2004

$$\alpha = \frac{1}{\xi}$$

$$\bar{f}_M(t) = \sum_{i=1}^{6} \bar{f}_M^{(i)}(t)$$

$$f_M(q^2) = \frac{eG_F}{4\pi^2\sqrt{2}} m_\nu \sum_{i=1}^{6} \bar{f}_M^{(i)}(q^2)$$

ν dipole magnetic form factor

=

● $m_\nu \ll m_e \ll M_W$ **light** ν

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

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

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

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

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

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

●

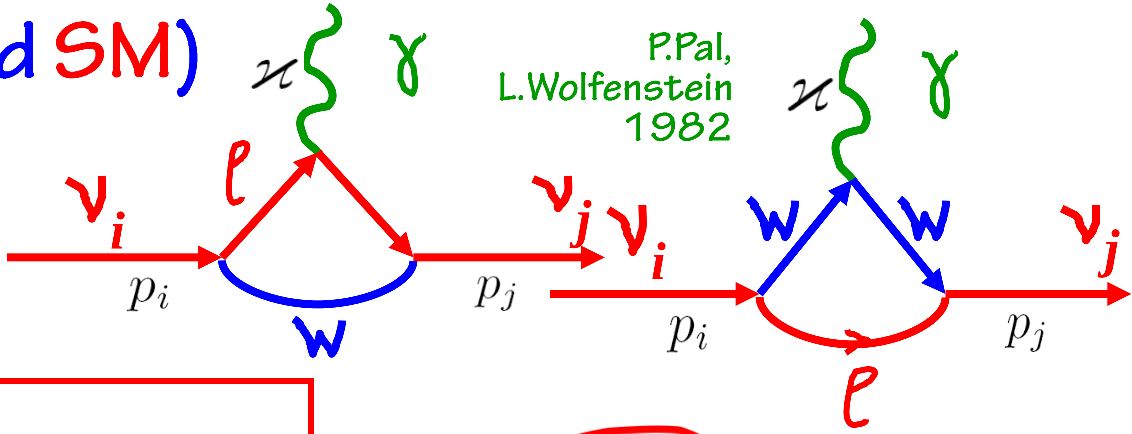
● $m_e \ll M_W \ll m_\nu$ **heavy** ν

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

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

... μ_ν **in case of mixing** ... $\Longrightarrow$

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



P.Pal,
L.Wolfenstein
1982

- **Dirac neutrino**

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

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

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

- $m_i, m_j \ll m_l, m_W$

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

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

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

!

- **Majorana neutrino**

only for $i \neq j$

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

or

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

… depending on relative CP phase of ν_i and ν_j

The first nonzero contribution from neutrino transition moments

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

GIM cancellation

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

!

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

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

… neutrino radiative decay is very slow

Dirac ν diagonal (i=j) magnetic moment

$$\epsilon^D_{ii} = 0$$ for CP-invariant interactions

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

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

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

- no GIM cancellation

Lee, Shrock, Fujikawa, 1977

- μ^D_{ii} - to leading order - independent on U_{li} and $m_{l=e,\ \mu,\ \tau}$

- $$\mu_e^2 = \sum_{i=1,2,3} \mid U_{ie}\mid^2 \mu^2_{ii}$$ …possibility to measure fundamental μ^D_{ii}

!

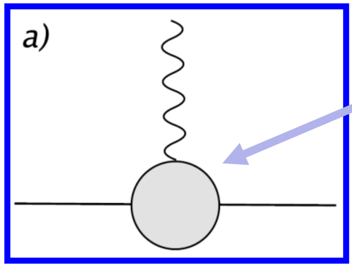
$\mu^D_{ii} = 0$ for massless ν (in the absence of right-handed charged currents)

3.3 Naïve relationship between m_ν and μ_ν

… problem to get large μ_ν and still acceptable m_ν

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

P. Vogel e.a., 2006

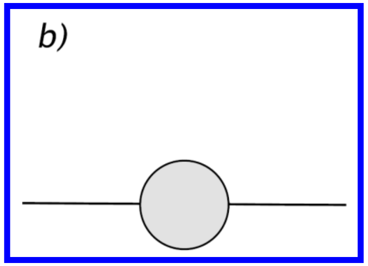


then

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

…combination of constants and loop factors…

contribution to m_ν given by



, then

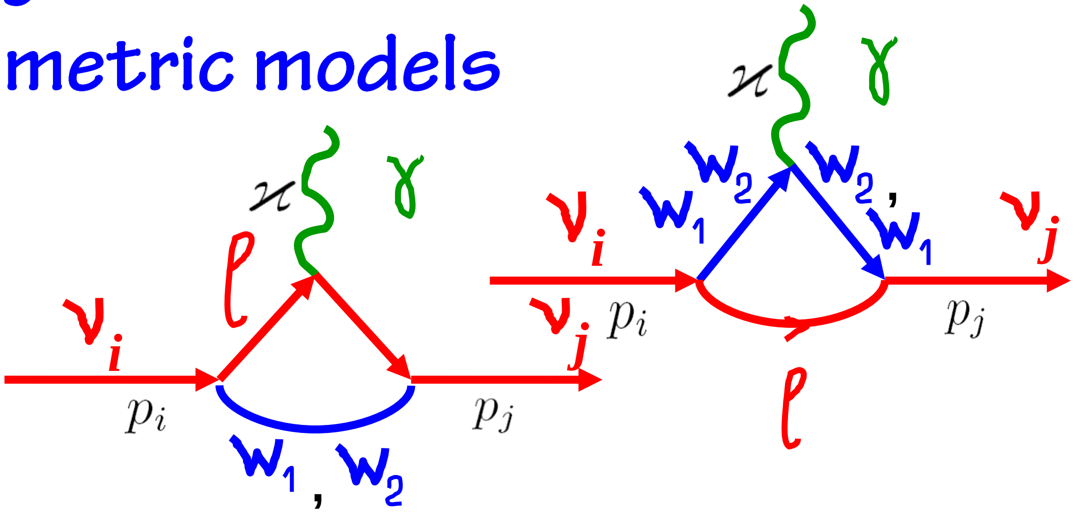
$$\boxed{m_\nu \sim G\Lambda}$$

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

Voloshin, 1988,
Barr, Freire,
Zee, 1990

3.6

Neutrino magnetic moment in left-right symmetric models



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

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

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

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

Kim, 1976; Marciano, Sanda, 1977

Beg, Marciano, Ruderman, 1978

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

… charged lepton mass … … neutrino mass …

Large magnetic moment $\mu_\nu = \mu_\nu(m_\nu, m_{B^+}, m_{e^-})$

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

Kim, 1976

Beg, Marciano, Ruderman, 1978

- Voloshin, 1988
  "On compatibility of small m_ν with large μ_ν of neutrino",
  Sov.J.Nucl.Phys. 48 (1988) 512

  … there may be $SU(2)_\nu$ symmetry that forbids m_ν but not μ_ν

- Bar, Freire, Zee, 1990
- supersymmetry
- extra dimensions

considerable enhancement of μ_ν to experimentally relevant range

K.Babu, Sidip Jana, M.Lindner,
"Large neutrino magnetic moments in the light of recent experiments"
JHEP 10 (2020) 040

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

- model-independent constraint μ_ν for BSM $(\Lambda \sim 1\ \mathrm{TeV})$ without fine tuning and under assumption $\boxed{\delta m_\nu \leq 1\ \mathrm{eV}}$

Bell, Cirigliano, Ramsey-Musolf, Vogel, Wise, 2005

!

$\boxed{\mu_\nu^D \leq 10^{-15}\mu_B}$ Dirac versus Majorana $\boxed{\mu_\nu^M \leq 10^{-14}\mu_B}$

!

… 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

- … General proof:

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

In SM : $\boxed{Q = I_3 + \frac{Y}{2}}$ …from Gell-Mann – Nishijima …

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 that is enough to fix all Y so that they, and consequently Q, are quantized

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

$\boxed{Q=0}$

Bardeen, Gastmans, Lautrup, 1972;
Cabral-Rosetti, Bernabeu, Vidal, Zepeda, 2000;
Beg, Marciano, Ruderman, 1978;
Marciano, Sirlin, 1980; Sakakibara, 1981;
● Dvornikov, Studenikin, 2004
(for SM in one-loop calculations)

- … Strict requirements for Q quantization may disappear in extensions of standard $SU(2)_L \times U(1)_Y$ EW model if ν_R with $Y \neq 0$ are included: in the absence of Y quantization electric charges Q gets dequantized ⇒ millicharged ν

●

ν charge radius and anapole moment

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

electric magnetic dipole electric anapole

- Although it is usually assumed that ν are electrically neutral (charge quant. Implies $Q \sim \frac{1}{3}e$), ν can be characterized by two ± charge distributions

$$\boxed{f_Q(q^2) = f_Q(0) + q^2 \frac{df_Q}{dq^2}(0) + \cdots,}$$ and $f_Q(q^2) \neq 0 \ for \ q^2 \neq 0$ even for electric charge $f_Q(0) = 0$

ν charge radius is introduced as $$\boxed{\langle r_\nu^2 \rangle = +6\, \frac{df_Q}{dq^2}(0)}$$

- … it is often claimed for SM massless ν anapole moment

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

…to be correct

Giunti, Studenikin Rev.Mod.Phys.2015

- for two-component massless left-handed Weyl spinors of SM

$$\boxed{\Lambda^{Q,A}_{\mathrm{SM}\mu}(q) = (\gamma_\mu q^2 - q_\mu \not{q})\, \mathfrak{f}^{\mathrm{SM}}(q^2)}$$

$$\boxed{\mathfrak{f}^{\mathrm{SM}}(q^2) = \tilde{\mathfrak{f}}_Q(q^2) - \mathfrak{f}_A(q^2) \xrightarrow[q^2\to 0]{} \frac{\langle r^2 \rangle}{6} - \mathfrak{a}}$$

- … in SM charge radius and anapole moment are not defined separately …

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 ν with m=0, $\langle r_\nu^2 \rangle$ and a_ν can be defined (finite and gauge independent) from scattering cross section.

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

? ? ? For massive ν ? ? ?

Carlo Giunti, A.S. arXiv:0812.3646

The definition of the neutrino charge radius follows an analogy with the elastic electron scattering off a static spherically symmetric charged distribution of density $\rho(r)$ $(r = |\mathbf{x}|)$, for which the differential cross section is determined [79–81] by the point particle cross section $\frac{d\sigma}{d\Omega}|_{point}$,

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{|point} |f(q^2)|^2, \tag{90}$$

where the correspondent form factor $f(q^2)$ in the so-called *Breit frame*, in which $q_0 = 0$, can be expressed as

$$f(q^2) = \int \rho(r) e^{i\mathbf{qx}} d^3x = 4\pi \int dr r^2 \rho(r) \frac{\sin(qr)}{qr}, \tag{91}$$

here $q = |\mathbf{q}|$. Thus, one has

$$\frac{df_Q}{dq^2} = \int \rho(r) \frac{qr\cos(qr) - \sin(qr)}{2q^{3/2}r} d^3x. \tag{92}$$

In the case of small q, we have $\lim_{q^2 \to 0} \frac{qr\cos(qr) - \sin(qr)}{2q^{3/2}r} = -\frac{r^2}{6}$ and

$$f(q^2) = 1 - |\mathbf{q}|^2 \frac{\langle r^2 \rangle}{6} + \ \dots \ . \tag{93}$$

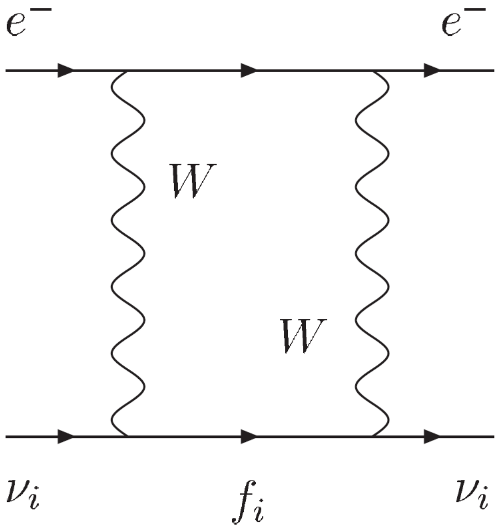
Therefore, the neutrino charge radius (in fact, it is the charge radius squared) is usually defined by

$$\boxed{\langle r_\nu^2 \rangle = -6 \frac{df_Q(q^2)}{dq^2}|_{q^2=0}.} \tag{94}$$

Since the neutrino charge density is not a positively defined quantity, $\langle r_\nu^2 \rangle$ can be negative.

To obtain ν electroweak radius as physical (finite, not divergent) quantity

Bernabeu,
Papavassiliou,
Vidal, 2004



Contribution of box diagram to

$$\nu_l + l' \to \nu_l + l'.$$

$$\boxed{\langle r^2_{\nu_i}\rangle = \frac{G_F}{4\sqrt{2}\pi^2}\left[3 - 2\log\left(\frac{m_i^2}{m_W^2}\right)\right]} \qquad i = e, \mu, \tau$$

$$\boxed{\langle r^2_{\nu_e}\rangle = 4\times 10^{-33}\,\mathrm{cm}^2}$$

…contribution to ν-e scattering experiments through (not the whole story, off-diagonal charge radius)

$$\boxed{g_V \to \frac{1}{2} + 2\sin^2\theta_W + \frac{2}{3}m_W^2\langle r^2_{\nu_e}\rangle\sin^2\theta_W}$$

- … theoretical predictions and present experimental limits are in agreement within one order of magnitude… !

- **Experimental constraints**

(from studies of terrestrial and astrophysical ν fluxes)

on μ_ν , q_ν and $< r^2_\nu >$

magnetic moment millicharge charge radius

Particle Data Group
Review of Particle Physics 2022, update 2023
and 2024

R.L.Workman et al. (Particle Data Group Collaboration),
Progress of Theoretical and Experimental Physics,
vol. 2022, no. 8, 083C01

S. Navas et al. (Particle Data Group Collaboration)
Phys. Rev. D 110 (2024) 030001

ν magnetic moment

- … most easily accepted are
  dipole magnetic and electric moments

  however most accessible for experimental studies are charge radii $< r^2_\nu >$

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

Cross-section:

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

!

where the Standard Model contribution

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

T is the electron recoil energy and

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

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

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

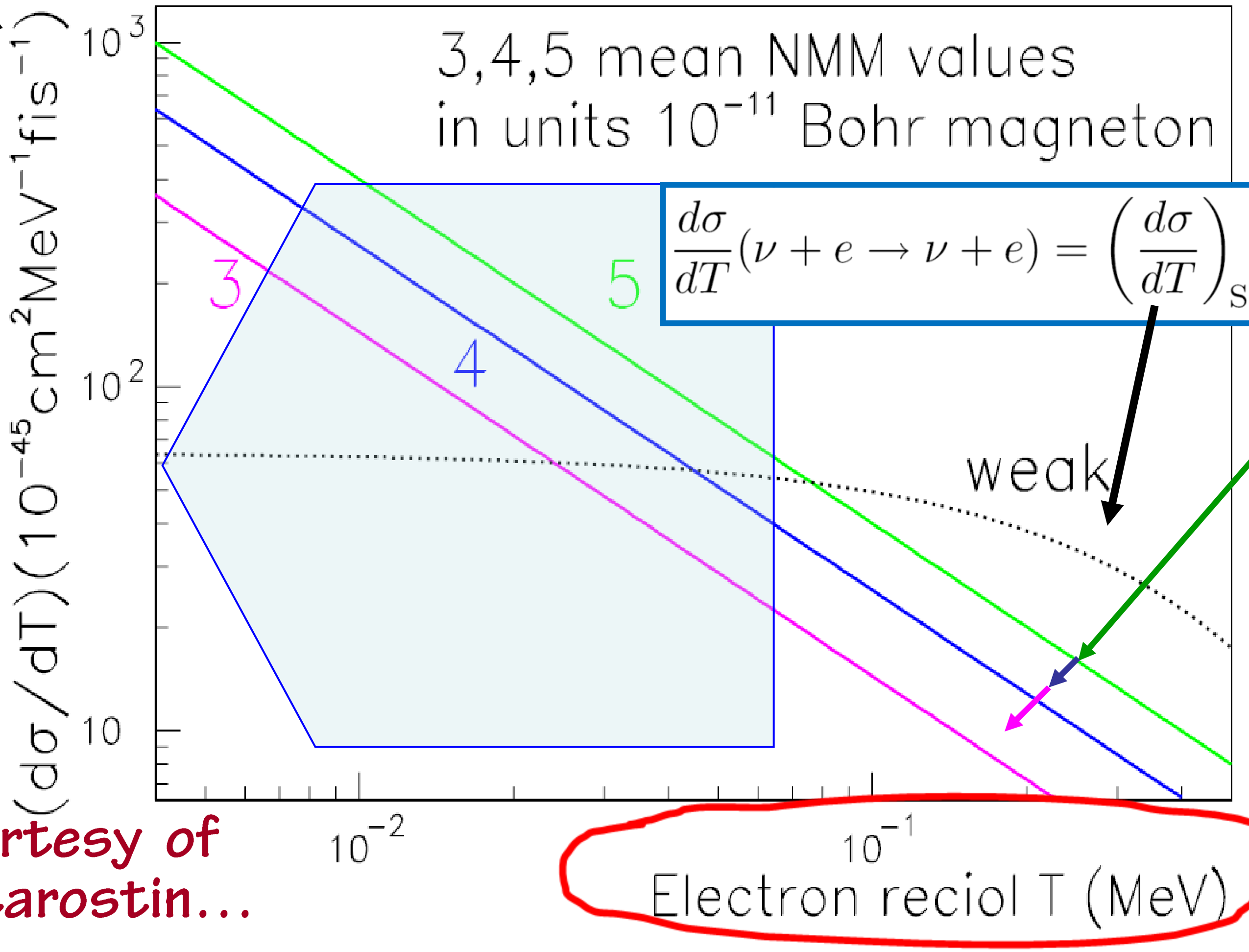
$$g_V = \begin{cases} 2\sin^2\theta_W + \frac{1}{2} & \text{for } \nu_e\,, \\ 2\sin^2\theta_W - \frac{1}{2} & \text{for } \nu_\mu, \nu_\tau\,, \end{cases} \qquad g_A = \begin{cases} \frac{1}{2} & \text{for } \nu_e\,, \\ -\frac{1}{2} & \text{for } \nu_\mu, \nu_\tau \end{cases}$$

for anti-neutrinos $g_A \rightarrow -g_A$

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

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

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



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

… courtesy of
A.Starostin…

Калининской атомной станции

(Удомля, Тверская область)

-

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

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

! World best experimental (reactor) limit

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

June 2012 ●

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

… quite realistic prospects for future …

● GEMMA-2 / νGeN experiment

… searching for μ_ν and CEνNS unprecedentedly low threshold $\boxed{T \sim 200 \quad eV}$

$$\boxed{\mu_\nu \sim (5-9) \times 10^{-12} \mu_B}$$

2024 + to appear soon ?

● first results on CEνNS : I.Alekseev etal., Phys.Rev.D 106 (2022) 5, L051101

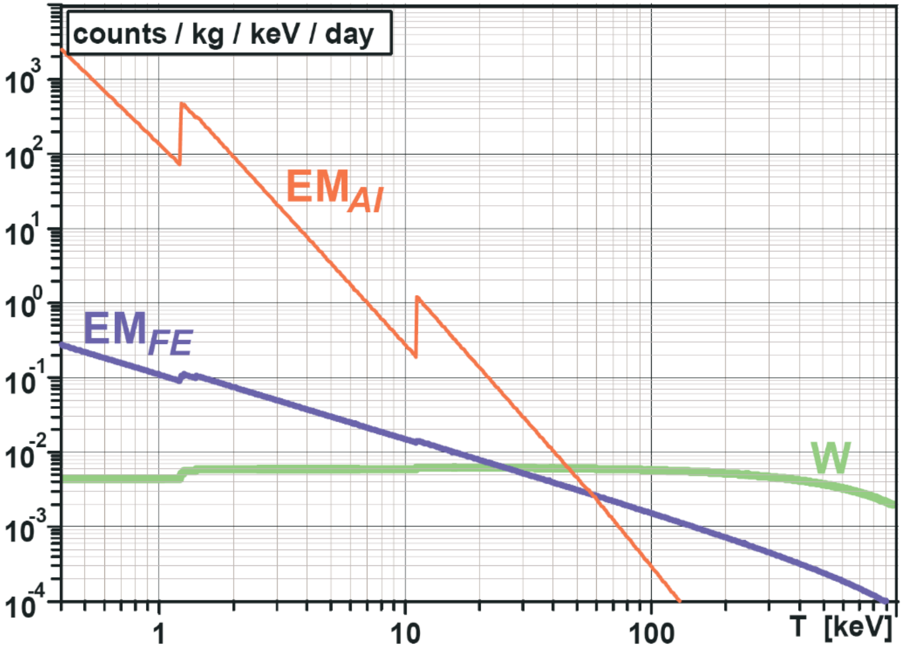
coherent elastic neutrino–nucleus scattering

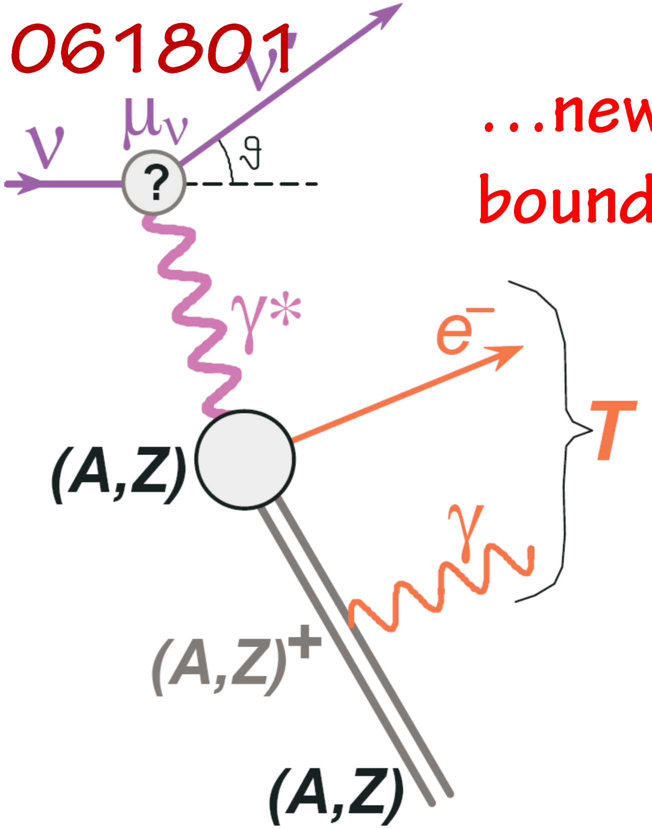
… claim that
ν-e cross section
should be increased by
Atomic Ionization effect:

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

?

H.Wong et al. (TEXONO Coll.),
arXiv: 1001.2074,
13 Jan 2010,
reported at
Neutrino 2010 Conference
(Athens, June 2010),
PRL 105 (2010)
061801





…new ⟹
bounds …

…much better limits on ν effective magnetic moment …

H.Wong et al.,
(TEXONO Coll.),
arXiv: 1001.2074
13 Jan 2010,

PRL 105 (2010)
061801

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

… atomic ionization effect accounted for …

Neutrino 2010 Conference,
Athens

… however …

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

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

… atomic ionization effect accounted for …

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

… ν-e scattering on free electrons …
(without atomic ionization)

K.Kouzakov, A.Studenikin

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

K.Kouzakov, A.Studenikin, M.Voloshin

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

M.Voloshin

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

–

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

K. Kouzakov, A. Studenikin,
"Theory of neutrino-atom collisions:
the history, present status, and BSM physics",

in: Special issue
"Through Neutrino Eyes: The Search for New Physics",
Adv. in High Energy Phys. 2014 (2014) 569409 (37pp)

editors: J. Bernabeu, G. Fogli, A. McDonald, K. Nishikawa

Mitglied der Helmholtz-Gemeinschaft

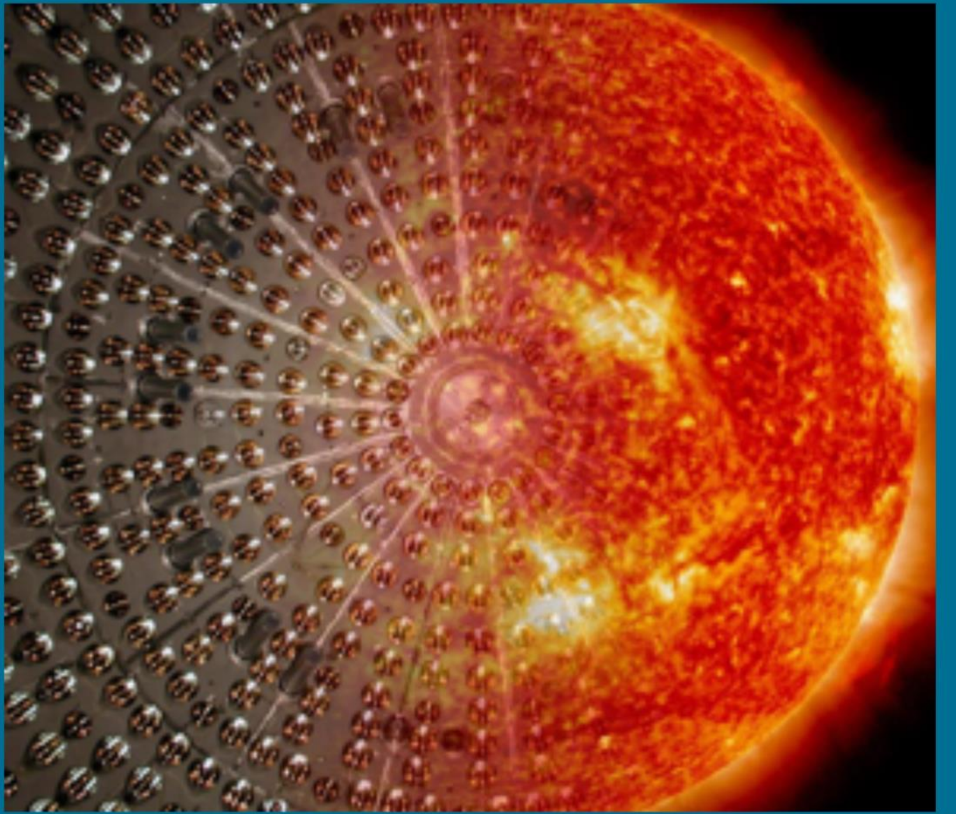
TAUP 2017
Topics in Astroparticle
and Underground Physics

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

NEW

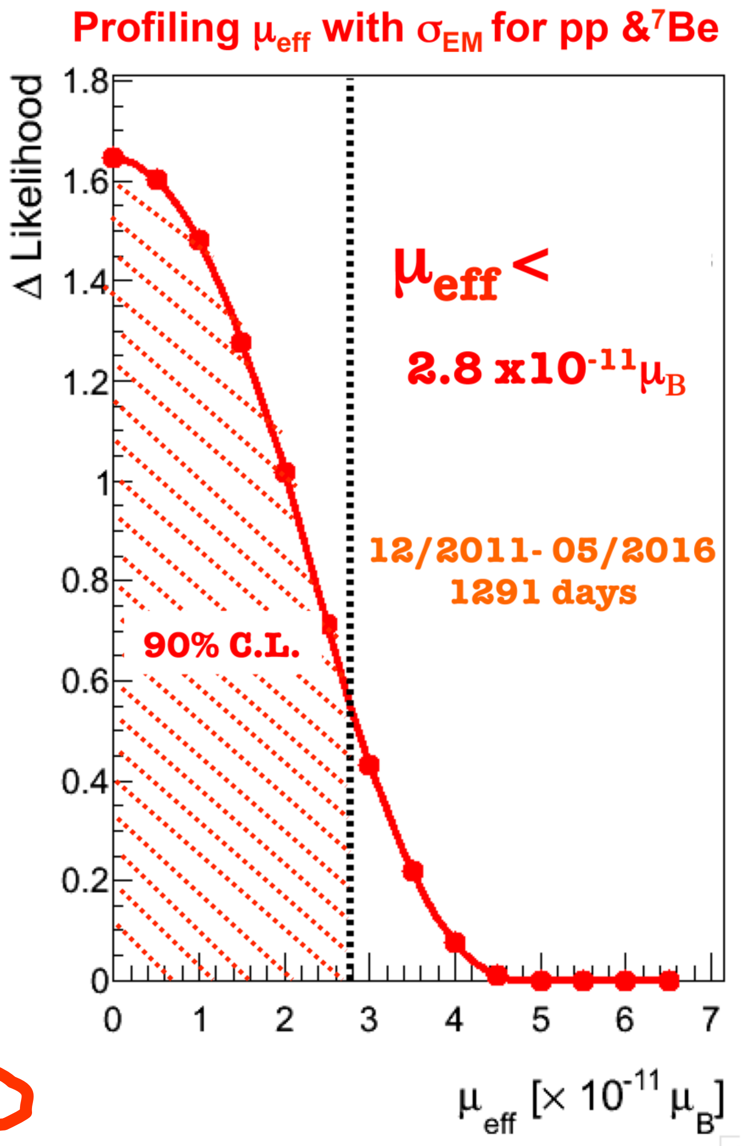
BOREXINO Collaboration (2017)
NMM results from Phase 2

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.)

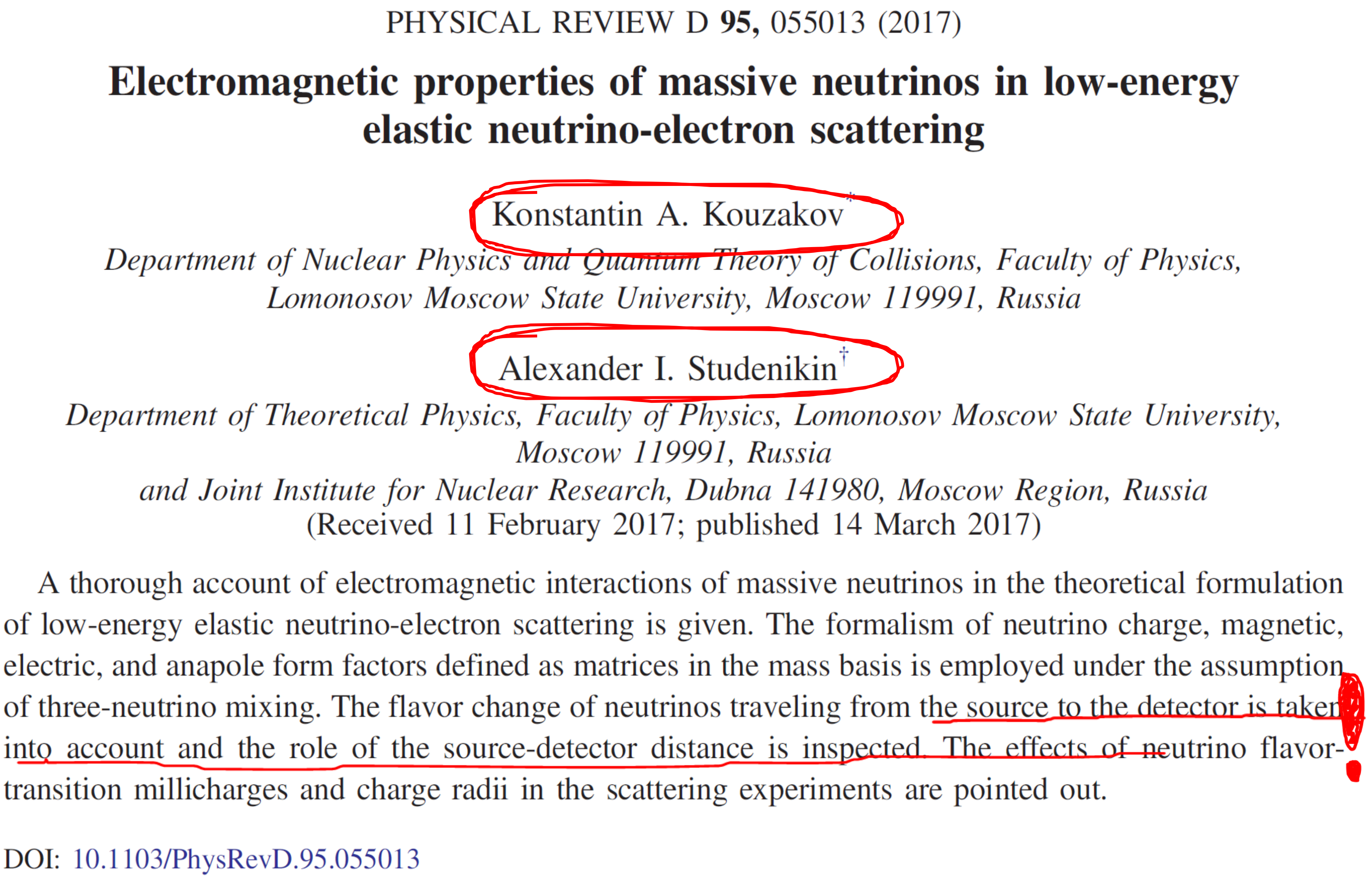
With radiochemical constraint
$\mu_{eff} < 2.6 \times 10^{-11} \mu_B$ (90% C.L.)
adding systematics
$\mu_{eff} < 2.8 \times 10^{-11} \mu_B$ (90% C.L.)



$\mu_{eff} <$ $2.8 \times 10^{-11} \mu_B$

12/2011- 05/2016
1291 days

… comprehensive analysis of ν-e scattering with account for ν mixing and oscillations …



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

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

Konstantin A. Kouzakov*
Department of Nuclear Physics and Quantum Theory of Collisions, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia

Alexander I. Studenikin†
Department of Theoretical Physics, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
and Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia

(Received 11 February 2017; published 14 March 2017)

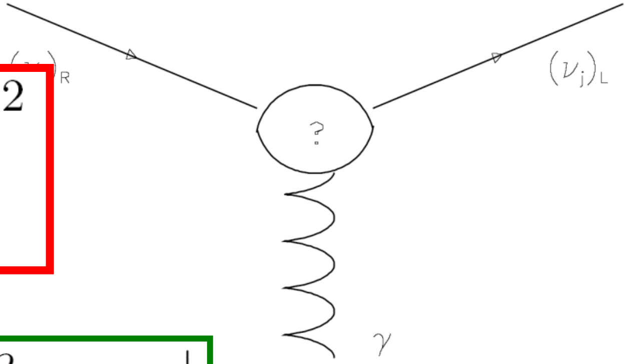
A thorough account of electromagnetic interactions of massive neutrinos in the theoretical formulation of low-energy elastic neutrino-electron scattering is given. The formalism of neutrino charge, magnetic, electric, and anapole form factors defined as matrices in the mass basis is employed under the 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

Effective ν magnetic moment in experiments

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



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

where **neutrino mixing matrix**

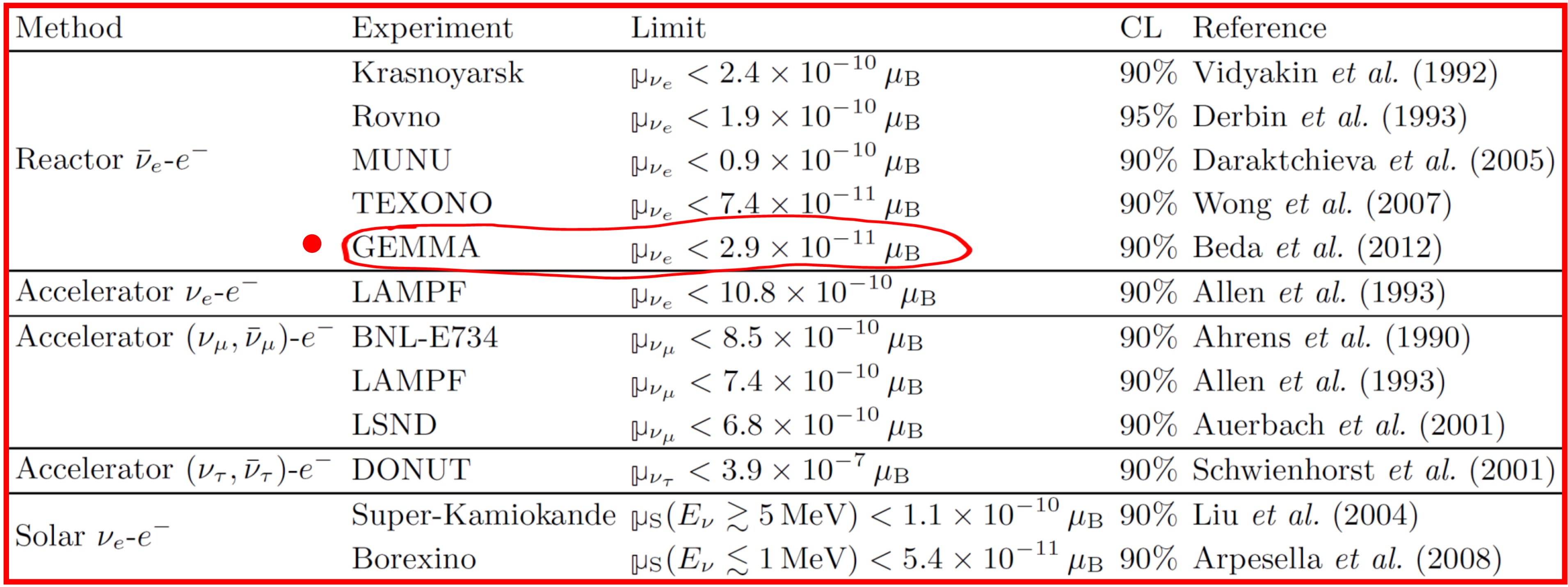
$$\mu_{ij} \equiv |\beta_{ij} - \varepsilon_{ij}|$$

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.

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, 2014-2022 and 2024

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

②

two not seen contributions:

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

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

ν-e cross-section

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

Bounds on q_ν from … unobserved effects of New Physics

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

!

Studenikin, Europhys. Lett. 107 (2014) 210011

Particle Data Group, 2016-2024

Expected new constraints from GEMMA:

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

!

2023+ few years data taking

νGeN experiment

$\mu_\nu \sim (5-9) \times 10^{-12} \mu_B$

… low threshold …

$T \sim 200\ \ eV$

Constraints on q_ν

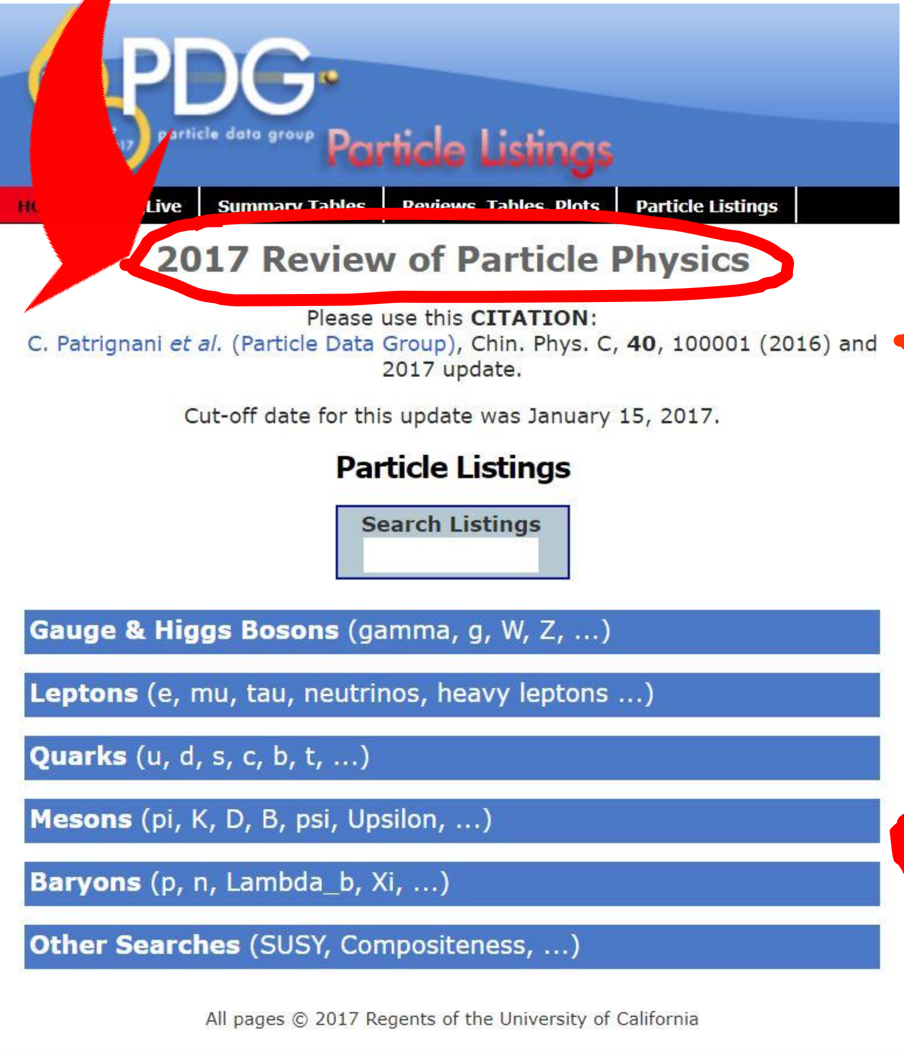
!

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

in ν Table of Particle Data Group since 2016

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

Particle Data Group collaboration 2016-2024



2017 Review of Particle Physics

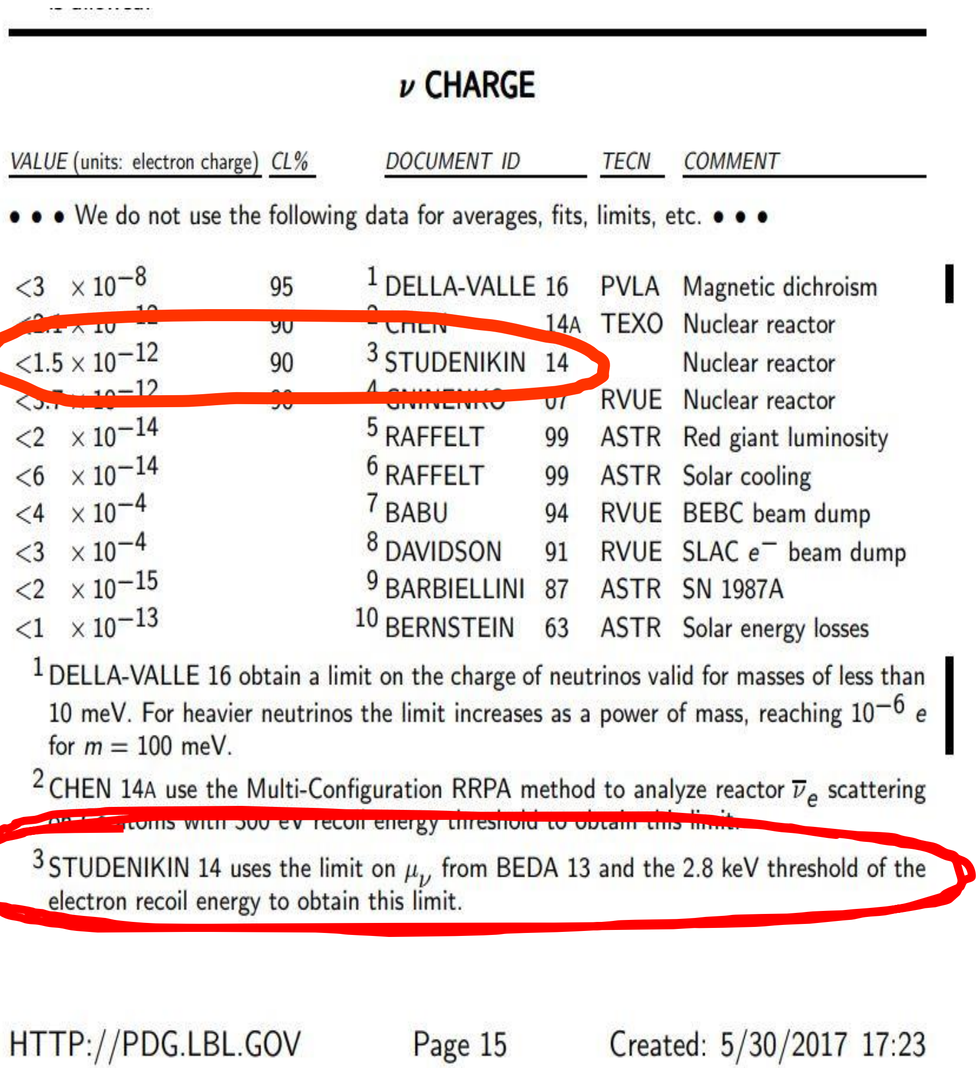
Please use this **CITATION**:
C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update.

Cut-off date for this update was January 15, 2017.

Particle Listings

- **Gauge & Higgs Bosons** (gamma, g, W, Z, ...)
- **Leptons** (e, mu, tau, neutrinos, heavy leptons ...)
- **Quarks** (u, d, s, c, b, t, ...)
- **Mesons** (pi, K, D, B, psi, Upsilon, ...)
- **Baryons** (p, n, Lambda_b, Xi, ...)
- **Other Searches** (SUSY, Compositeness, ...)

All pages © 2017 Regents of the University of California



ν CHARGE

VALUE (units: electron charge)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3 \times 10^{-8}$	95	[1] DELLA-VALLE	16	PVLA	Magnetic dichroism
$<2.1 \times 10^{-12}$	90	[2] CHEN	14A	TEXO	Nuclear reactor
$<1.5 \times 10^{-12}$	90	[3] STUDENIKIN	14		Nuclear reactor
$<3.7 \times 10^{-12}$	90	[4] GNINENKO	07	RVUE	Nuclear reactor
$<2 \times 10^{-14}$		[5] RAFFELT	99	ASTR	Red giant luminosity
$<6 \times 10^{-14}$		[6] RAFFELT	99	ASTR	Solar cooling
$<4 \times 10^{-4}$		[7] BABU	94	RVUE	BEBC beam dump
$<3 \times 10^{-4}$		[8] DAVIDSON	91	RVUE	SLAC e^- beam dump
$<2 \times 10^{-15}$		[9] BARBIELLINI	87	ASTR	SN 1987A
$<1 \times 10^{-13}$		[10] BERNSTEIN	63	ASTR	Solar energy losses

[1] DELLA-VALLE 16 obtain a limit on the charge of neutrinos valid for masses of less than 10 meV. For heavier neutrinos the limit increases as a power of mass, reaching 10^{-6} e for m = 100 meV.

[2] CHEN 14A use the Multi-Configuration RRPA method to analyze reactor $\overline{\nu}_e$ scattering on atoms with 300 eV recoil energy threshold to obtain this limit.

[3] STUDENIKIN 14 uses the limit on μ_ν from BEDA 13 and the 2.8 keV threshold of the electron recoil energy to obtain this limit.

HTTP://PDG.LBL.GOV Page 15 Created: 5/30/2017 17:23

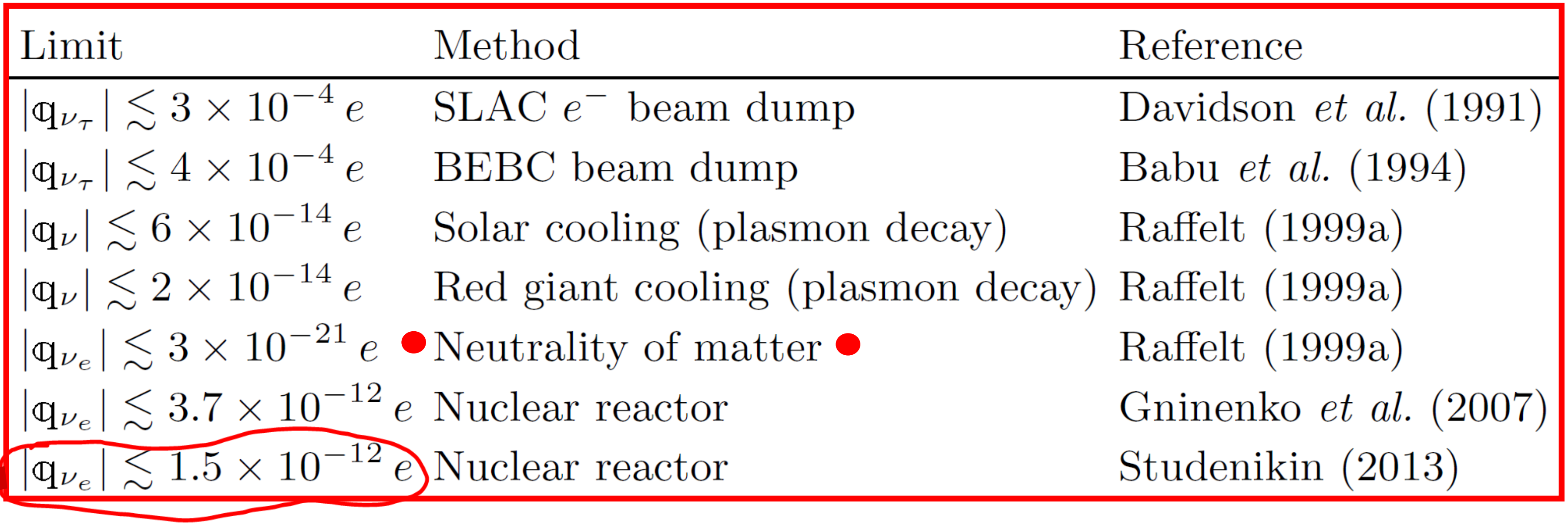
- Studenikin, New bounds on neutrino electric millicharge from limits on neutrino magnetic moment, Europhysics Letters 107 (2014) 21001

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

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

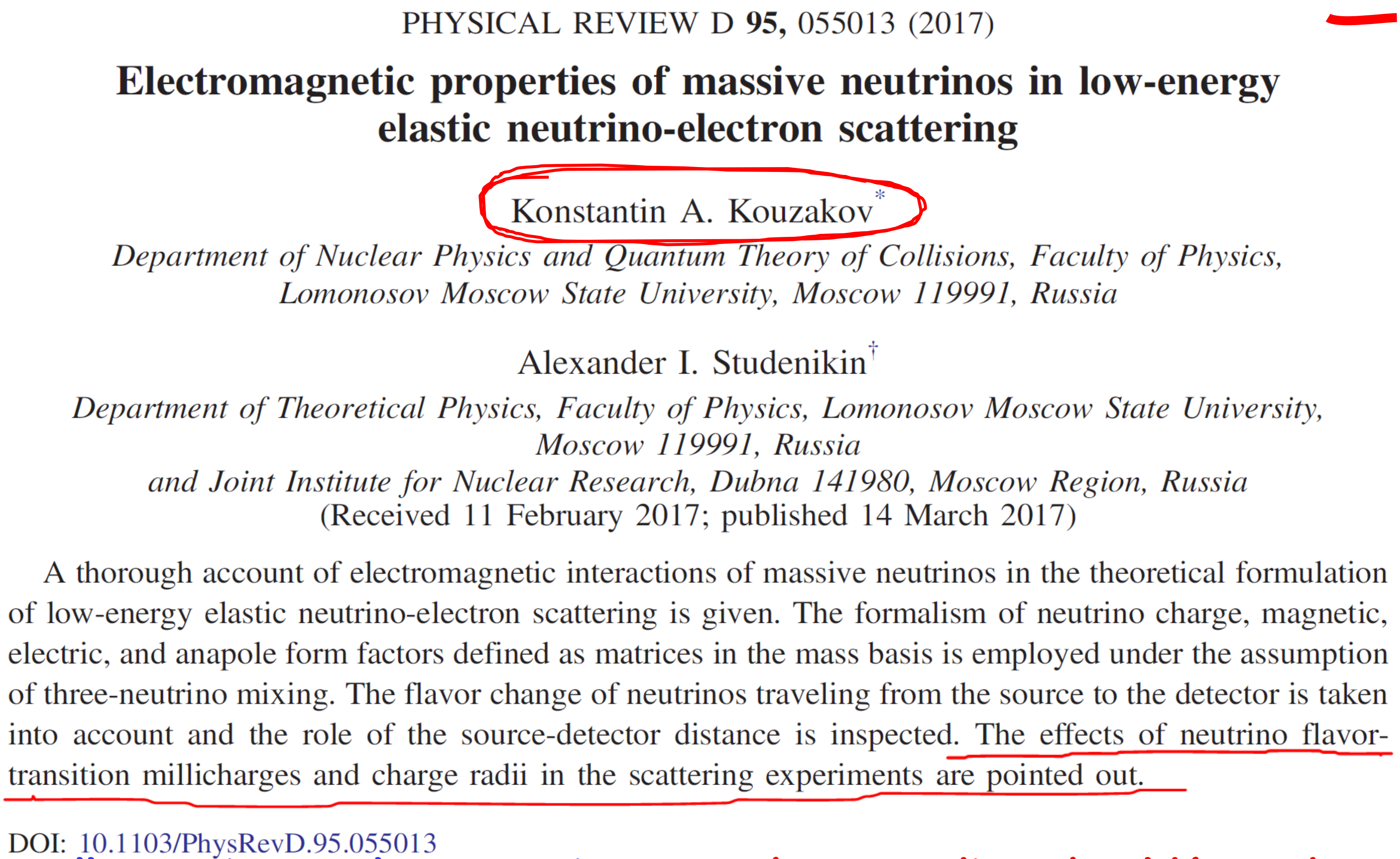
ν charge radii

… most accessible for experimental studies are charge radii $< r_\nu^2 >$

Bernabeu, Papavassiliou, Vidal, 2004

… astrophysical bounds ???

… comprehensive analysis of ν-e scattering …



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

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

Konstantin A. Kouzakov[*]

Department of Nuclear Physics and Quantum Theory of Collisions, Faculty of Physics,
Lomonosov Moscow State University, Moscow 119991, Russia

Alexander I. Studenikin[†]

Department of Theoretical Physics, Faculty of Physics, Lomonosov Moscow State University,
Moscow 119991, Russia
and Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia

(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

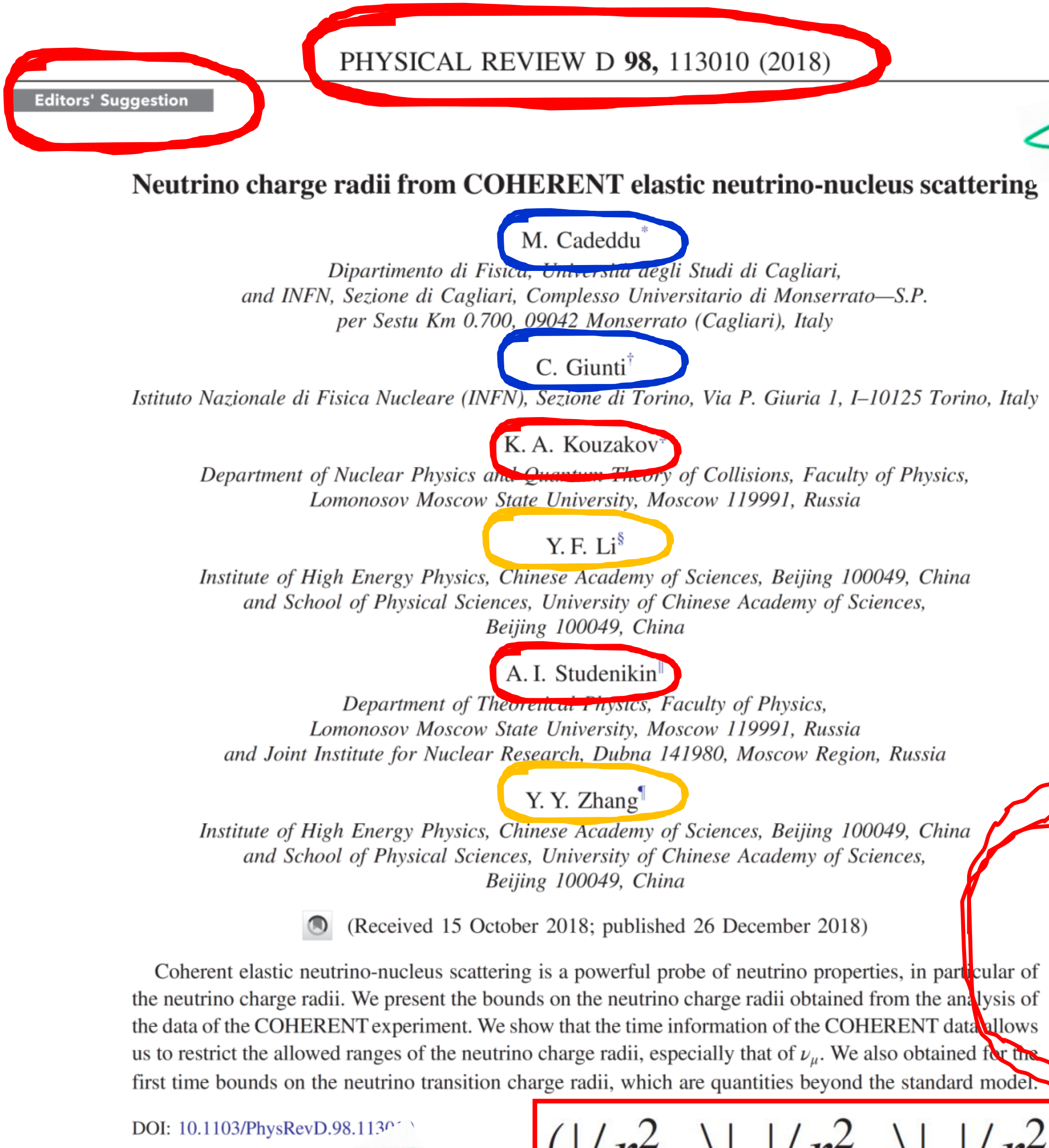
Concluding remarks

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

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

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



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

Editors' Suggestion

Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering

M. Cadeddu[*]
Dipartimento di Fisica, Università degli Studi di Cagliari,
and INFN, Sezione di Cagliari, Complesso Universitario di Monserrato—S.P.
per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy

C. Giunti[†]
Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Via P. Giuria 1, I–10125 Torino, Italy

K. A. Kouzakov[‡]
Department of Nuclear Physics and Quantum Theory of Collisions, Faculty of Physics,
Lomonosov Moscow State University, Moscow 119991, Russia

Y. F. Li[§]
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
and School of Physical Sciences, University of Chinese Academy of Sciences,
Beijing 100049, China

A. I. Studenikin[∥]
Department of Theoretical Physics, Faculty of Physics,
Lomonosov Moscow State University, Moscow 119991, Russia
and Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia

Y. Y. Zhang[¶]
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
and School of Physical Sciences, University of Chinese Academy of Sciences,
Beijing 100049, China

(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

Ch – It – Ru collaboration

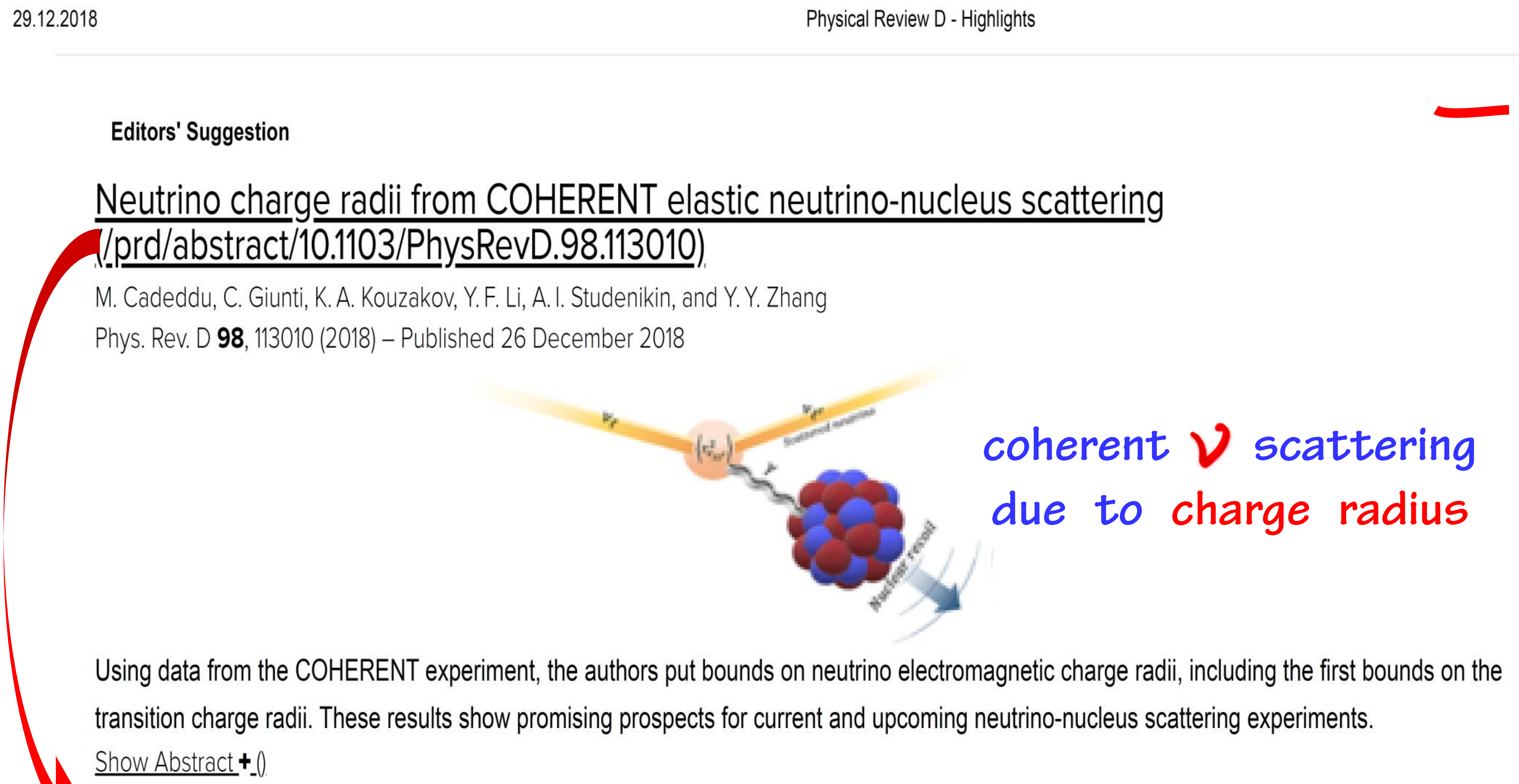
Physical Review D – Highlights 2018 – Editors' Suggestion

"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"

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

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



29.12.2018 Physical Review D - Highlights

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

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.

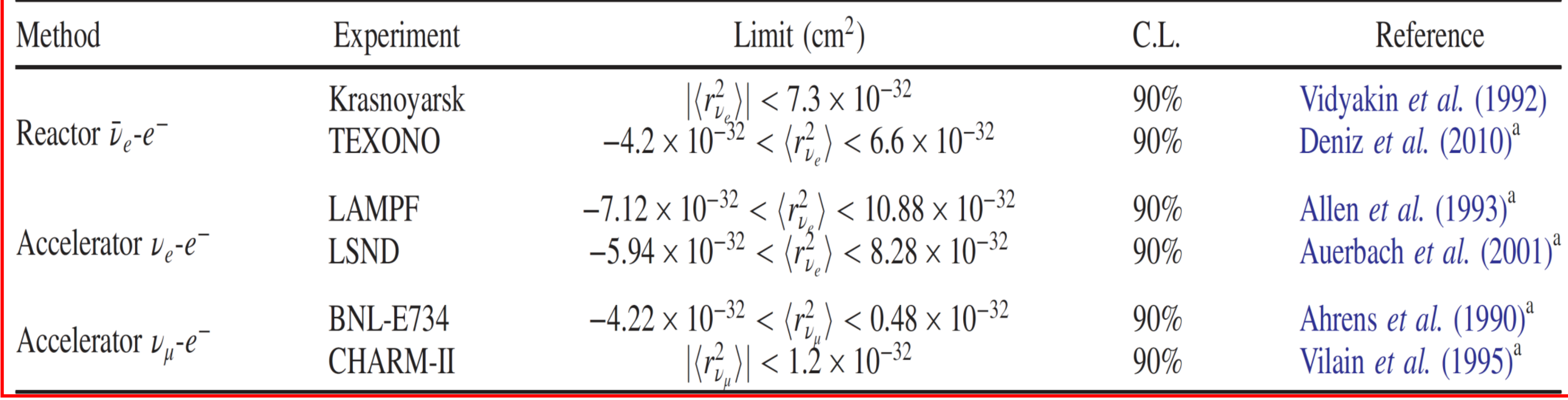
Show Abstract + ()

coherent ν scattering
due to charge radius

Particle Data Group,
Review of Particle Physics (2018-2024)

Experimental limits on ν charge radius $< r_\nu^2 >$

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	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3\times10^{-32}$	90%	Vidyakin *et al.* (1992)
	TEXONO	$-4.2\times10^{-32} < \langle r^2_{\nu_e}\rangle < 6.6\times10^{-32}$	90%	Deniz *et al.* (2010)[a]
Accelerator ν_e-e^-	LAMPF	$-7.12\times10^{-32} < \langle r^2_{\nu_e}\rangle < 10.88\times10^{-32}$	90%	Allen *et al.* (1993)[a]
	LSND	$-5.94\times10^{-32} < \langle r^2_{\nu_e}\rangle < 8.28\times10^{-32}$	90%	Auerbach *et al.* (2001)[a]
Accelerator ν_μ-e^-	BNL-E734	$-4.22\times10^{-32} < \langle r^2_{\nu_\mu}\rangle < 0.48\times10^{-32}$	90%	Ahrens *et al.* (1990)[a]
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2\times10^{-32}$	90%	Vilain *et al.* (1995)[a]

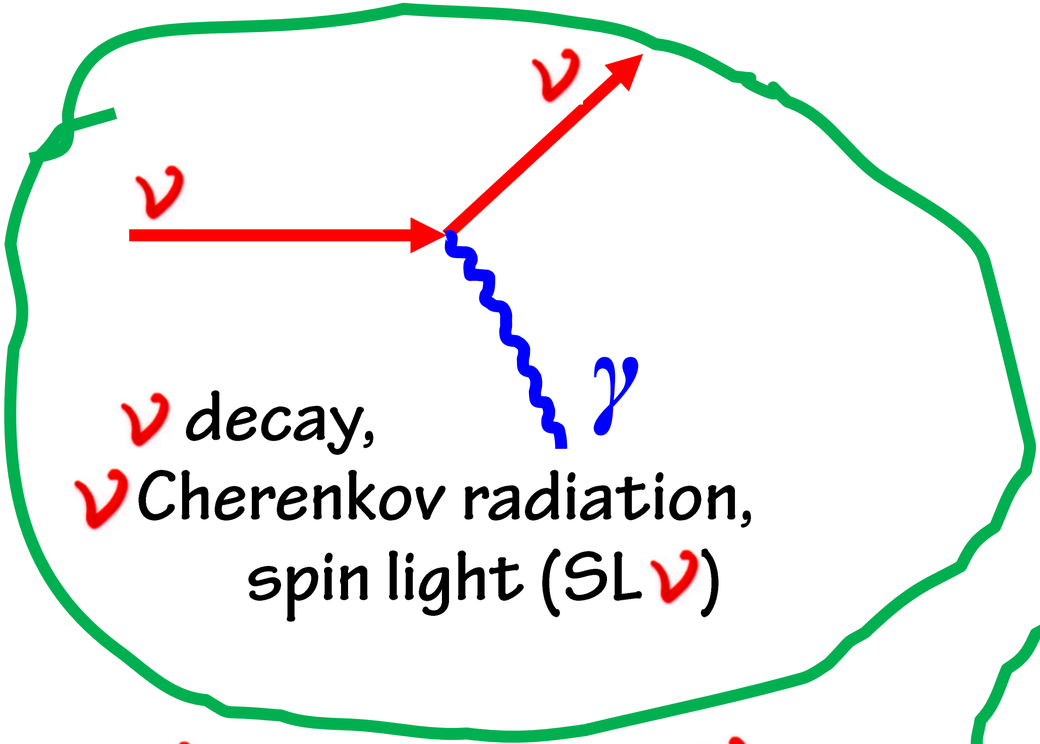
… updated by the recent constraints (effects of physics Beyond Standard Model)

$$\boxed{(|\langle r^2_{\nu_{e\mu}}\rangle|, |\langle r^2_{\nu_{e\tau}}\rangle|, |\langle r^2_{\nu_{\mu\tau}}\rangle| < (28, 30, 35) \times 10^{-32} cm^2}$$

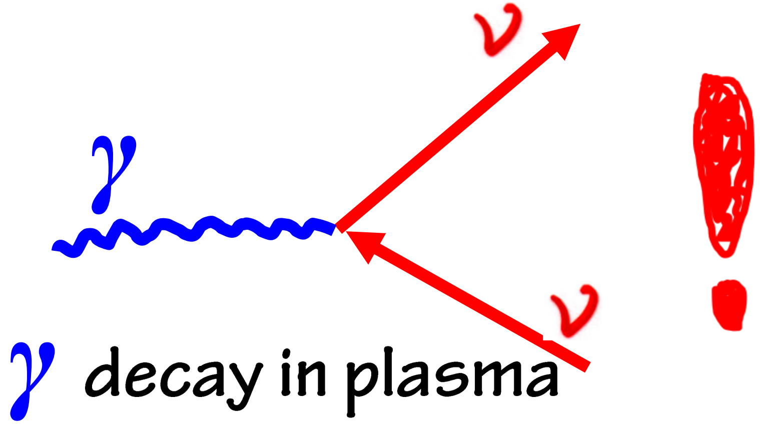
M.Cadeddu, C. Giunti, K.Kouzakov,
Yu-Feng Li, A. Studenikin, Y.Y.Zhang,
Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering, Phys.Rev.D 98 (2018) 113010

Electromagnetic ν in astrophycis and bounds on μ_ν and q_ν

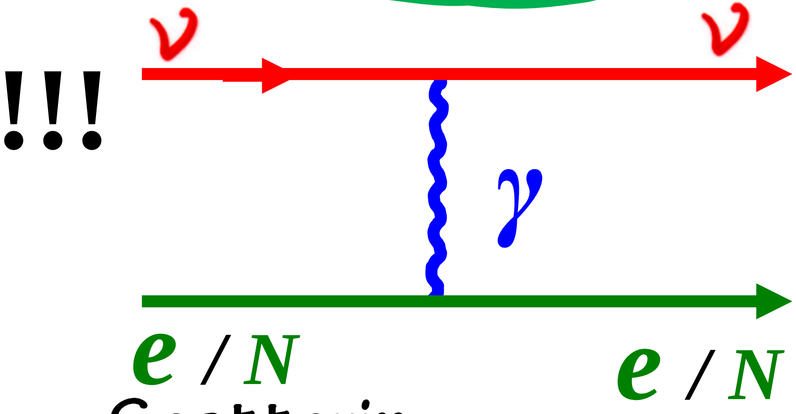
ν electromagnetic interactions



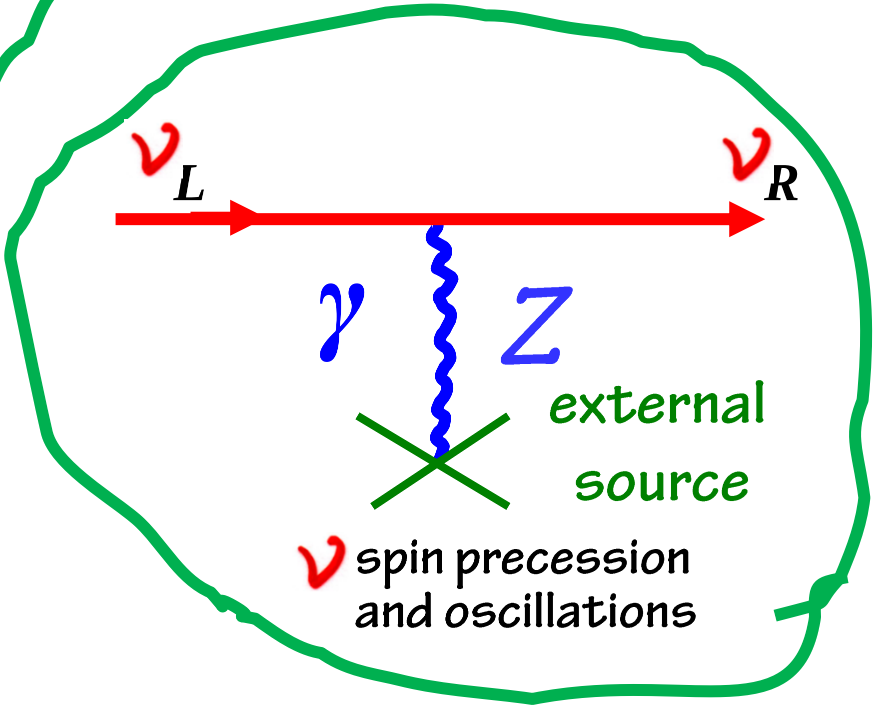
ν decay,
ν Cherenkov radiation,
spin light (SLν)



γ decay in plasma



Scattering

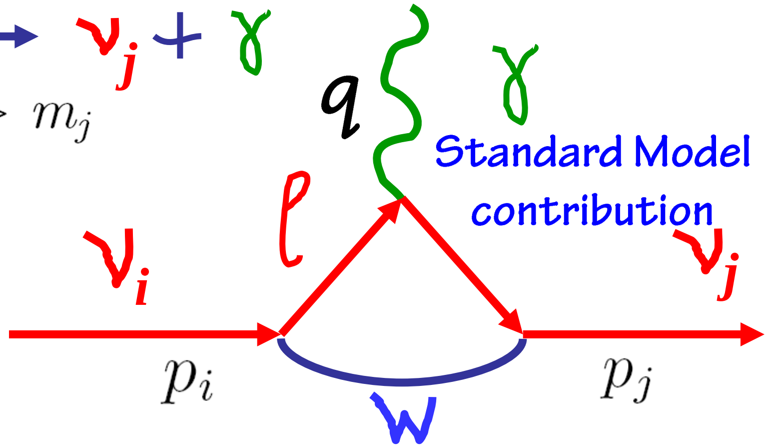


ν spin precession
and oscillations

Neutrino radiative decay $\nu_i \longrightarrow \nu_j + \gamma$

$$\boxed{\mathcal{L}_{int} = \frac{1}{2}\bar{\psi}_i \sigma_{\mu\nu}(\mu_{if} + i\gamma_5 d_{if})\psi_j F^{\mu\nu} + h.c.}$$

$m_i > m_j$



$$\boxed{\Lambda_\mu^{if}(q) = -i\sigma_{\mu\nu}q^\nu(\mu_{if} + i\gamma_5 d_{if})}$$

Petkov 1977; Zatsepin, Smirnov 1978;
Bilenky, Petkov 1987; Pal, Wolfenstein 1982

Radiative decay rate

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

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

transition magnetic and electric moments
(for Dirac and Majorana ν)

$$\boxed{\tau^{\mathrm{rf}}_{\nu_i \to \nu_f + \gamma} \simeq 0.19\left(\frac{m_i^2}{m_i^2 - m_f^2}\right)^3\left(\frac{\mathrm{eV}}{m_i}\right)^3\left(\frac{\mu_\mathrm{B}}{\mu_{fi}^{\mathrm{eff}}}\right)^2\ \mathrm{s}}$$

- ν life time is indeed **huge** … !

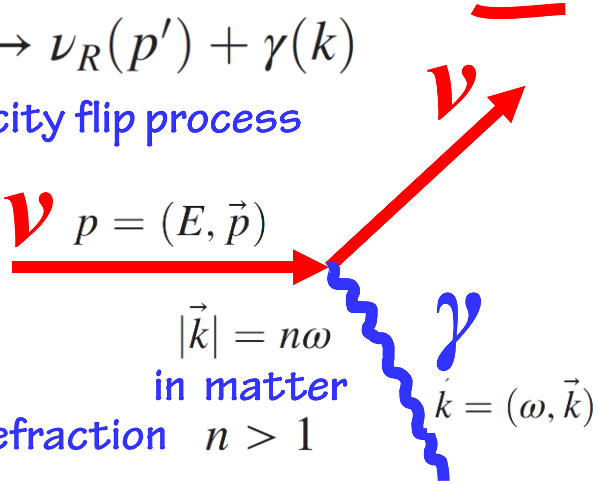
! Radiative decay has been constrained from absence of decay photons: ●

1) reactor $\bar{\nu}_e$ and solar ν_e fluxes,
2) SN 1987A ν burst (all flavours)
3) spectral distortion of CMBR

Raffelt 1999
Kolb, Turner 1990
Ressell, Turner 1990

Neutrino Cherenkov radiation $\nu_L(p) \to \nu_R(p') + \gamma(k)$

helicity flip process



ν transition amplitude due to μ_ν

$$M = \frac{\mu}{n}\overline{u^{(+)}}(p')\sigma_{\mu\nu}k^\mu u^{(-)}(p)\varepsilon^\nu(k,\lambda)$$

!

index of refraction $n > 1$

Cherenkov radiation

Cherenkov process rate

$$\boxed{\Gamma = \frac{1}{2(2\pi)^2 E}\int \frac{d^3p'}{2E'}\frac{d^3k}{2\omega}|M|^2\delta^4(p-p'-k)}$$

after integration

$$\Gamma = \frac{1}{16\pi E^2 v}\int n^2 d\omega\, d(\cos\theta)|M|^2 \boxed{\delta\left(\cos\theta - \frac{2\omega E + (n^2-1)\omega^2}{2n\omega E v}\right)}$$

$$\boxed{v = |\vec{p}|/E}$$

photon emission angle

$$\boxed{|\cos\theta| \leq 1} \qquad \boxed{\cos\theta = \frac{1}{nv}\left(1 + (n^2-1)\frac{\omega}{2E}\right)}$$

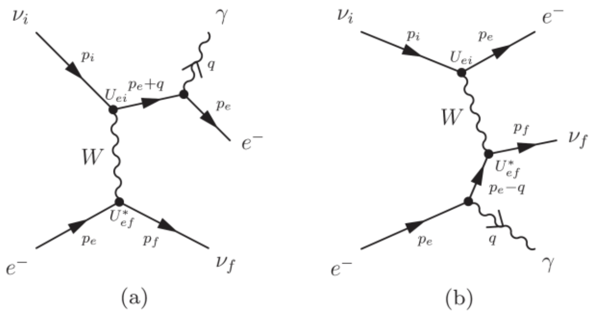
$$\Gamma = \frac{\mu^2}{4\pi E^2 v}\int_{\omega_{\min}}^{\omega_{\max}}\left\{\left[\frac{(n^2-1)^2}{n^2}E^2 + (n^2-1)m_\nu^2\right]\omega^2 - \frac{(n^2-1)^2}{n^2}E\omega^3 - \frac{(n^2-1)^3}{4n^2}\omega^4\right\}d\omega$$

! Solar νs with $\mu_\nu \sim 3 \times 10^{-11}\mu_B$ emit 5 γ per day in 1 Km^3 water detector ●

Grimus & Neufeld, 1993

ν radiative decay and Cherenkov radiation — in external environments

coherent forward elastic scattering
on (electron) background also
generates $\nu_i \rightarrow \nu_j + \gamma$
not suppressed by GIM
D'Olive, Nieves, Pal (1990)



(a) (b)

Giunti et al (1992)

- Cherenkov radiation by ν in magnetic field

  Galtsov, Nikitina (1972)
  Ioannisian & Raffelt (1997)

  B induces effective ν-γ vertex and modifies γ dispersion relation
  (no need for BSM)

- ν in medium acquire induce q as a consequence of weak interactions

  Oraevsky, Semikoz, Smorodinsky (1986)

  another mechanism of Cherenkov radiation in medium

  Sawyer (1992)
  D'Olive, Nieves, Pal (1996)

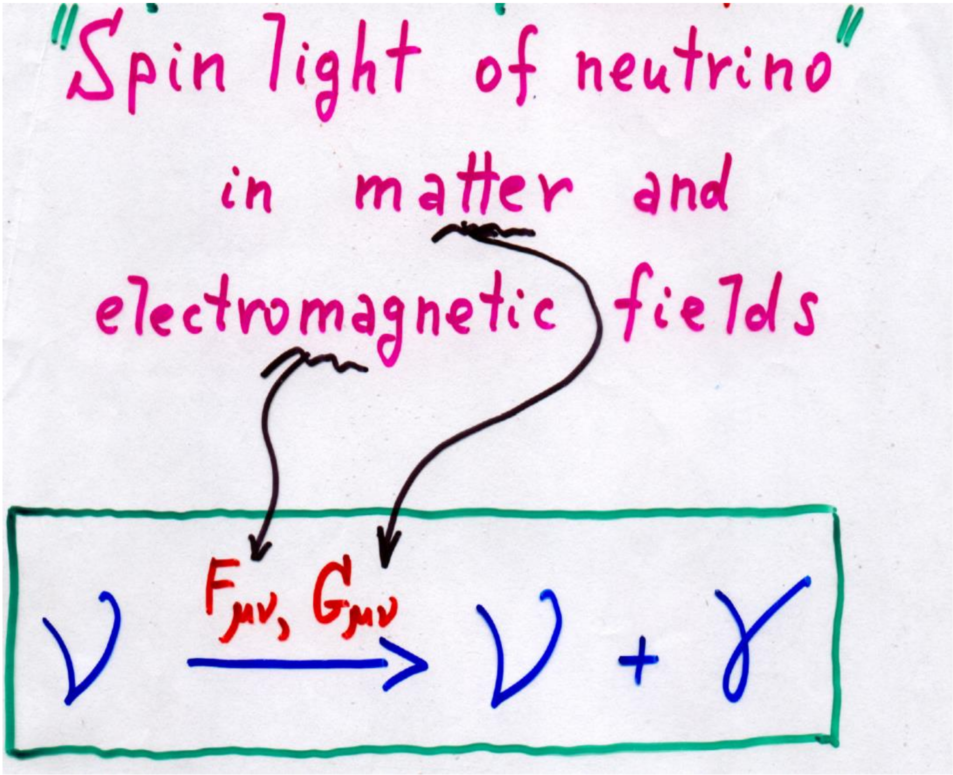
  effect for $m_\nu = 0$ in SM (without physics BSM)

- other particular cases for $\nu_i \rightarrow \nu_j + \gamma$
  in em fields and matter

  Skobelev (1976)
  Borisov, Zhukosky, Ternov (1988)
  Ternov (2016)

New mechanism of electromagnetic radiation

$SL\nu$



- ... quasi-classical approach to ν spin evolution in external field

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

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

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

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

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

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

Grigoriev, Studenikin, Ternov,
JCAP 11 (2017) 024
- Eur. Phys. J. C (2022) 82 : 287

#4

New mechanism of e.m. radiation by ν in matter and e.m. fields, and gravitational fields

$$\boxed{\nu \xrightarrow[\text{environment}]{\text{background}} \nu + \gamma,}$$

||

"Spin Light of Neutrino": "$SL\nu$"

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

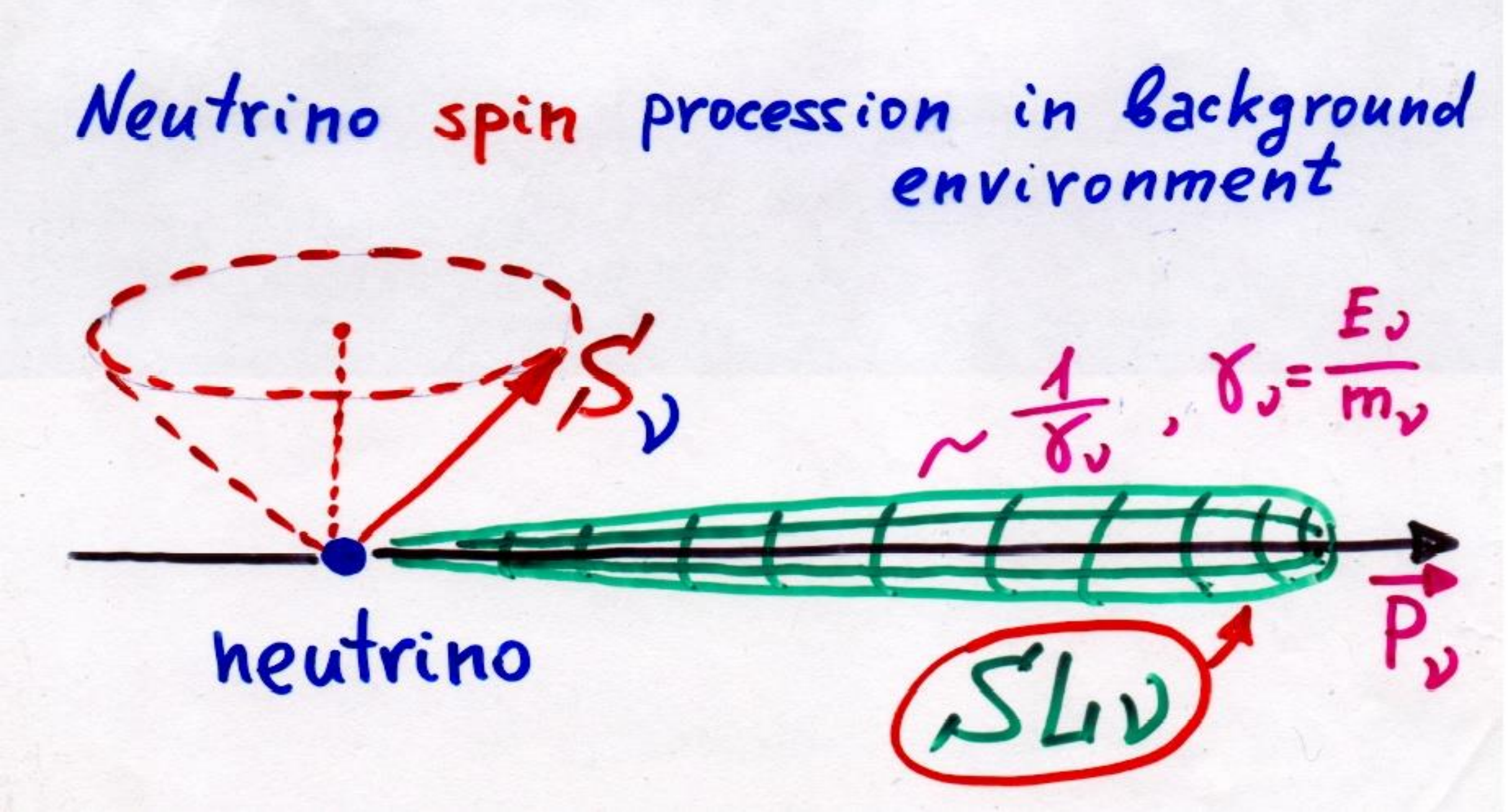
!

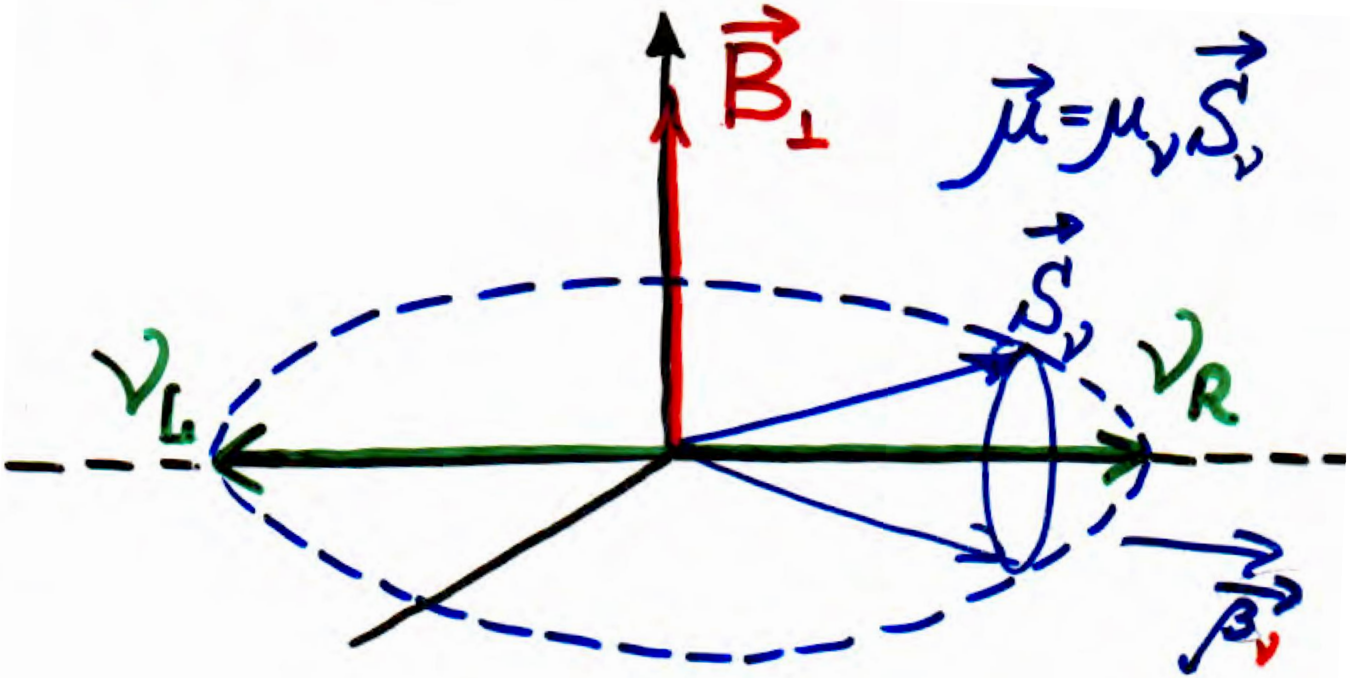
… quasi-classical approach to ν spin evolution in external fields

Quasi-classical theory of spin light of neutrino in matter and gravitational field

$SL\nu$

A.Lobanov, A.Studenikin, Phys.Lett. B 564 (2003) 27,
Phys.Lett. B 601 (2004) 171;
M.Dvornikov, A.Grigoriev, A.Studenikin, Int.J.Mod.Phys. D 14 (2005) 309





$$\frac{d\vec{S}_\nu}{dt} = 2\mu_\nu[\vec{S}_\nu \times \underline{\underline{\vec{B}}}\,] + \boxed{2\mu_\nu[\vec{S}_\nu \times \vec{G}\,]}\,.$$

electromagnetic interacton with e.m. field

weak interaction with matter

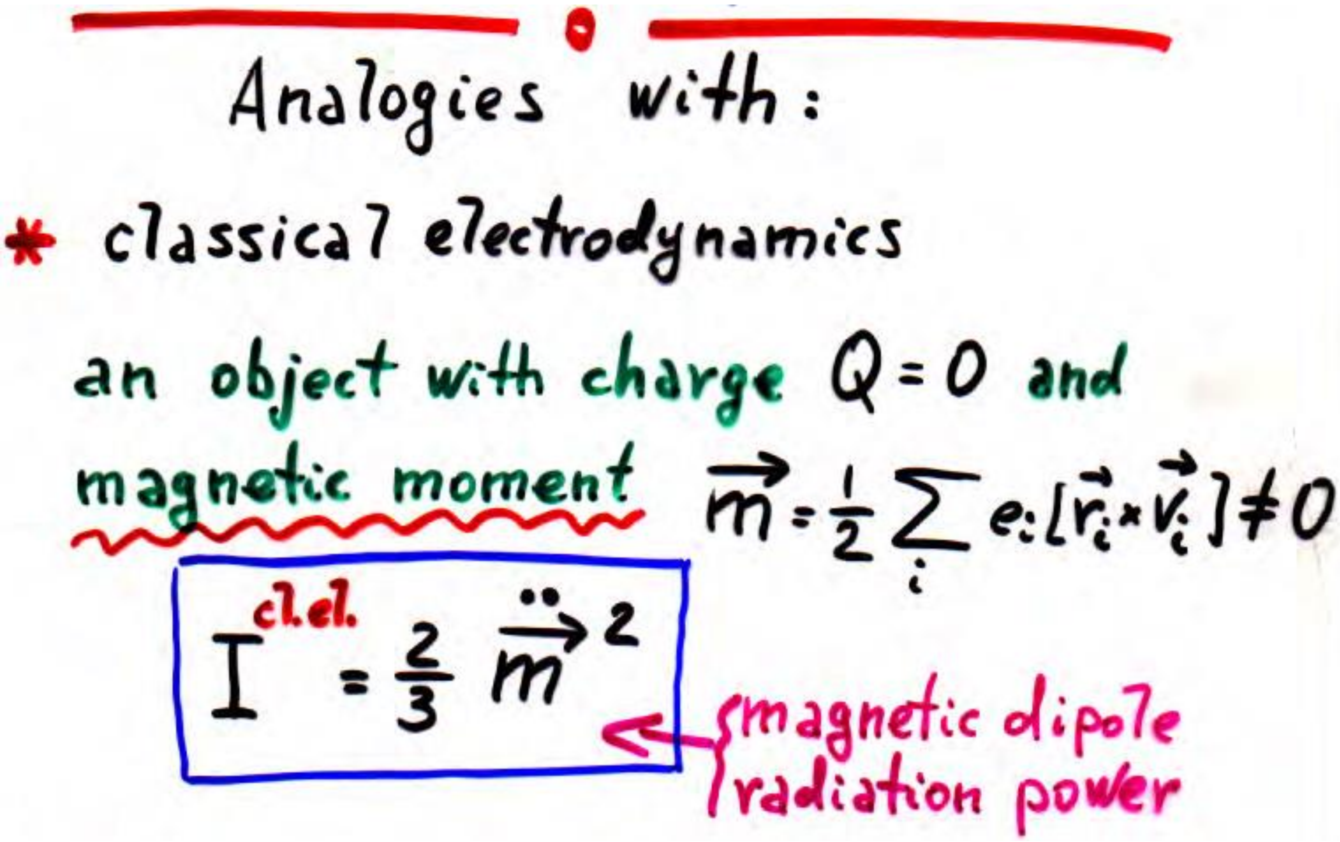
New mechanism of electromagnetic radiation

? Why Spin Light

of neutrino $\boxed{SL\nu}$

of electron $\boxed{SLe}$

in matter



Analogies with:

- classical electrodynamics

an object with charge $Q=0$ and magnetic moment $\vec{m}=\frac{1}{2}\sum_i e_i[\vec{r}_i\times\vec{v}_i]\neq 0$

$$\boxed{I^{cl.el.}=\frac{2}{3}\ddot{\vec{m}}^{2}}$$

magnetic dipole radiation power

ν spin evolution in presence of general external fields

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

General types non-derivative interaction with external fields

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

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

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

Relativistic equation (quasiclassical) for ν spin vector:

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

- Neither S nor π nor V contributes to spin evolution

- **Electromagnetic interaction**

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

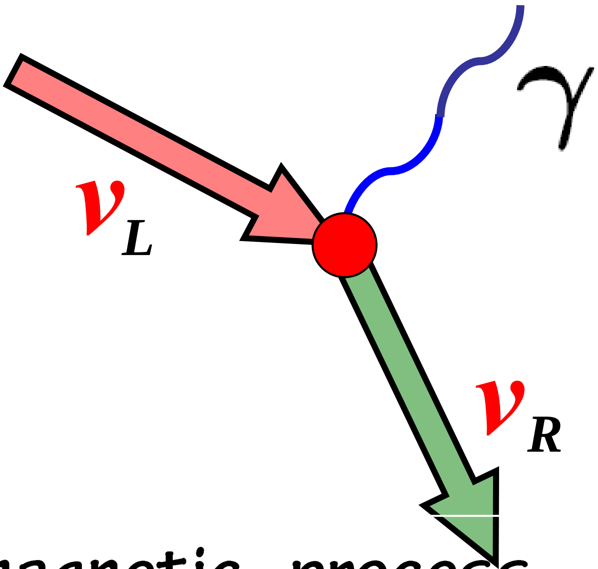
- **SM weak interaction**

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

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

- … quantum theory of $\boxed{SL\nu}$

Spin light of neutrino in matter



new mechanism of the electromagnetic process stimulated by the presence of matter, in which neutrino with **nonzero magnetic moment** emits light

A.Lobanov, A.Studenikin, Phys.Lett. B 564 (2003) 27,
Phys.Lett. B 601 (2004) 171
A.S., A.Ternov, Phys.Lett. B 608 (2005) 107
A.Grigoriev, A.S., A.Ternov, Phys.Lett. B 622 (2005) 199
A.S., J.Phys.A: Math.Theor. 41 (2008) 16402
A.S., J.Phys.A: Math.Gen. 39 (2006) 6769

A.Grigoriev, A.Lokhov, A.Ternov, A.Studenikin,
Phys. Lett. B 718 (2012) 512
JCAP 11 (2017) 024

Method of exact solutions

Modified Dirac equations for ν and (e)

(containing effective electromagnetic and matter potentials)

+

Exact solutions (particles wave functions)

a basis for investigation of different phenomena which can proceed when neutrinos (and electrons) move in dense magnetized media (astrophysical and cosmological environments)

«method of exact solutions»

Interaction of particles in external electromagnetic fields

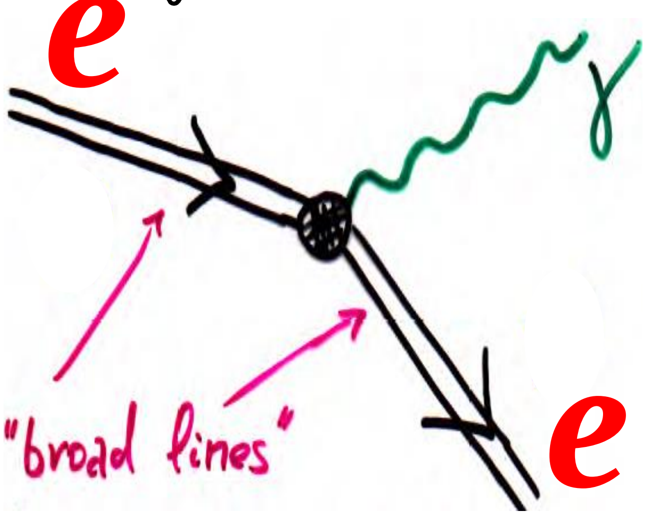
(Furry representation in quantum electrodynamics)

Potential of electromagnetic field

$$\boxed{A_\mu(x) = A_\mu^q(x) + A_\mu^{ext}(x)}$$

$$e \xrightarrow{\mathbf{B}_\perp} e + \gamma$$

synchrotron radiation



quantized part of potential

evolution operator

$$\boxed{U_F(t_1, t_2) = T exp\Big[- i \int_{t_1}^{t_2} j^\mu(x) A_\mu^q(x) dx \Big]}$$

charged particles **current** $\boxed{j_\mu(x) = \frac{e}{2}[\overline{\Psi}_F \gamma_\mu, \Psi_F]}$

Dirac equation in **external classical (nonquantized) field** $A_\mu^{ext}(x)$

$$\boxed{\Big\{ \gamma^\mu \Big(i\partial_\mu - e A_\mu^{ext}(x) \Big) - m_e \Big\} \Psi_F(x) = 0}$$

- …beyond perturbation series expansion, strong fields and non linear effects…

ν in external electromagnetic fields

ν in dense matter

…«method of exact solutions »…

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 (20 p)

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

- ν quantum states in dense magnetized matter

… new effect of …

Spin Light of ν in matter

$\boxed{SL\nu}$

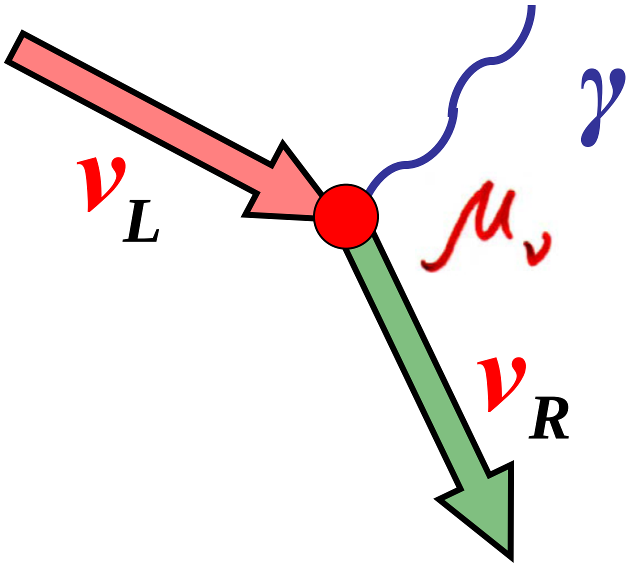
$\Longrightarrow$

… phenomenological consequences in astrophysics (pulsars)

ν energy quantization in rotating matter

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

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 …

=

Modified Dirac equation for neutrino in matter !

Addition to the vacuum neutrino Lagrangian

$$\Delta L_{eff} = \Delta L^{CC}_{eff} + \Delta L^{NC}_{eff} = -f^{\mu}\left(\bar{\nu}\gamma_{\mu}\frac{1+\gamma^{5}}{2}\nu\right)$$

matter current

where $$f^{\mu} = \frac{G_F}{\sqrt{2}}\left((1+4\sin^{2}\theta_W)j^{\mu} - \lambda^{\mu}\right)$$

matter polarization

$$\boxed{\left\{i\gamma_{\mu}\partial^{\mu} - \frac{1}{2}\gamma_{\mu}(1+\gamma_{5})f^{\mu} - m\right\}\Psi(x) = 0}$$

A.Studenikin, A.Ternov, hep-ph/0410297;
Phys.Lett.B 608 (2005) 107

It is supposed that there is a macroscopic amount of electrons in the scale of a neutrino de Broglie wave length. Therefore, **the interaction of a neutrino with the matter (electrons) is coherent.**

L.Chang, R.Zia,'88; J.Panteleone,'91; K.Kiers, N.Weiss, M.Tytgat,'97-'98; P.Manheim,'88; D.Nötzold, G.Raffelt,'88; J.Nieves,'89; V.Oraevsky, V.Semikoz, Ya.Smorodinsky,89; W.Naxton, W-M.Zhang'91; M.Kachelriess,'98; A.Kusenko, M.Postma,'02.

This is the most general equation of motion of a neutrino in which the effective potential accounts for both the **charged** and **neutral-current** interactions with the background matter and also for the possible effects of the matter **motion** and **polarization**.

Quantum theory of spin light of neutrino

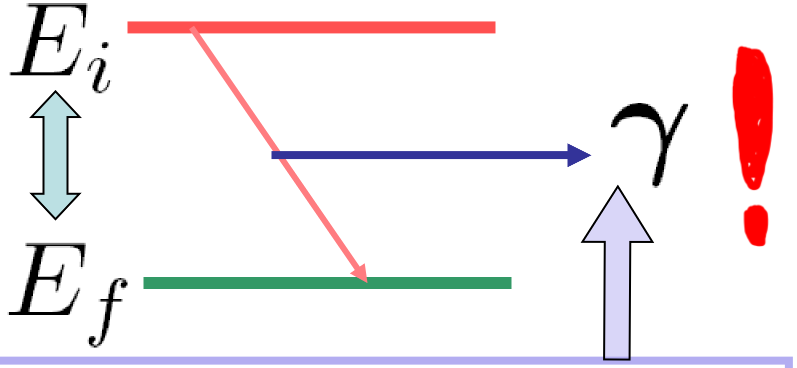
$SL\nu$

Quantum treatment of *spin light of neutrino* in matter
showns that this process originates from the two subdivided phenomena:

the shift of the neutrino energy levels in the presence of the background matter, which is different for the two opposite **neutrino helicity states**,

$$E = \sqrt{\mathbf{p}^2\left(1 - s\alpha\frac{m}{p}\right)^2 + m^2} + \alpha m$$

$$s = \pm 1$$



the radiation of the photon in the process of the neutrino transition from the **“excited” helicity state** to the **low-lying helicity** state in matter

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

A.Grigoriev, A.Studenikin, A.Ternov, Phys.Lett.B 622 (2005) 199;
Grav. & Cosm. 14 (2005) 132;

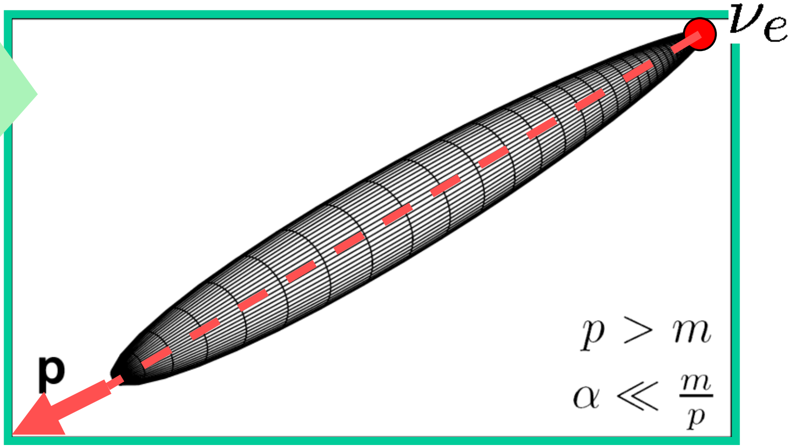
neutrino-spin self-polarization effect in the matter

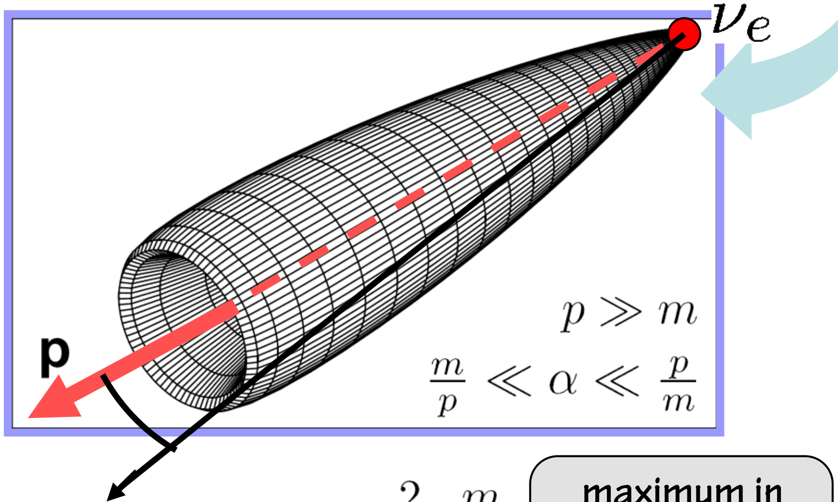
A.Lobanov, A.Studenikin, Phys.Lett.B 564 (2003) 27;
Phys.Lett.B 601 (2004) 171

Spatial distribution of radiation power

From the angular distribution of $\boxed{SL\nu}$

$$\boxed{I=\mu^2\int_0^{\pi}\omega^4\left[(\tilde\beta\tilde\beta'+1)(1-y\cos\theta)-(\tilde\beta+\tilde\beta')(\cos\theta-y)\right]\frac{\sin\theta}{1+\tilde\beta' y}d\theta}$$





for $p/m = 5$ and $\alpha = 0.01$

$\boxed{n \approx 10^{35} cm^{-3}}$

neutrino momentum

mass

matter density

$$\cos\theta_{max} \simeq 1 - \frac{2}{3}\alpha\frac{m}{p}$$

maximum in radiation power distribution

for $p/m = 10^3$ and $\alpha = 100$

$\boxed{n \approx 10^{39} cm^{-3}}$

projector-like distribution → increase of matter density → **cap-like distribution**

! It is possible to have $$\tau = \frac{1}{\Gamma_{\boxed{SL\nu}}} \;<<\; \text{age of the Universe} \,?$$

For ultra-relativistic ν

with momentum $p \sim 10^{20} eV$

! and magnetic moment $\mu \sim 10^{-10} \mu_B$

in very dense matter $n \sim 10^{40} cm^{-3}$

from $$\Gamma_{\boxed{SL\nu}} = 4\mu^2 \alpha^2 m_\nu^2 p$$

$$\alpha m_\nu = \frac{1}{2\sqrt{2}} G_F n (1 + sin^2\theta_W)$$

$$p \gg m_{plasmon}$$

also discussed by
A.Kuznetsov,
N.Mikheev,
IJMP A 2007

A.Lobanov, A.S., PLB 2003; PLB 2004
A.Grigoriev, A.S., PLB 2005
A.Grigoriev, A.S., A.Ternov, PLB 2005
A.Grigories, A.Lokhov, A.S., A.Ternov, PLB 2012

it follows that

$$\tau_{\boxed{SL\nu}} = \frac{1}{\Gamma} = 1.5 \times 10^{-8} s$$

A.Grigoriev, A.Lokhov,
A.Ternov, A.Studenikin

- The effect of plasmon mass on Spin Light of Neutrino in dense matter

Phys.Lett. B 718
(2012) 512-515

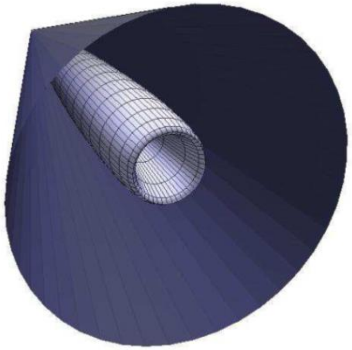


Figure 1: 3D representation of the radiation power distribution.

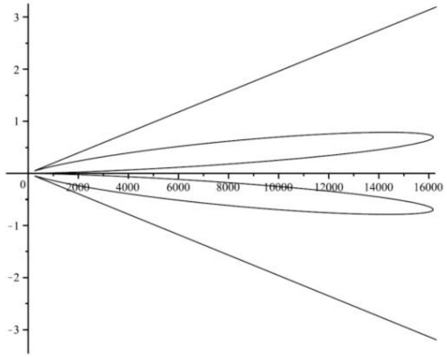


Figure 2: The two-dimensional cut along the symmetry axis. Relative units are used.

4. Conclusions

We developed a detailed evaluation of the spin light of neutrino in matter accounting for effects of the emitted plasmon mass. On the base of the exact solution of the modified Dirac equation for the neutrino wave function in the presence of the background matter the appearance of the threshold for the considered process is confirmed. The obtained exact and explicit threshold condition relation exhibit a rather complicated dependance on the matter density and neutrino mass. The dependance of the rate and power on the neutrino energy, matter density and the angular distribution of the $SL\nu$ is investigated in details. It is shown how the rate and power wash out when the threshold parameter $a = m_\gamma^2/4\tilde{n}p$ approaching unity. From the performed detailed analysis it is shown that the $SL\nu$ mechanism is practically insensitive to the emitted plasmon mass for very high densities of matter (even up to $n = 10^{41} cm^{-3}$) for ultra-high energy neutrinos for a wide range of energies starting from $E = 1$ TeV. This conclusion is of interest for astrophysical applications of $SL\nu$ radiation mechanism in light of the recently reported hints of $1 \div 10$ PeV neutrinos observed by IceCube [17].

!

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Spin light of neutrino in astrophysical environments

Alexander Grigoriev,[b,c] **Alexey Lokhov,**[d] **Alexander Studenikin**[a,e,1]
and Alexei Ternov[c]

[a]Department of Theoretical Physics, Moscow State University,
119992 Moscow, Russia
[b]Skobeltsyn Institute of Nuclear Physics, Moscow State University,
119992 Moscow, Russia
[c]Department of Theoretical Physics, Moscow Institute of Physics and Technology,
141701 Dolgoprudny, Russia
[d]Institute for Nuclear Research, Russian Academy of Sciences,
117312 Moscow, Russia
[e]Dzhelepov Laboratory of Nuclear Problems, Joint Institute for Nuclear Research,
141980 Dubna, Russia

E-mail: ax.grigoriev@mail.ru, lokhov.alex@gmail.com, studenik@srd.sinp.msu.ru,
ternov.ai@mipt.ru

Received May 23, 2017
Revised October 16, 2017
Accepted October 31, 2017
Published November 16, 2017

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

SLν in neutron matter of real astrophysical objects [4]

❑ **Plasma effects [5]**

- Photon dispersion with plasmon mass in the degenerate electron gas:

$$\boxed{\omega = \sqrt{\mathbf{k}^2 + m_\gamma^2}}$$

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

- Threshold condition for the *SLν* [10]: $(Y_e = n_e/n_n)$

$$\boxed{\frac{m_\gamma^2 + 2\,m_\gamma m_\nu}{4\tilde{n}p} < 1}$$

- **Neutron matter:** (antineutrinos act)

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

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

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

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

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

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

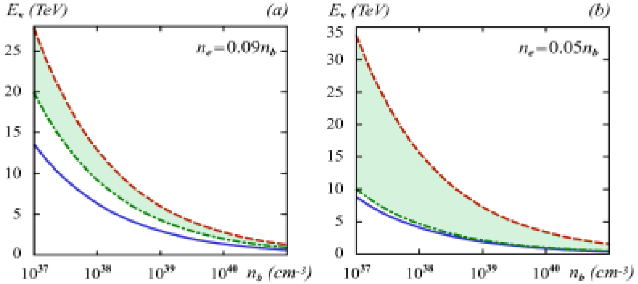


Figure 2. The allowed range of electron antineutrino energies for the $SL\nu$ in the matter of a neutron star depending on the neutron density. Solid line: the $SL\nu$ process threshold without account for the $\bar{\nu}_e e$-scattering; dash-dotted line: the $SL\nu$ process threshold with account for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

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

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

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

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

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

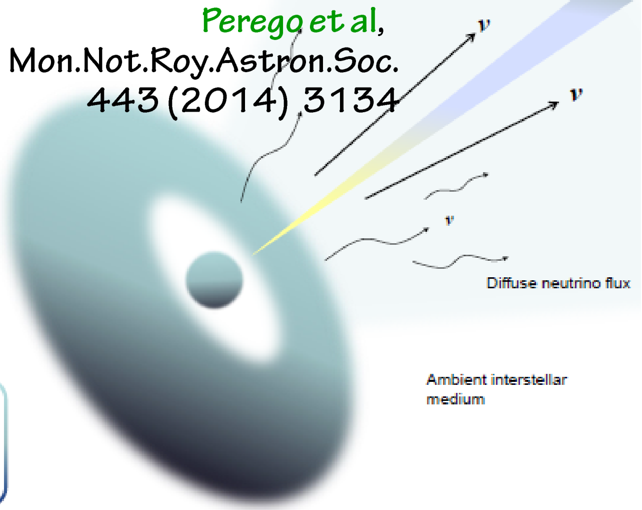
Factors for best *SLν* generation efficiency

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

!

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

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



Matter characteristics[6]:

- neutrinos

$$n_\nu \sim 10^{32}\ \mathrm{cm}^{-3}$$

- electrons

$$Y_e = 0.01$$
$$T = 0.1\ \mathrm{MeV}$$
$$\rho = 5 \times 10^3\ \mathrm{g/cm}^3$$

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

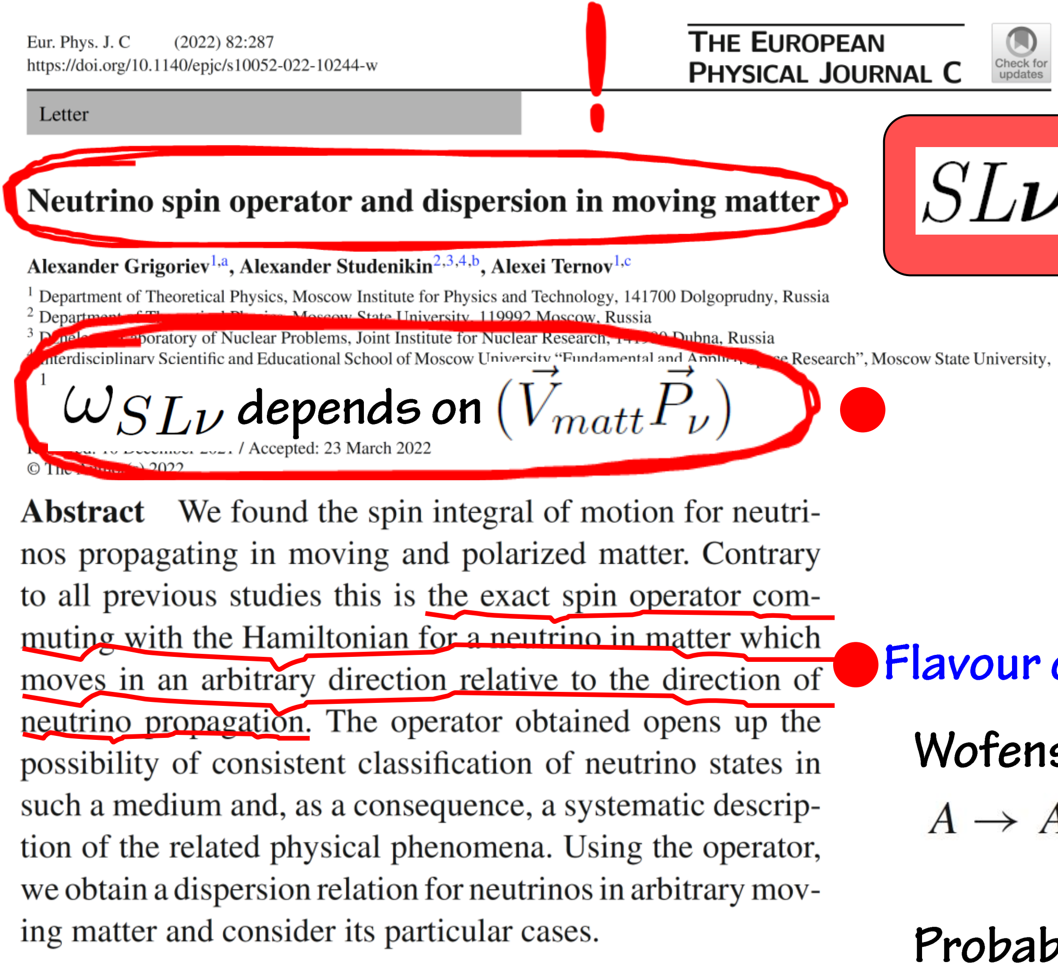
Radiation time

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

Neutrino parameters:

$$\mu \simeq 2.9 \times 10^{-11}\mu_B$$
$$E_\nu \sim 10^{12}\text{–}10^{18}\ \mathrm{eV}$$

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



Eur. Phys. J. C (2022) 82:287
https://doi.org/10.1140/epjc/s10052-022-10244-w

THE EUROPEAN PHYSICAL JOURNAL C

Letter

Neutrino spin operator and dispersion in moving matter

Alexander Grigoriev[1,a], **Alexander Studenikin**[2,3,4,b], **Alexei Ternov**[1,c]

[1] Department of Theoretical Physics, Moscow Institute for Physics and Technology, 141700 Dolgoprudny, Russia
[2] Department of Theoretical Physics, Moscow State University, 119992 Moscow, Russia
[3] [illegible] Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, [illegible] Dubna, Russia
[4] Interdisciplinary Scientific and Educational School of Moscow University "Fundamental and Appli[illegible] Research", Moscow State University,
1

$SL\nu$

$\omega_{SL\nu}$ depends on $(\vec{V}_{matt}\vec{P}_{\nu})$ ●

Received: [illegible] / Accepted: 23 March 2022

Abstract We found the spin integral of motion for neutrinos propagating in moving and polarized matter. Contrary to all previous studies this is the exact spin operator commuting with the Hamiltonian for a neutrino in matter which moves in an arbitrary direction relative to the direction of neutrino propagation. The operator obtained opens up the possibility of consistent classification of neutrino states in such a medium and, as a consequence, a systematic description of the related physical phenomena. Using the operator, we obtain a dispersion relation for neutrinos in arbitrary moving matter and consider its particular cases.

$$\left\{i\gamma_\mu\partial^\mu - \frac{1}{2}\gamma_\mu(1+\gamma^5)f^\mu - m\right\}\Psi(x) = 0$$

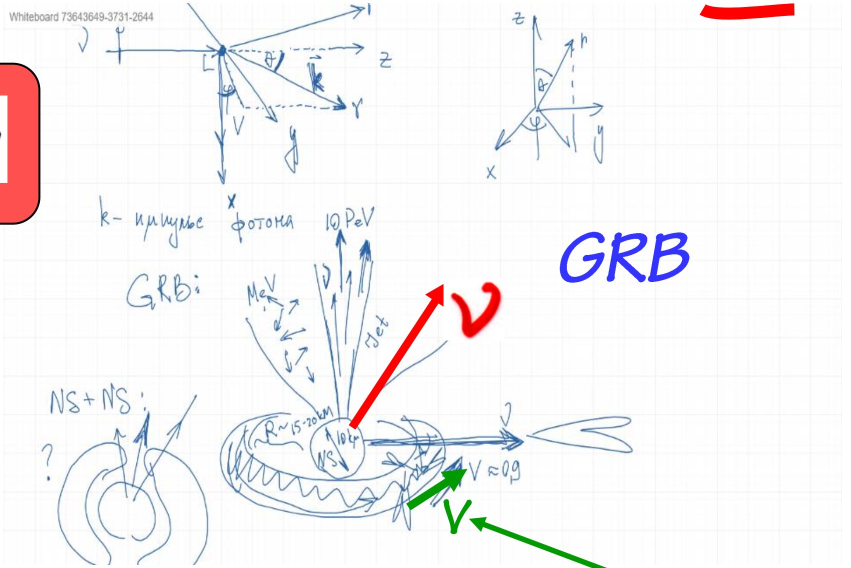
$$\frac{1}{2}f^\mu = \tilde{n}_0 v^\mu, \quad \tilde{n}_0 = \frac{1}{2\sqrt{2}}G_F(1+4\sin^2\theta_W)n_0$$

$$n = \gamma n_0 \quad \gamma = 1/\sqrt{1-\mathrm{v}^2}$$

● $$\boxed{\mathrm{S} = \gamma\left[\gamma^5\gamma^0 m - \gamma^5(\tilde{\mathrm{H}} - (\tilde{\mathbf{p}}\mathbf{v})) - m\gamma^0(\boldsymbol{\Sigma}\mathbf{v})\right]}$$

$$E_{s=+1} = \sqrt{(\mathrm{p}-\tilde{n})^2 + m^2} + \tilde{n},$$

$$E_{s=-1} = \sqrt{\mathrm{p}^2 + 4\tilde{n}^2\mathrm{v}^2 + m^2} + 2\tilde{n}$$



● **Flavour oscillations** $\boxed{\nu_e \leftrightarrow \nu_\mu}$ **in moving matter**

Wofenstein term

$$A \rightarrow A' = \sqrt{2}G_F n + 8\frac{G_F^2 n^2 \mathrm{v}^2}{\mathrm{p}}\sin^2\theta_W$$

Probability of oscillations

$$P = \frac{1}{2}\frac{\Delta^2\sin^2 2\theta}{(\Delta\cos 2\theta - 2\mathrm{p}A')^2 + \Delta^2\sin^2 2\theta}$$

Resonance condition

● $$\boxed{\frac{\Delta}{2\mathrm{p}}\cos 2\theta = A + 8\frac{G_F^2 n^2 \mathrm{v}^2}{\mathrm{p}}\sin^2\theta_W}$$

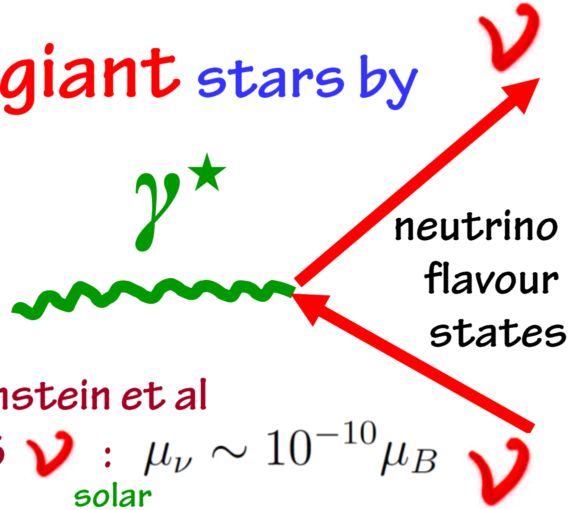
two terms are of same order for extra-dense matter $n \sim 10^{41}\ \mathrm{cm}^{-3}$ and $V \sim 0.9$, $P \sim 10$ keV

Electromagnetic ν in astrophycis and bounds on μ_ν and q_ν

Astrophysical bounds on μ_ν

② Astrophysical bound on μ_ν

G.Raffelt, PRL 1990



! comes from cooling (observed luminosity) of **red giant** stars by plasmon decay $\gamma^\star \to \nu\nu$

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

J.Bernstein et al 1963 ν_{solar} : $\mu_\nu \sim 10^{-10}\mu_B$

Matrix element

$$|M|^2 = M_{\alpha\beta}p^\alpha p^\beta, \quad M_{\alpha\beta} = 4\mu^2(2k_\alpha k_\beta - 2k^2\epsilon^*_\alpha\epsilon_\beta - k^2 g_{\alpha,\beta}), \quad \epsilon_\alpha k^\alpha = 0$$

Decay rate

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

= 0 in vacuum $\omega = k$

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

Energy-loss rate per unit volume

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

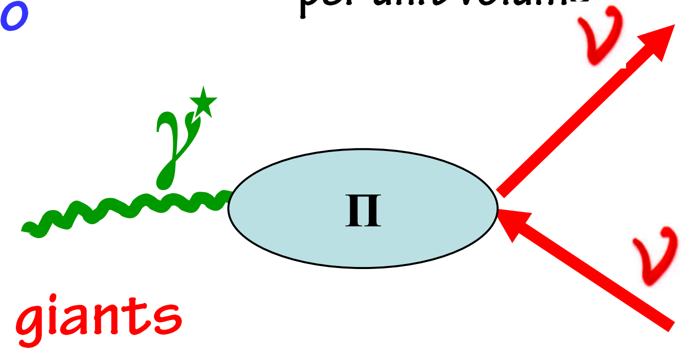
$$\mu^2 \to \sum_{a,b}\left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2\right)$$

distribution function of plasmons

Astrophysical bound on μ_ν

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

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

slightly reducing the core temperature

delay of helium ignition in low-mass red giants

(due to nonstandard ν losses)

astronomical observable

can be related to luminosity of stars before and after helium flash

! … in order not to delay helium ignition in an unacceptable way

(a significant brightness increase is constraint by observations …)

- … best astrophysical limit on ν magnetic moment…

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

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

G.Raffelt, PRL 1990

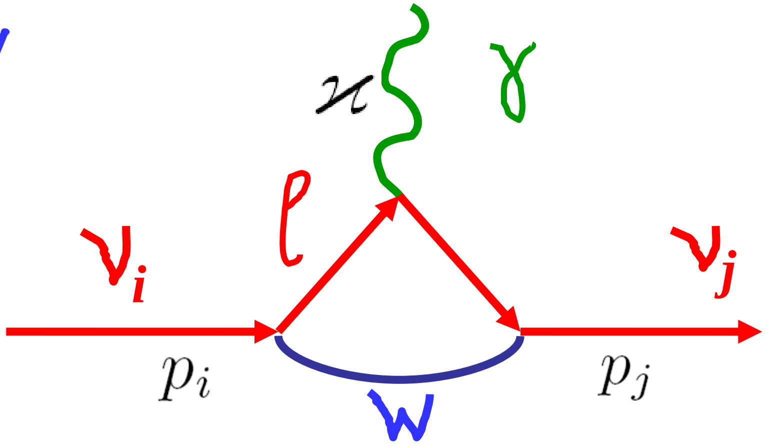
D+M

Neutrino radiative decay

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

$$m_i > m_j$$

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



Petkov 1977; Zatsepin, Smirnov 1978;
Bilenky, Petkov 1987; Pal, Wolfenstein 1982

Radiative decay rate

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

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

- Radiative decay has been constrained from absence of decay photons:
  1) reactor $\bar{\nu}_e$ and solar ν_e fluxes,
  2) SN 1987A ν burst (all flavours),
  3) spectral distortion of CMBR

Raffelt 1999

Kolb, Turner 1990;
Ressell, Turner 1990

! ① ... important for astrophysics consequence of

• μ_ν is appearance ν_R ... examples 1-3 ...

a) helicity change in ν magnetic moment scattering on e (p, n)

(active) (sterile)

$$\nu_L \Rightarrow \nu_R$$

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

effective μ_ν

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

b) spin (spin-flavor) precession in $B_\perp$

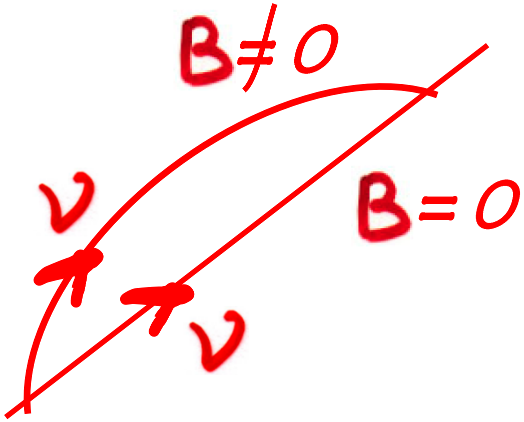
$$\mu_{ij} \to |\mu_{ij} - i\epsilon_{ij}|$$

electric dipole moment

! c) spin (spin-flavor) precession in transversal matter currents $j_\perp$ or polarization $\zeta_\perp$

$$\nu_L \overset{j_\perp}{\Longleftrightarrow} \nu_R \qquad \nu_L \overset{\zeta_\perp}{\Longleftrightarrow} \nu_R$$

② ... important for astrophysics consequence of $q_\nu \neq 0$ is ν deviation from a rectilinear trajectory



… example 4 …

Astrophysics bounds on μ_ν

1) SN 1987A provides energy-loss limit on μ_ν related to observed duration of ν signal

(also d_ν and transition moments)

…in magnetic moment scattering $\nu_e^L + e \to \nu_e^R + e$

due to change of helicity $\nu_L \Rightarrow \nu_R$

Dar, Nussinov & Rephaeli,
Goldman et al, Notzol, Voloshin,
Ayla et al, Balantekin et 1988

proto-neutron star formed in core-collapse SN can cool faster since ν_R are sterile and not trapped in a core like ν_L for a few sec

- escaping ν_R will cool the core very efficient and fast (~ 1 s)

the observed 5-10 s pulse duration in Kamioka II and IMB is in agreement with the standard model ν_L trapping …

! $\Downarrow$

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

… inconsistent with SN1987A observed cooling time

Barbieri, Mahapatra
Lattimer, Cooperstein,
1988
Raffelt, 1996

Astrophysics bounds on μ_ν

… example 5…

2) SN 1987A provides energy-loss limit on μ_ν related to observed ν energies

… helicity change in ν magnetic moment scattering $\nu_e^L + e \to \nu_e^R + e$

on e (p , n)

ν_R from inner SN core have larger energy than ν_L emitted from neutrino sphere

then $\nu_R \overset{B}{\longleftrightarrow} \nu_L$ in galactic B and higher-energy ν_L would arrive to detector as a signal of SN 1987A

! ⇒ from absence of anomalous high-energy ν

Nötzold
1988

$\Downarrow$

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

Astrophysics bounds on μ_ν

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

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 system,
- on assumption on the neutrino properties .

Generic assumption:

- absence of other nonstandard interactions accept for μ_ν

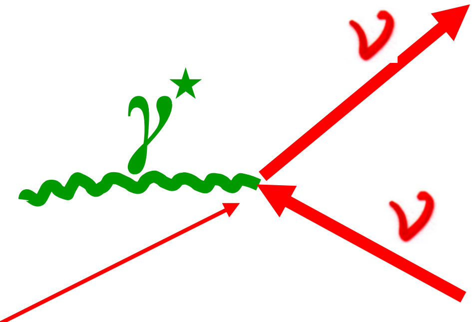
A **global treatment** would be desirable, incorporating **oscillations** and **matter effects**, as well as the complications due to **interference** and **competitions** among **various channels**

Astrophysical bounds on q_ν

Constraints on neutrino millicharge from red giants cooling

- **Plasma process** (photon decay)

$\gamma^\star \longrightarrow \nu\nu$



Interaction Lagrangian

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

millicharge

Decay rate

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

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

Delay of helium ignition in low-mass red gians due to nonstandard ν losses

$$\boxed{q_\nu \le 2\times 10^{-14} e}$$

…to avoid delay of helium ignition in low-mass red giants

Halt, Raffelt, Weiss, PRL1994

$$\boxed{q_\nu \le 3\times 10^{-17} e}$$

… absence of anomalous energy-dependent dispersion of SN1987A ν signal, most model independent

$$\boxed{q_\nu \le 3\times 10^{-21} e}$$

… from "charge neutrality" of neutron…

- … astrophysical bound on millicharge q_ν from

ν energy quantization
in rotating
magnetized star

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 star

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

- Studenikin, Tokarev, Nucl.Phys.B (2014)

Modified Dirac equation for ν wave function

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

external magnetic field

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

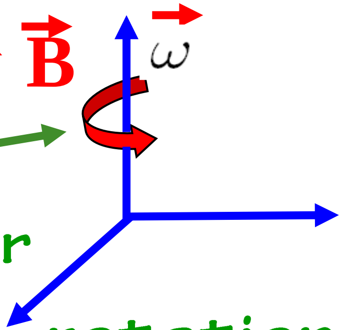
$$c_l = 1$$

matter potential

rotating matter

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

matter density



rotation angular frequency

- ν energy is quantized in rotating and magnetized star

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

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

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

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

integer number

matter
rotation
frequency

millicharge

scalar potential
of electric field

! ν energy is quantized in rotating matter like electron energy in magnetic field (Landau energy levels):

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

!

In quasi-classical approach

✓ quantum states in rotating matter

✓ motion in circular orbits

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

N=1,2,3 …

due to effective Lorentz force

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

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

$$q_{eff}\mathbf{E}_{eff}=q_m\mathbf{E}_m+q_0\mathbf{E}$$

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

matter density

matter rotation frequency

where

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

matter induced “charge”, “electric” field , “magnetic” fields

=

... we predict :

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

$E \sim 1\ eV$

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

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

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

2) rotating neutron stars as

filters for low-energy relic ν ?

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

Millicharged ν as star rotation engine

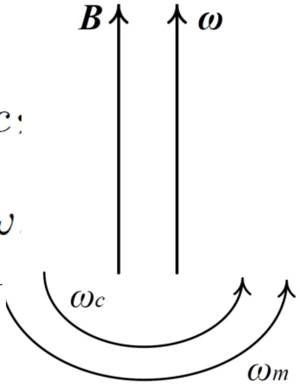
- Single ν generates feedback force with projection on rotation plane

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

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

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

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

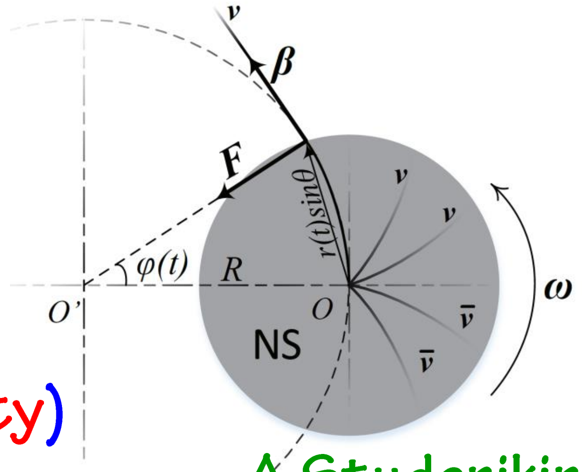


single ν torque

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

total N_ν torque

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



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

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

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

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

• νStar Turning mechanism (νST)

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

- Escaping millicharged νs move on curved orbits inside magnetized rotating star and feedback of effective Lorentz force should effect initial star rotation
- New astrophysical constraint on ν millicharge

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

- $|\Delta\omega| < \omega_0$! ...to avoid contradiction of νST impact with observational data on pulsars ...
- $\boxed{q_0 < 1.3 \times 10^{-19} e_0}$ .. best astrophysical bound ... !

= Main steps in ν oscillations

67 years!

early history of ν oscillations

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

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

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

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

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

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

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

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

Bruno Pontecorvo
1913–1993

only in $B_\perp$
and
matter at rest

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

$$\nu_{e_L} \longleftrightarrow \nu_{\mu_R} \qquad \boxed{B = |\mathbf{B}_\perp| e^{i\phi(t)}}$$

- … twisting magnetic field …

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

$$\boxed{\Omega^2 = (\mu_{e\mu}B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2} \qquad \boxed{\Delta_{LR} = \frac{\Delta m^2}{2}(\cos 2\theta + 1) - 2EV_{\nu_e} + 2E\dot{\phi}}$$

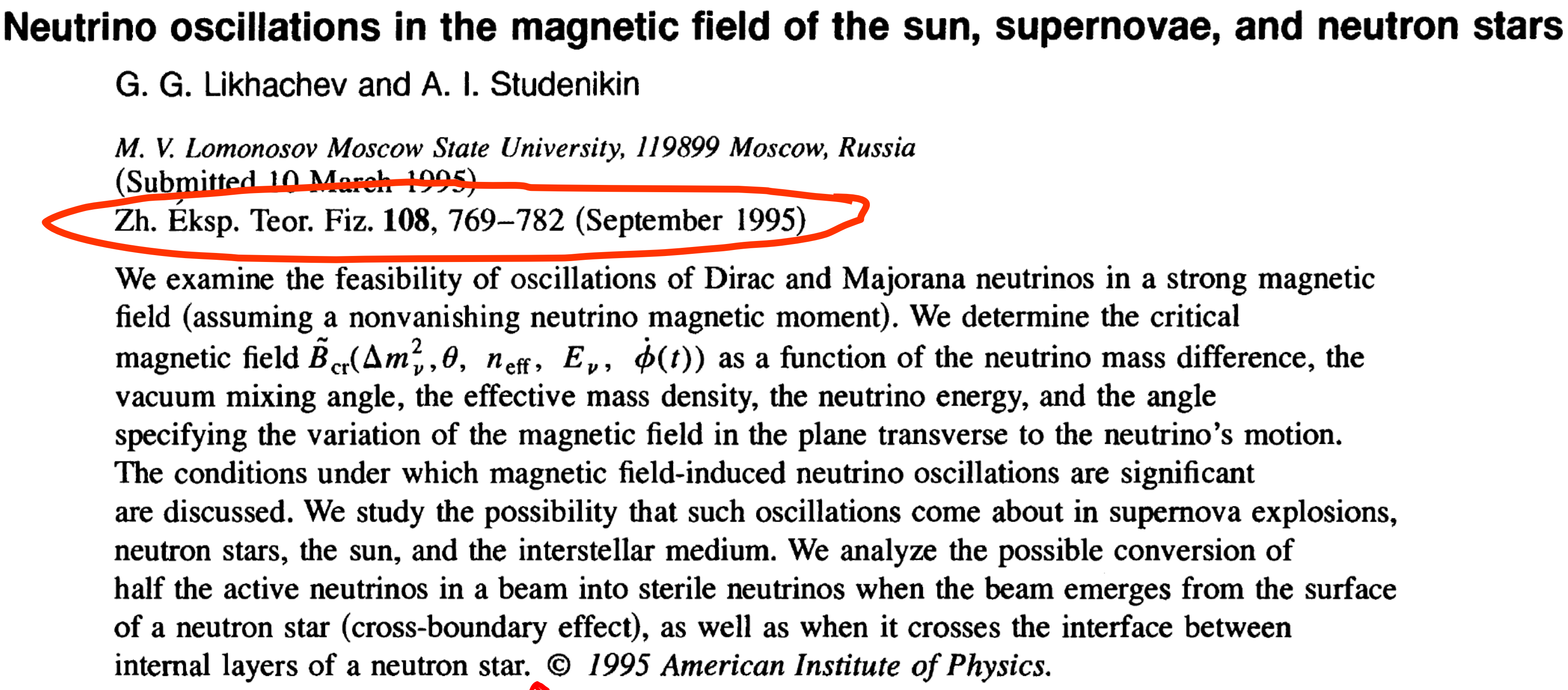
- Resonance amplification of oscillations in matter:

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

Akhmedov, 1988
Lim, Marciano

… similar to
MSW effect

… the first paper of our group on neutrino spin and spin-flavour oscillations in magnetic fields and matter …



Neutrino oscillations in the magnetic field of the sun, supernovae, and neutron stars

G. G. Likhachev and A. I. Studenikin

M. V. Lomonosov Moscow State University, 119899 Moscow, Russia

(Submitted 10 March 1995)
Zh. Éksp. Teor. Fiz. **108**, 769–782 (September 1995)

We examine the feasibility of oscillations of Dirac and Majorana neutrinos in a strong magnetic field (assuming a nonvanishing neutrino magnetic moment). We determine the critical magnetic field $\tilde{B}_{\rm cr}(\Delta m_\nu^2, \theta, n_{\rm eff}, E_\nu, \dot{\phi}(t))$ as a function of the neutrino mass difference, the vacuum mixing angle, the effective mass density, the neutrino energy, and the angle specifying the variation of the magnetic field in the plane transverse to the neutrino's motion. The conditions under which magnetic field-induced neutrino oscillations are significant are discussed. We study the possibility that such oscillations come about in supernova explosions, neutron stars, the sun, and the interstellar medium. We analyze the possible conversion of half the active neutrinos in a beam into sterile neutrinos when the beam emerges from the surface of a neutron star (cross-boundary effect), as well as when it crosses the interface between internal layers of a neutron star. © *1995 American Institute of Physics.*

!

"cross-boundary effect" →

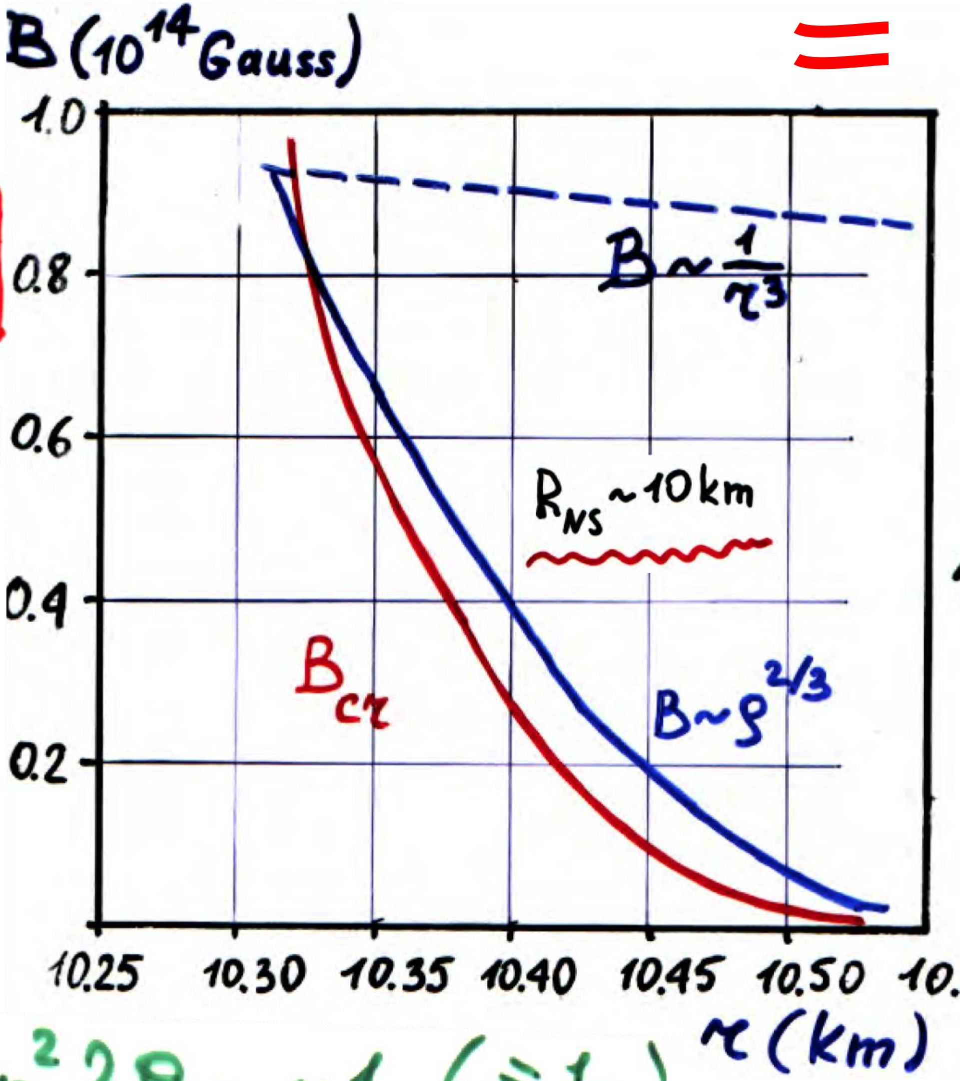
$\tilde{B}_{cr}$ “critical magnetic field”

$$\tilde{B}_{cr} = \left| \frac{1}{2\tilde{\mu}} \left(\frac{\Delta m_{\nu}^2}{2E_{\nu}} A - \boxed{\sqrt{2}\, G_F\, n_{\text{eff}}} + \dot{\phi} \right) \right|$$

$$\tilde{B} = 10^2 \frac{\mu_B}{\tilde{\mu}} \left| -\frac{n_{\text{eff}}}{10^{31}\,\text{cm}^{-3}} + 0.4\, A \left(\frac{\Delta m^2}{1\,\text{eV}^2}\right)\left(\frac{1\,\text{MeV}}{E}\right) + \frac{1\,\text{m}}{L_{\dot{\phi}}} \right|$$

$$\boxed{\underset{\text{active neutrino}}{\nu_L} \rightarrow \underset{\text{sterile neutrino}}{\nu_R}}$$

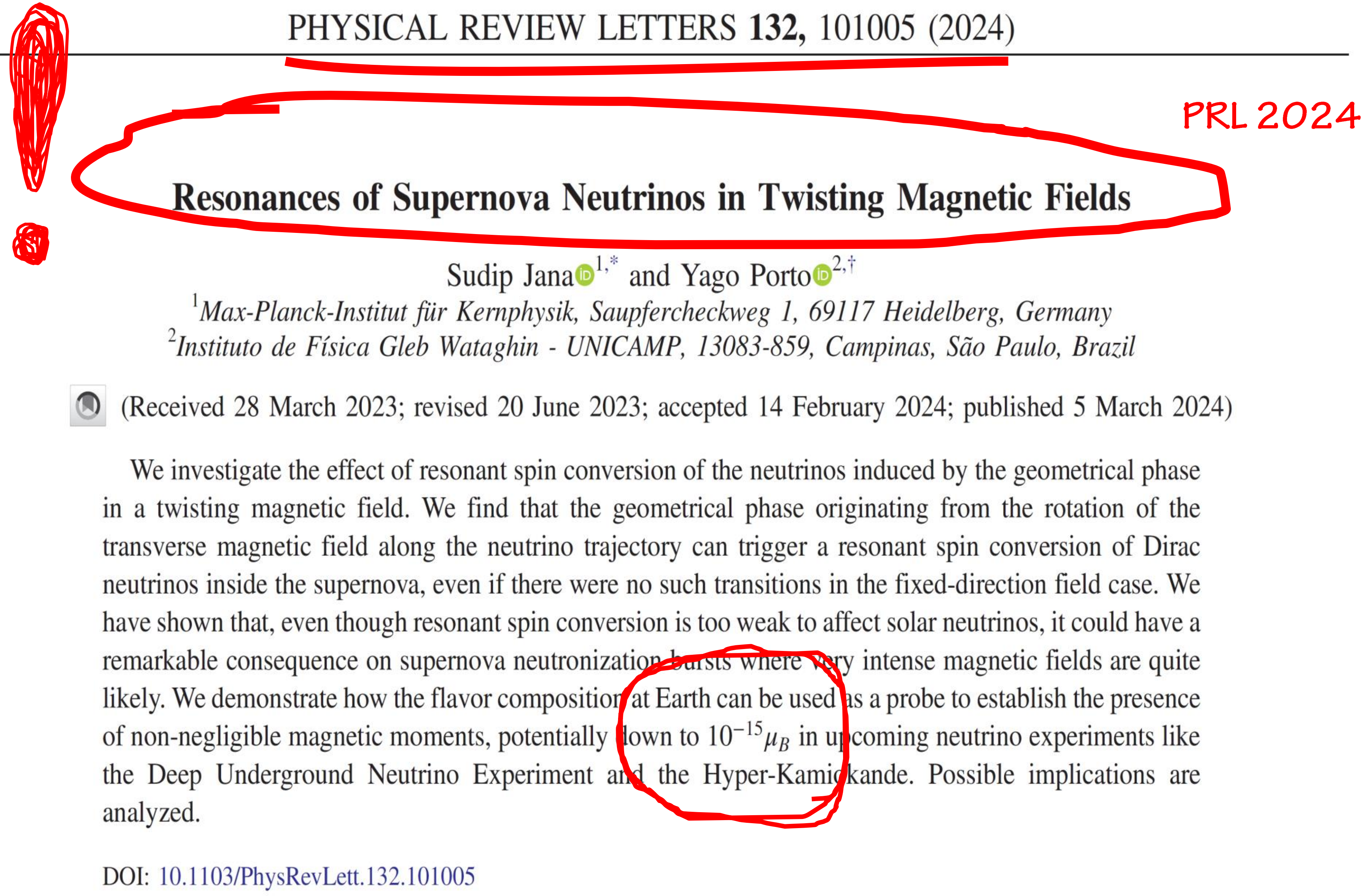
$$\bar{P}_{\nu_R} = \frac{1}{2} \sin^2 2\,\theta_{\text{eff}}$$



If $B \gtrsim \tilde{B}_{cr} \Rightarrow \sin^2 2\theta_{\text{eff}} \sim 1 \; (\gtrsim \frac{1}{2})$

“cross-boundary effect”

Likhachev, Studenikin,
Preprint ICTP, IC/94/70, 1994
Sov. Phys. JETP 108 (1995)



!

PHYSICAL REVIEW LETTERS **132,** 101005 (2024)

PRL 2024

Resonances of Supernova Neutrinos in Twisting Magnetic Fields

Sudip Jana[1,*] and Yago Porto[2,†]
[1]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[2]Instituto de Física Gleb Wataghin - UNICAMP, 13083-859, Campinas, São Paulo, Brazil

(Received 28 March 2023; revised 20 June 2023; accepted 14 February 2024; published 5 March 2024)

We investigate the effect of resonant spin conversion of the neutrinos induced by the geometrical phase in a twisting magnetic field. We find that the geometrical phase originating from the rotation of the transverse magnetic field along the neutrino trajectory can trigger a resonant spin conversion of Dirac neutrinos inside the supernova, even if there were no such transitions in the fixed-direction field case. We have shown that, even though resonant spin conversion is too weak to affect solar neutrinos, it could have a remarkable consequence on supernova neutronization bursts where very intense magnetic fields are quite likely. We demonstrate how the flavor composition at Earth can be used as a probe to establish the presence of non-negligible magnetic moments, potentially down to $10^{-15}\mu_B$ in upcoming neutrino experiments like the Deep Underground Neutrino Experiment and the Hyper-Kamiokande. Possible implications are analyzed.

DOI: 10.1103/PhysRevLett.132.101005

New developments in ν spin and flavour oscillation

… new astrophysical probes of ν

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

P.Pustoshny, Studenikin,
Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions
- Phys. Rev. D98 (2018) 113009

Studenikin, Neutrino in electromagnetic fields and moving matter
- Phys.Atom.Nucl. 67 (2004) 993-1002

② inherent interplay of ν spin and flavour oscillations in B

A. Popov, Studenikin,
Neutrino eigenstates and flavour, spin and spin-flavor oscillations in a constant magnetic field
- Eur. Phys. J. C79 (2019) 144

① ✓

Neutrino spin $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$ and spin-flavour $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R$ oscillations engendered by transversal matter current $j_\perp$

! without $(\cancel{\mu_\nu B})$

A. Studenikin,
Neutrino in electromagnetic fields and moving matter,
Phys. Atom. Nucl. 67 (2004) 993-1002

P. Pustoshny, A. Studenikin,
Neutrino spin and spin-flavour oscillations in
transversal matter currents with standard
and non-standard interactions, Phys. Rev. D98 (2018) 113009

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[*]

Moscow State University, Vorob'evy gory, Moscow, 119899 Russia

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.

Consider spin
spin-flavour

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

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

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

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

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

- transversal current $\mathbf{j}_\perp$

speed of ν

transversal speed of matter

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

matter density

$\parallel$

$\perp$

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

where

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

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

… the effect of ν helicity conversions and oscillations induced by transversal matter currents has been confirmed in studies of ν propagation in astrophysical media:

- 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: $\boxed{n = \frac{n_0}{\sqrt{1-v^2}}}$ neutron number density in laboratory reference frame

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

- $$\boxed{L_{\rm int} = -f^\mu \sum_l \bar{\nu}_l(x)\gamma_\mu \frac{1+\gamma_5}{2}\nu_l(x)}\boxed{= -f^\mu \sum_i \bar{\nu}_i(x)\gamma_\mu \frac{1+\gamma_5}{2}\nu_i(x)}$$

$l = e,\ or\ \mu$

$i = 1,\ 2$

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

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

$$\boxed{\begin{aligned} \nu_e^\pm &= \nu_1^\pm \cos\theta + \nu_2^\pm \sin\theta, \\ \nu_\mu^\pm &= -\nu_1^\pm \sin\theta + \nu_2^\pm \cos\theta \end{aligned}}$$

ν flavour and mass states

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

ν (2 flavours x 2 helicities) evolution equation

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

vacuum

matter at rest

moving matter

B

matter at rest

moving matter

Standard Model

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

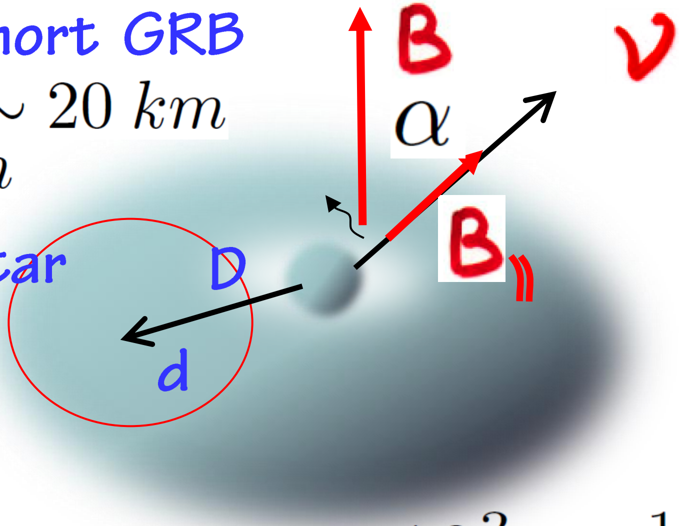
P. Pustoshny, A. Studenikin, Phys. Rev. D98 (2018) 113009

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

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: $B_{||} = B \sin\alpha \sim \frac{1}{2}B$

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

- transversal velocity of matter

$$v_\perp = \omega D = 0.067 \quad \text{and} \quad \gamma_n = 1.002$$

- Perego et al,
Mon.Not.Roy.Astron.Soc.
443 (2014) 3134
- Grigoriev, Lokhov,
Studenikin, Ternov,
JCAP 1711 (2017) 024

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

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

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

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

resonance condition

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

-

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:

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

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

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

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

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

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

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

$$\sin^2\theta = 0.297$$

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

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

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

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

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

②

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

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

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

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

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

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

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

$$\boxed{\begin{aligned}\nu_i^L(t) &= c_i^+\nu_i^+(t) + c_i^-\nu_i^-(t),\\ \nu_i^R(t) &= d_i^+\nu_i^+(t) + d_i^-\nu_i^-(t)\end{aligned}} \Lleftarrow \boxed{\nu_i^{-(+)}}$$

stationary states in B

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

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

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

"bra-ket" products

- $$\boxed{\hat{S}_i = \frac{1}{N}\left[\boldsymbol{\Sigma B} - \frac{i}{m_i}\gamma_0\gamma_5[\boldsymbol{\Sigma} \times \boldsymbol{p}]\boldsymbol{B}\right]} \quad \boxed{\hat{S}_i \left|\nu_i^s\right\rangle = s\left|\nu_i^s\right\rangle, s = \pm 1}$$

$$\langle\nu_i^s|\nu_k^{s'}\rangle = \delta_{ik}\delta_{ss'}$$ ●

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

- ν energy spectrum $$\boxed{E_i^s = \sqrt{m_i^2 + p^2 + {\mu_i}^2\mathbf{B}^2 + 2\mu_i s\sqrt{m_i^2\mathbf{B}^2 + p^2B_\perp^2}}}$$

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

$\nu_e^L \leftrightarrow \nu_\mu^L$ $\quad P_{\nu_e^L\to\nu_\mu^L}(t) = \left|\langle\nu_\mu^L|\nu_e^L(t)\rangle\right|^2$

$\mu_\pm = \frac{1}{2}(\mu_1 \pm \mu_2)$ magnetic moments of ν mass states

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

flavour

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

spin

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

spin-flavour

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

!

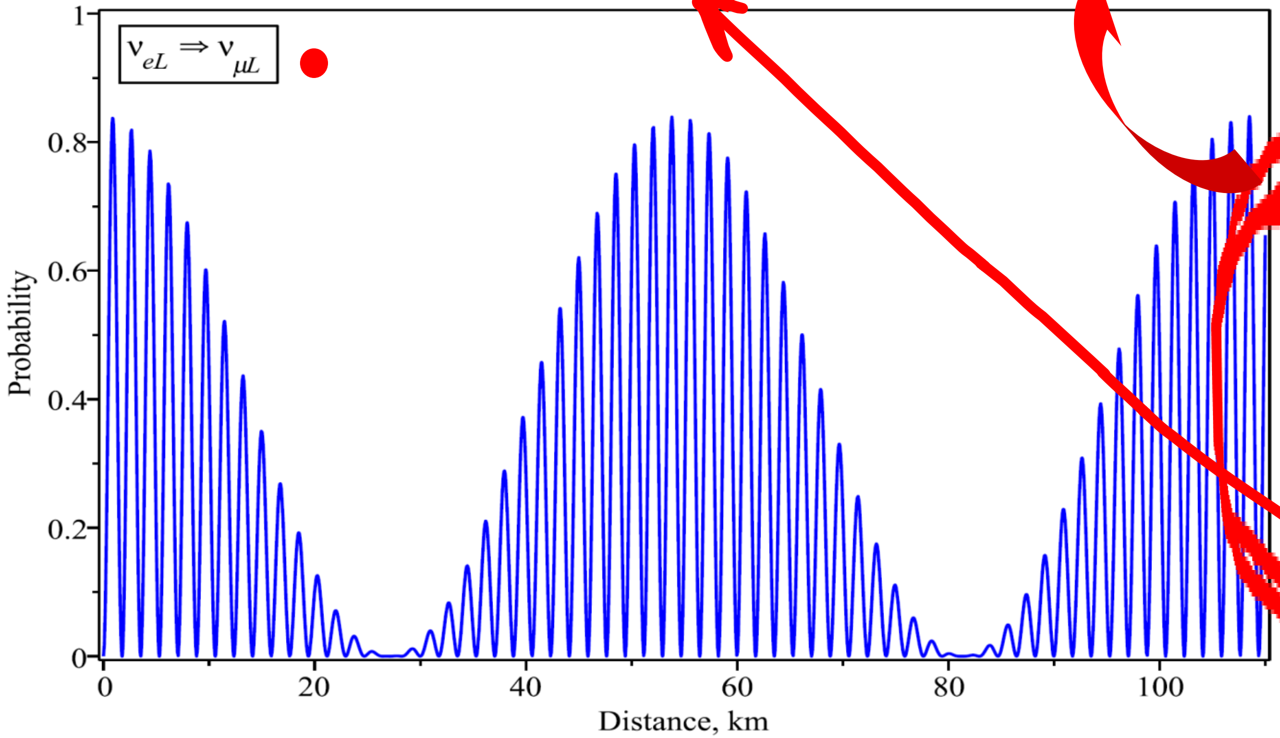
A.Popov, A.S., Eur. Phys .J. C79 (2019) 144

- 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



... amplitude of flavour oscillations on vacuum frequency $\omega_{vac} = \frac{\Delta m^2}{4p}$

is modulated by magnetic frequency $\omega_B = \mu B_\perp$

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 $\mu_1 = \mu_2 = 10^{-20}\mu_B$.

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

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

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

no flavour 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

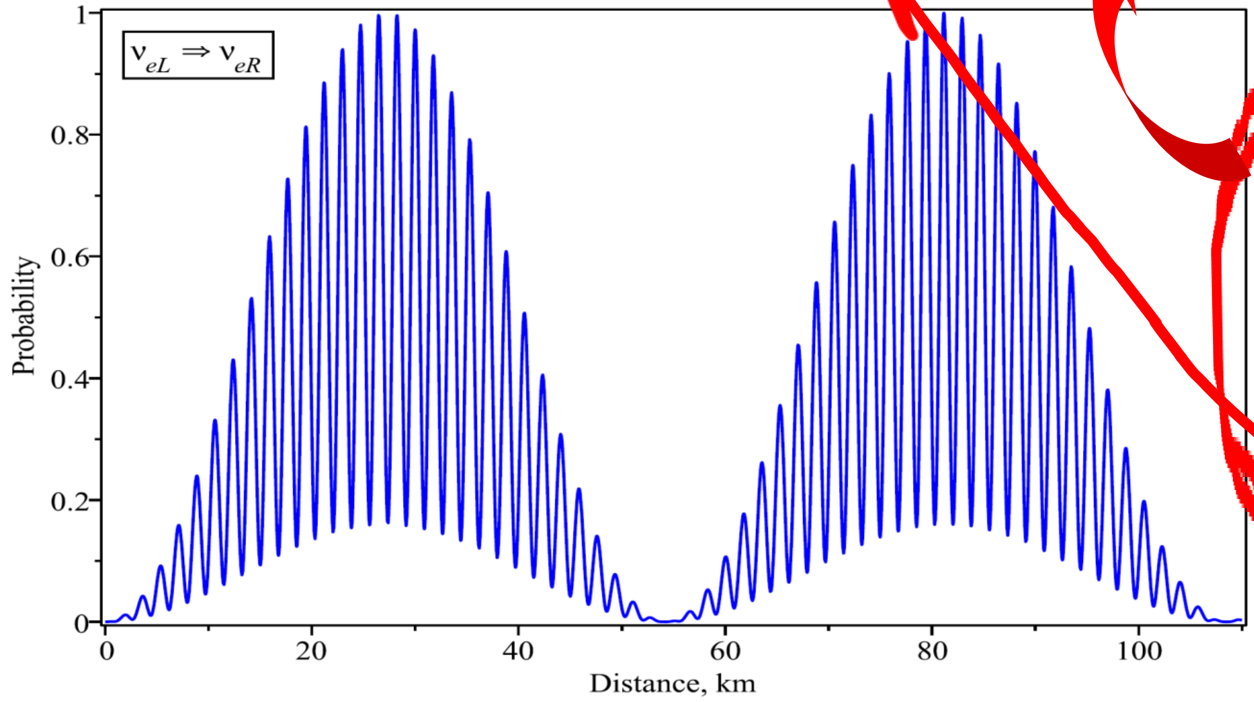


Fig. 2 The probability of the neutrino spin oscillations $\nu_e^L \to \nu_e^R$ in the transversal magnetic field $B_\perp = 10^{16}$ G for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7\times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20}\mu_B$.

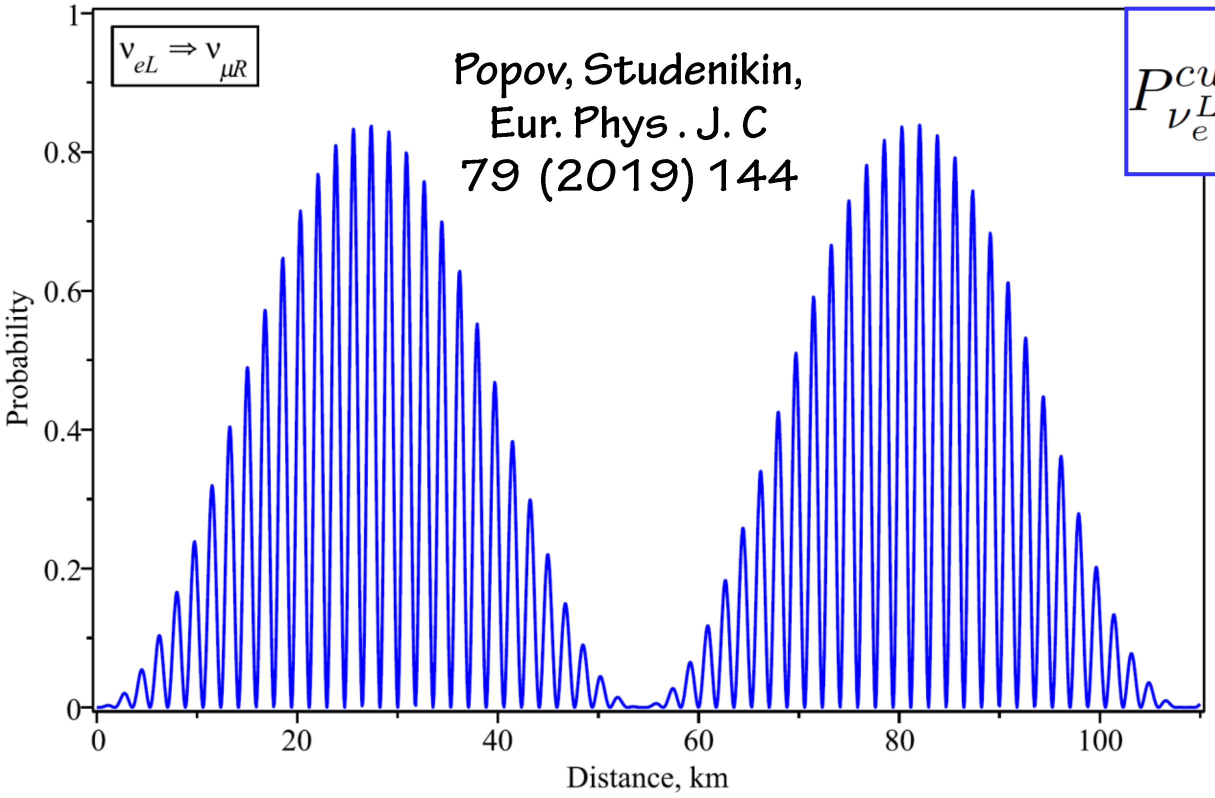
… amplitude of spin oscillations on magnetic frequency $\omega_B = \mu B_\perp$ is modulated by vacuum frequency $\omega_{vac} = \frac{\Delta m^2}{4p}$

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

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

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

spin-flavour



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

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 $\mu_1 = \mu_2 = 10^{-20}\mu_B$.

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

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

… interplay of oscillations

on vacuum $\omega_{vac} = \frac{\Delta m^2}{4p}$

and

on magnetic $\omega_B = \mu B_\perp$

frequencies

… in literature usually:

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

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

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

- ● … M. Dvornikov, J. Maalampi, Phys. Lett. B 657 (2007) 217

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

… depends on μ_ν and B

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

Σ 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

the discovered correspondence between flavour and spin oscillations in B can be important in studies of ν propagation in astrophysical environments

③ New effect in ν flavor oscillation in moving matter

$$\boxed{\nu_e^L \Leftarrow (j_{||}, j_\perp) \Rightarrow \nu_\mu^L} \qquad \boldsymbol{j}_\perp = n\boldsymbol{v}_\perp$$

longitudinal transversal
matter currents

invariant number density

Studenikin,
Physics of Particles and Nuclei 55 (2024) 1444
+ arXiv: 1912.12491

- Equal role of $\boldsymbol{j}_\perp$ and $\boldsymbol{B}_\perp$ in generation of

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

oscillations

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

- Probability of ν flavor oscillations $\nu_e^L \Leftarrow (j_{||}, j_\perp) \Rightarrow \nu_\mu^L$ in moving matter

$$\boxed{P^{(j_{||}+j_\perp)}_{\nu_e^L\to\nu_\mu^L}(t) = \underbrace{\left(1 - P^{(j_\perp)}_{\nu_e^L\to\nu_e^R} - P^{(j_\perp)}_{\nu_e^L\to\nu_\mu^R}\right)}_{} P^{(j_{||})}_{\nu_e^L\to\nu_\mu^L}}$$

probability of spin survival
(not spin flip)

$$\boxed{P^{(j_{||})}_{\nu_e^L\to\nu_\mu^L}(t) = \sin^2 2\theta_{eff}\sin^2\omega_{eff}t, \quad \omega_{eff} = \frac{\Delta m^2_{eff}}{4p_0^\nu}}$$

probability of flavor oscillations in $j_{||}$

$$\boxed{P^{j_\perp}_{\nu_e^L\to\nu_e^R}(t) = \frac{\left(\frac{\eta}{\gamma}\right)^2_{ee} v_\perp^2}{\left(\frac{\eta}{\gamma}\right)^2_{ee} v_\perp^2 + (1-\boldsymbol{v}\boldsymbol{\beta})^2}\sin^2\omega^{j_\perp}_{ee}t}$$

spin oscillations in $\boldsymbol{j}_\perp$

$$\boxed{P^{j_\perp}_{\nu_e^L\to\nu_\mu^R}(t) = \frac{\left(\frac{\eta}{\gamma}\right)^2_{e\mu} v_\perp^2}{\left(\frac{\eta}{\gamma}\right)^2_{e\mu} v_\perp^2 + \left(\frac{\Delta M}{\tilde{G}n} - (1-\boldsymbol{v}\boldsymbol{\beta})\right)^2}\sin^2\omega^{j_\perp}_{e\mu}t}$$

spin-flavor oscillations in $\boldsymbol{j}_\perp$

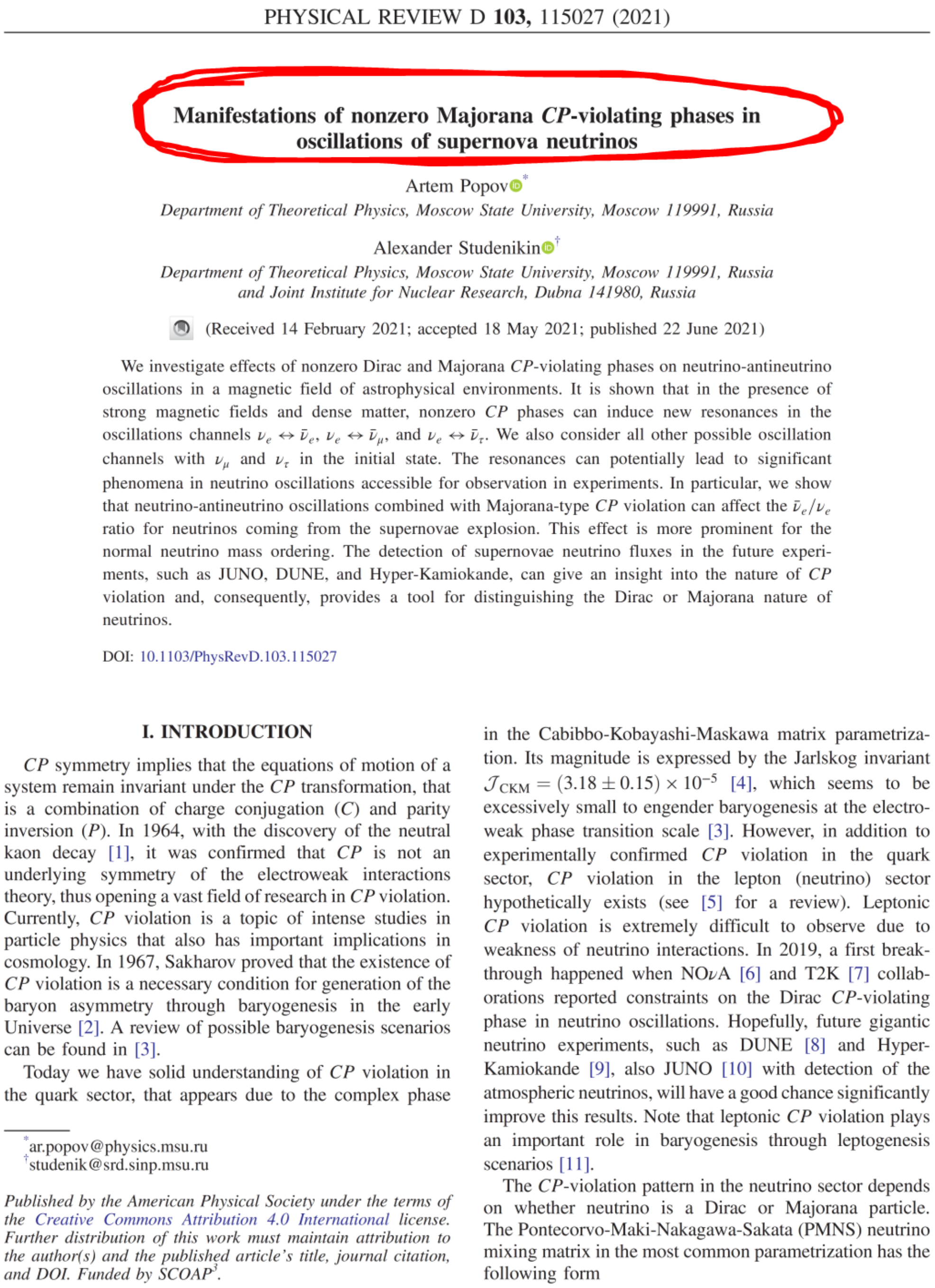
$$\boxed{\omega^{j_\perp}_{ee} = \tilde{G}n\sqrt{\left(\frac{\eta}{\gamma}\right)^2_{ee} v_\perp^2 + (1-\boldsymbol{v}\boldsymbol{\beta})^2}}$$

… is modulated by
two “matter”
frequencies …

$$\boxed{\omega^{j_\perp}_{e\mu} = \tilde{G}n\sqrt{\left(\frac{\eta}{\gamma}\right)^2_{e\mu} v_\perp^2 + \left(\frac{\Delta M}{\tilde{G}n} - (1-\boldsymbol{v}\boldsymbol{\beta})\right)^2}}$$

$$\left(\frac{\eta}{\gamma}\right)_{ee} = \frac{\cos^2\theta}{\gamma_{11}} + \frac{\sin^2\theta}{\gamma_{22}} \qquad {\gamma_{\alpha\alpha'}}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} + \gamma_{\alpha'}^{-1}\right) \qquad \gamma_\alpha^{-1} = \frac{m_\alpha}{E_\alpha}$$

$$\left(\frac{\eta}{\gamma}\right)_{e\mu} = \frac{\sin 2\theta}{\tilde{\gamma}_{21}} \qquad \tilde{\gamma}^{-1}_{\alpha\alpha'} = \frac{1}{2}\left(\gamma_\alpha^{-1} - \gamma_{\alpha'}^{-1}\right)$$



PHYSICAL REVIEW D **103,** 115027 (2021)

Manifestations of nonzero Majorana *CP*-violating phases in oscillations of supernova neutrinos

Artem Popov[*]
Department of Theoretical Physics, Moscow State University, Moscow 119991, Russia

Alexander Studenikin[†]
Department of Theoretical Physics, Moscow State University, Moscow 119991, Russia
and Joint Institute for Nuclear Research, Dubna 141980, Russia

(Received 14 February 2021; accepted 18 May 2021; published 22 June 2021)

We investigate effects of nonzero Dirac and Majorana *CP*-violating phases on neutrino-antineutrino oscillations in a magnetic field of astrophysical environments. It is shown that in the presence of strong magnetic fields and dense matter, nonzero *CP* phases can induce new resonances in the oscillations channels $\nu_e \leftrightarrow \bar{\nu}_e$, $\nu_e \leftrightarrow \bar{\nu}_\mu$, and $\nu_e \leftrightarrow \bar{\nu}_\tau$. We also consider all other possible oscillation channels with ν_μ and ν_τ in the initial state. The resonances can potentially lead to significant phenomena in neutrino oscillations accessible for observation in experiments. In particular, we show that neutrino-antineutrino oscillations combined with Majorana-type *CP* violation can affect the $\bar{\nu}_e/\nu_e$ ratio for neutrinos coming from the supernovae explosion. This effect is more prominent for the normal neutrino mass ordering. The detection of supernovae neutrino fluxes in the future experiments, such as JUNO, DUNE, and Hyper-Kamiokande, can give an insight into the nature of *CP* violation and, consequently, provides a tool for distinguishing the Dirac or Majorana nature of neutrinos.

DOI: 10.1103/PhysRevD.103.115027

I. INTRODUCTION

CP symmetry implies that the equations of motion of a system remain invariant under the *CP* transformation, that is a combination of charge conjugation (*C*) and parity inversion (*P*). In 1964, with the discovery of the neutral kaon decay [1], it was confirmed that *CP* is not an underlying symmetry of the electroweak interactions theory, thus opening a vast field of research in *CP* violation. Currently, *CP* violation is a topic of intense studies in particle physics that also has important implications in cosmology. In 1967, Sakharov proved that the existence of *CP* violation is a necessary condition for generation of the baryon asymmetry through baryogenesis in the early Universe [2]. A review of possible baryogenesis scenarios can be found in [3].

Today we have solid understanding of *CP* violation in the quark sector, that appears due to the complex phase in the Cabibbo-Kobayashi-Maskawa matrix parametrization. Its magnitude is expressed by the Jarlskog invariant $\mathcal{J}_{\rm CKM} = (3.18 \pm 0.15) \times 10^{-5}$ [4], which seems to be excessively small to engender baryogenesis at the electroweak phase transition scale [3]. However, in addition to experimentally confirmed *CP* violation in the quark sector, *CP* violation in the lepton (neutrino) sector hypothetically exists (see [5] for a review). Leptonic *CP* violation is extremely difficult to observe due to weakness of neutrino interactions. In 2019, a first breakthrough happened when NOνA [6] and T2K [7] collaborations reported constraints on the Dirac *CP*-violating phase in neutrino oscillations. Hopefully, future gigantic neutrino experiments, such as DUNE [8] and Hyper-Kamiokande [9], also JUNO [10] with detection of the atmospheric neutrinos, will have a good chance significantly improve this results. Note that leptonic *CP* violation plays an important role in baryogenesis through leptogenesis scenarios [11].

The *CP*-violation pattern in the neutrino sector depends on whether neutrino is a Dirac or Majorana particle. The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix in the most common parametrization has the following form

---

[*] ar.popov@physics.msu.ru
[†] studenik@srd.sinp.msu.ru

A.Popov, A.Studenikin
Phys. Rev. D103 (2021) 115027

… the role of Majorana CP-violating phases in neutrino oscillations

$$\nu_e \leftrightarrow \bar{\nu}_{e,\mu,\tau}$$

in strong B and dense matter of supernovae for two mass hierarchies

… Majorana CP phases induce new resonances

… a tool for distinguishing Dirac-Majorana nature of ν

μ_ν

see presentation by
Artem Popov

PHYSICAL REVIEW D **101,** 056004 (2020)

Neutrino quantum decoherence engendered by neutrino radiative decay

Konstantin Stankevich[*]
Department of Theoretical Physics, Faculty of Physics, Lomonosov Moscow State University, 119992 Moscow, Russia

Alexander Studenikin[†]
Department of Theoretical Physics, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
and Dzhelepov Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia

(Received 26 November 2019; accepted 6 February 2020; published 5 March 2020)

A new theoretical framework, based on the quantum field theory of open systems applied to neutrinos, has been developed to describe the neutrino evolution in external environments accounting for the effect of the neutrino quantum decoherence. The developed new approach enables one to obtain the explicit expressions of the decoherence and relaxation parameters that account for a particular process, in which the neutrino participates, and also for the characteristics of an external environment and of the neutrino itself, including the neutrino energy. We have used this approach to consider a new mechanism of the neutrino quantum decoherence engendered by the neutrino radiative decay to photons and dark photons in an astrophysical environment. The importance of the performed studies is highlighted by the prospects of the forthcoming new large volume neutrino detectors that will provide new frontier in high-statistics measurements of neutrino fluxes from supernovae.

DOI: 10.1103/PhysRevD.101.056004

I. INTRODUCTION

Half a century ago Gribov and Pontecorvo derived [1] the first analytical expression for the neutrino oscillation probability that has opened a new era in the theoretical and experimental studies of the neutrino oscillation phenomenon. The neutrino oscillation patterns can be modified by neutrino interactions with external environments including electromagnetic fields that can influence neutrinos in the case neutrinos have nonzero electromagnetic properties [2]. The phenomenon of neutrino oscillations can proceed only in the case of the coherent superposition of neutrino mass states. An external environment can modify a neutrino evolution in a way that conditions for the coherent superposition of neutrino mass states are violated. Such a violation is called quantum decoherence of neutrino states and leads to the suppression of flavor neutrino oscillations. It should be noted that the quantum neutrino decoherence differs from the standard neutrino decoherence that appears due to separation of neutrino wave packets, the effect that is not considered below.

The quantum neutrino decoherence has attracted a growing interest during the last 15 years. Within reasonable amount of the performed studies, the method based on the Lindblad master equation [3,4] for describing neutrino evolution has been used. This approach is usually considered as the most general one that gives a possibility to study neutrino quantum decoherence as a consequence of standard and nonstandard interactions of a neutrino system with an external environment [5–15].

The Lindblad master equation can be written in the following form (see, for instance, [13]):

$$\frac{\partial \rho_\nu(t)}{\partial t} = -i[H_S, \rho_\nu(t)] + D[\rho_\nu], \tag{1}$$

where ρ_ν is the density matrix that describes the neutrino evolution, H_S is the Hamiltonian, and the dissipation term (or dissipator) is given by

$$D[\rho_\nu(t)] = \frac{1}{2}\sum_{k=1}^{N^2-1}[V_k, \rho_\nu V_k^\dagger] + [V_k \rho_\nu, V_k^\dagger], \tag{2}$$

where V_k are dissipative operators that arise from interaction between the neutrino system and the external

---

[*] kl.stankevich@physics.msu.ru
[†] studenik@srd.sinp.msu.ru

Stankevich, Studenikin,
Neutrino quantum decoherence engendered by neutrino radiative decay
Phys.Rev.D 101 (2020) 056004

… ν radiative decay as a source of quantum decoherence in extreme astrophycal environments

⇓ μ_ν

… observable consequences for SN ν
(JUNO, DUNE, Hyper-Kamiokande)

see presentations by
Konstantin Stankevich
and
Van Degan

… Conclusions …

① Electromagnetic Properties of ν

MSU Alexander Studenikin NCPM

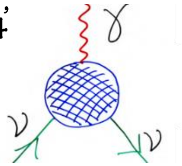
National Center FOR PHYSICS AND MATHEMATICS

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

Studenikin,
“Overview of ν electromagnetic
properties 2022”, arXiv:2301.06071;

“Electromagnetic properties of neutrino 2023”,
Physics of Particles and Nuclei 55 (2024) 1144

① νEP theory - ν vertex function



matrices in ν mass
eigenstates space

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

electric charge

magnetic moment

electric moment

anapole moment

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

Dirac ν Majorana

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

CPT
+
charge concervation

Hermiticity and discrete symmetries of EM current

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

② $\boxed{\mu_{jj}^D = \dfrac{3e_0G_Fm_j}{8\sqrt{2}\pi^2} \approx 3.2\times10^{-19}\mu_B\left(\dfrac{m_j}{1\ \mathrm{eV}}\right)}$

Fujikawa & Shrock, 1980

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

③ ν EMP experimental bounds

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

GEMMA 2012

Borexino 2017 ~ XENON1T 2020

astrophys., Raffelt ea 1988, 2020

Arcoa Dias ea 2015

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

reactor ν scattering
AS ‘14, Chen ea ‘14

AS ‘14 (astrophysics)

neutrality of matter

- charge rad. $<r_\nu^2>$ is most accessible for exp. observations ●

② ν electromagnetic properties: Future prospects

- new constraintson μ_ν (and q_ν) from GEMMA-2/νGeN and Borexino (?)

- XENON1T an excess in electronic recoil events in < 7 keV (2-3 keV) over known backgrnds $\Longrightarrow$ $\boxed{\mu_\nu \in (1.4,\ 2.9) \times 10^{-11}\ \mu_B}$

  E. Aprile et al, XENON1T coll., Phys Rev. D 102 (2020) 072004

  ! XENONnT

  O.Miranda, D. Papoulias, M. Tórtola, J. W. F. Valle,
  XENON1T signal from transition neutrino magnetic moments, Phys.Lett. B 808 (2020) 135685

- new improved limit from stellar evolution data for global cluster ω-Centauri $\Longrightarrow$ $\boxed{\mu_\nu < 2.2 \times 10^{-12} \mu_B}$

  S. Arceo-Diaz, K.-P.Schroder, K.Zuber, D.Jack,
  Astropart.Phys. 70 (2015) 1

- new improved limit $\boxed{\mu_\nu < 1.2 \times 10^{-12} \mu_B}$

  F.Capozzi, G.Raffelt,
  Phys. Rev. D 102 (2020) 083007

  comes from improved new calibrations of tip of red-giant branch which allows one to constrain novel energy losses

- new setup to observe coherent elastic neutrino-atom scattering using electron antineutrinos from tritium decay and a liquid helium target $\Longrightarrow$ upper limit

  M.Cadeddu, F.Dordei, C.Giunti,
  K.Kouzakov, E.Picciau, A.Studenikin,
  Potentialities of a low-energy detector based on 4 He evaporation to observe atomic effects in coherent neutrino scattering and physics perspectives, Phys. Rev. D100 (2019) no.7, 073014

  $\boxed{\mu_\nu < 7 \times 10^{-13} \mu_B}$

⇒ **XENONnT Collaboration** E.Aprile et al. (XENON Coll.), Search for New Physics in electronic recoil data from XENONnT, Phys.Rev.Lett. 122 (2022) 161805

- Upgraded experiment has managed to rule out the so-called XENON1T excess by using a new larger liquid xenon (LXe)

Implications of first LUX-ZEPLIN and XENONnT results

A.Khan, Light new physics and neutrino electromagnetic interactions in XENONnT, Phys.Lett.B 837 (2023) 137650

M.Atzori Corona, W.Bonivento, M.Cadeddu, N.Cargioli, F.Dordei, New constraint on neutrino magnetic moment from LZ dark matter search results, Phys.Rev.D107 (2023) 053001

K.ShivaSankar, A.Majumdar, D.Papoulias, H.Prajapati, R. Srivastava, Phys.Lett. B 839 (2023) 137742

C.Giunti, C.Ternes, Testing neutrino electromagnetic properties at current and future dark matter experiments, Phys. Rev. D 108 (2023) 095044

J. Aalbers et al., A next-generation liquid xenon observatory for dark matter and neutrino physics, J.Phys.G 50 (2023) 1, 013001

… new stringent upper limits $\mu_\nu \sim few \times 10^{-12} \mu_B$

… new stringent upper limits on $q_\nu \sim 10^{-13}\ e_0$

2024 + soon …

$\mu_\nu \sim (5-9) \times 10^{-12} \mu_B$

νGeN experiment … low threshold … $T \sim 200\ \ eV$

I.Alekseev et al., First results of the νGeN experiment on coherent elastic neutrino-nucleus scattering, Phys.Rev.D 106 (2022) 5, L051101

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

⇒ A.Studenikin, Europhys. Lett. 107 (2014) 210011

- Initial interest in effect of ν spin oscillations in B on supernovae ν fluxes

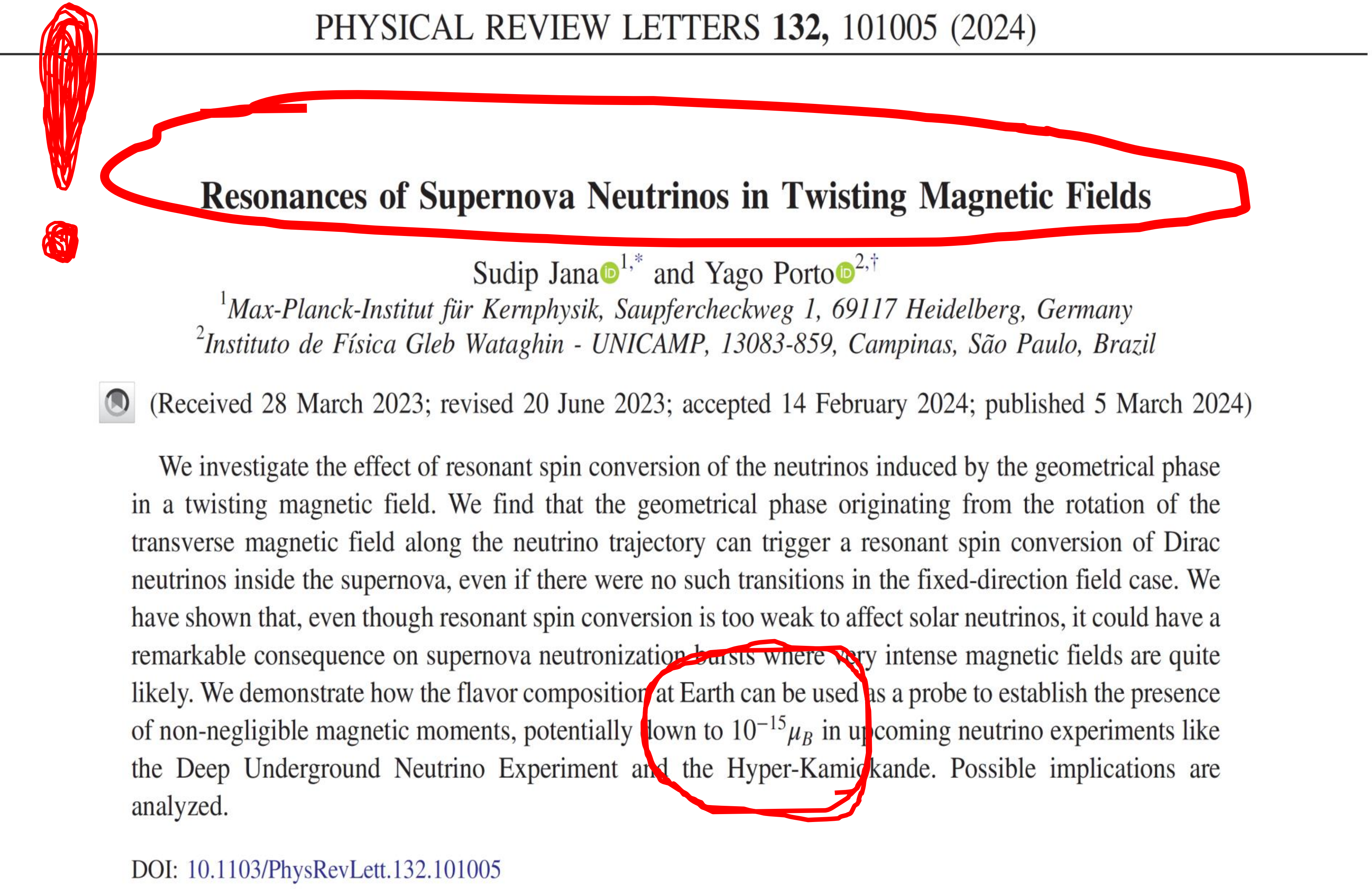
  - H.Nunokawa, R.Tomas, J. W. F. Valle,
    Type-II supernovae and neutrino magnetic moment,
    Astropart.Phys.11 (1999) 317

has recently increased again

(new large-volume ν detectors, DUNE, Hyper-Kamiokande and JUNO, open up new possibilities in precise determination of flavour ratios in supernovae ν fluxes)

- V.Brdar, A.de Gouvêa, Y.-Y Li, P. Machado,
  The neutrino magnetic moment portal and supernovae: New constraints and multimessenger opportunities, Phys.Rev. D 107 (2023) 073005
- E.Wang, Resonant spin-flavor precession of sterile neutrinos, JCAP 05 (2024) 056
- S.Jana, Y.Porto, New resonances of supernova neutrinos in magnetic fields,
  Phys. Rev. Lett. 132 (2024) 101005

probe non-negligible μ_ν $\boxed{\text{potentially down to} \sim 10^{-15}\mu_B}$



PHYSICAL REVIEW LETTERS **132,** 101005 (2024)

Resonances of Supernova Neutrinos in Twisting Magnetic Fields

Sudip Jana[1,*] and Yago Porto[2,†]
[1] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[2] *Instituto de Física Gleb Wataghin - UNICAMP, 13083-859, Campinas, São Paulo, Brazil*

(Received 28 March 2023; revised 20 June 2023; accepted 14 February 2024; published 5 March 2024)

We investigate the effect of resonant spin conversion of the neutrinos induced by the geometrical phase in a twisting magnetic field. We find that the geometrical phase originating from the rotation of the transverse magnetic field along the neutrino trajectory can trigger a resonant spin conversion of Dirac neutrinos inside the supernova, even if there were no such transitions in the fixed-direction field case. We have shown that, even though resonant spin conversion is too weak to affect solar neutrinos, it could have a remarkable consequence on supernova neutronization bursts where very intense magnetic fields are quite likely. We demonstrate how the flavor composition at Earth can be used as a probe to establish the presence of non-negligible magnetic moments, potentially down to $10^{-15}\mu_B$ in upcoming neutrino experiments like the Deep Underground Neutrino Experiment and the Hyper-Kamiokande. Possible implications are analyzed.

DOI: 10.1103/PhysRevLett.132.101005

The search for coherent elastic neutrino-atom scattering and ν magnetic moment in Sarov

NCPhM Scientific Programme, Direction # 8 “Physics of Hydrogen Isotopes”

Sarov Tritium Neutrino Experiment = SATURNE Collaboration

Matteo Cadeddu (INFN, Cagliari), Francesca Derdei (INFN, Cagliari), Carlo Giunti (INFN, Turin),
Konstantin Kouzakov (MSU), Bayarto Lubsandorzhiev (INR RAS), Oleg Moskalev, (VNIIEF, Sarov),
Ivan Stepantsov (MSU), Alexander Studenikin (MSU), Vladimir Trofimov (JINR),
Maxim Vyalkov (MSU), Arkady Yukhimchuk (VNIIEF, Sarov)

PHYSICAL REVIEW D **100,** 073014 (2019)

Potentialities of a low-energy detector based on ^{4}He evaporation to observe atomic effects in coherent neutrino scattering and physics perspectives

M. Cadeddu,[1,*] F. Dordei,[2,†] C. Giunti,[3,‡] K. A. Kouzakov,[4,§] E. Picciau,[1,‖] and A. I. Studenikin[5,6,¶]
[1] *Università degli studi di Cagliari and Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Cagliari, Complesso Universitario di Monserrato—S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy*
[2] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Cagliari, Complesso Universitario di Monserrato—S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy*
[3] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy*
[4] *Department of Nuclear Physics and Quantum Theory of Collisions, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia*
[5] *Department of Theoretical Physics, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia*
[6] *Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia*

(Received 14 July 2019; published 29 October 2019)

We propose an experimental setup to observe coherent elastic neutrino-atom scattering (CEνAS) using electron antineutrinos from tritium decay and a liquid helium target. In this scattering process with the whole atom, that has not been observed so far, the electrons tend to screen the weak charge of the nucleus as seen by the electron antineutrino probe. The interference between the nucleus and the electron cloud produces a sharp dip in the recoil spectrum at atomic recoil energies of about 9 meV, reducing sizably the number of expected events with respect to the coherent elastic neutrino-nucleus scattering case. We estimate that with a 60 g tritium source surrounded by 500 kg of liquid helium in a cylindrical tank, one could observe the existence of CEνAS processes at 3σ in 5 yr of data taking. Keeping the same amount of helium and the same data-taking period, we test the sensitivity to the Weinberg angle and a possible neutrino magnetic moment for three different scenarios: 60, 160, and 500 g of tritium. In the latter scenario, the Standard Model (SM) value of the Weinberg angle can be measured with a statistical uncertainty of $\sin^2\vartheta_W^{\mathrm{SM}}{}^{+0.015}_{-0.016}$. This would represent the lowest-energy measurement of $\sin^2\vartheta_W$, with the advantage of being not affected by the uncertainties on the neutron form factor of the nucleus as the current lowest-energy determination. Finally, we study the sensitivity of this apparatus to a possible electron neutrino magnetic moment and we find that using 60 g of tritium it is possible to set an upper limit of about $7\times10^{-13}\mu_B$ at 90% C.L., that is more than one order of magnitude smaller than the current experimental limit.

DOI: 10.1103/PhysRevD.100.073014

I. INTRODUCTION

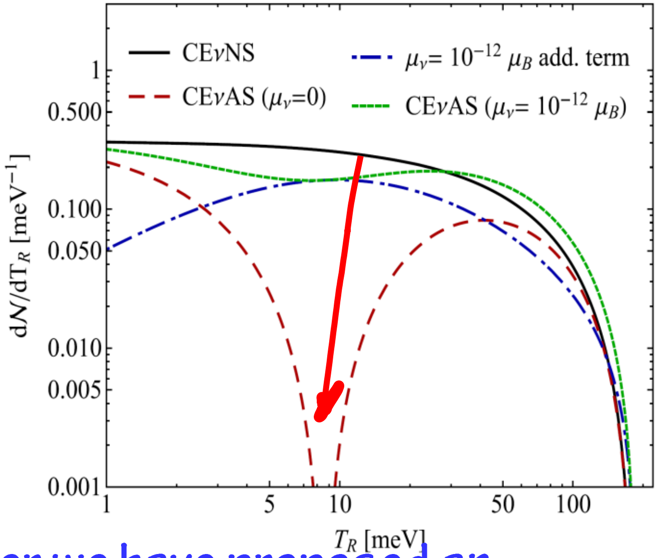
Coherent elastic neutrino-nucleus scattering (CEνNS) has been recently observed by the COHERENT experiment [1,2], after many decades from its prediction [3–5]. This observation triggered a lot of attention from the scientific community and unlocked a new and powerful tool to study many and diverse physical phenomena: nuclear physics [6,7], neutrino properties [8–10], physics beyond the Standard Model (SM) [11–17], and electroweak interactions [18,19]. The experimental challenge related to the CEνNS observation is due to the fact that in order to meet the coherence requirement $qR \ll 1$ [20], where $q = |\vec{q}|$ is the three-momentum transfer and R is the nuclear radius, one has to detect very small nuclear recoil energies E_R, lower than a few keV.

At even lower momentum transfers, such that $qR_{\mathrm{atom}} \ll 1$, where R_{atom} is the radius of the target atom including the electron shells, the reaction can be viewed as taking place on the atom as a whole [21]. This effect should be visible for $qR_{\mathrm{atom}} \sim 1$, i.e., for momentum

---

[*] matteo.cadeddu@ca.infn.it
[†] francesca.dordei@cern.ch
[‡] carlo.giunti@to.infn.it
[§] kouzakov@gmail.com
[‖] emmanuele.picciau@ca.infn.it
[¶] studenik@srd.sinp.msu.ru

2470-0010/2019/100(7)/073014(9) 073014-1 Published by the American Physical Society



In our paper we have proposed an experimental setup to observe coherent elastic neutrino-atom scattering (CEνAS) using electron antineutrinos from tritium decay and a supefluid ^{4}He target.

In this scattering process with the whole atom, that has not been observed so far, the electrons tend to screen the weak charge of the nucleus as seen by the electron antineutrino probe.

$$\mu_\nu \sim 10^{-13}\mu_B$$

supefluid ^{4}He target technology (HeRALD) for direct detection of sub-GeV DM has been recently proposed in: S.Hartel et al., Phys.Rev.D 100 (2019) 9, 092007

Национальный центр
ФИЗИКИ и МАТЕМАТИКИ

The SATURNE Collaboration

- see talk by
  Konstantin Kouzakov

RUSSIAN FEDERAL NUCLEAR CENTER
ALL-RUSSIAN RESEARCH INSTITUTE OF EXPERIMENTAL PHYSICS

PRODUCTION ASSOCIATION
MAYAK

NIZHNY NOVGOROD STATE TECHNICAL UNIVERSITY N.A. R.E. ALEKSEEV

LOMONOSOV MOSCOW STATE UNIVERSITY

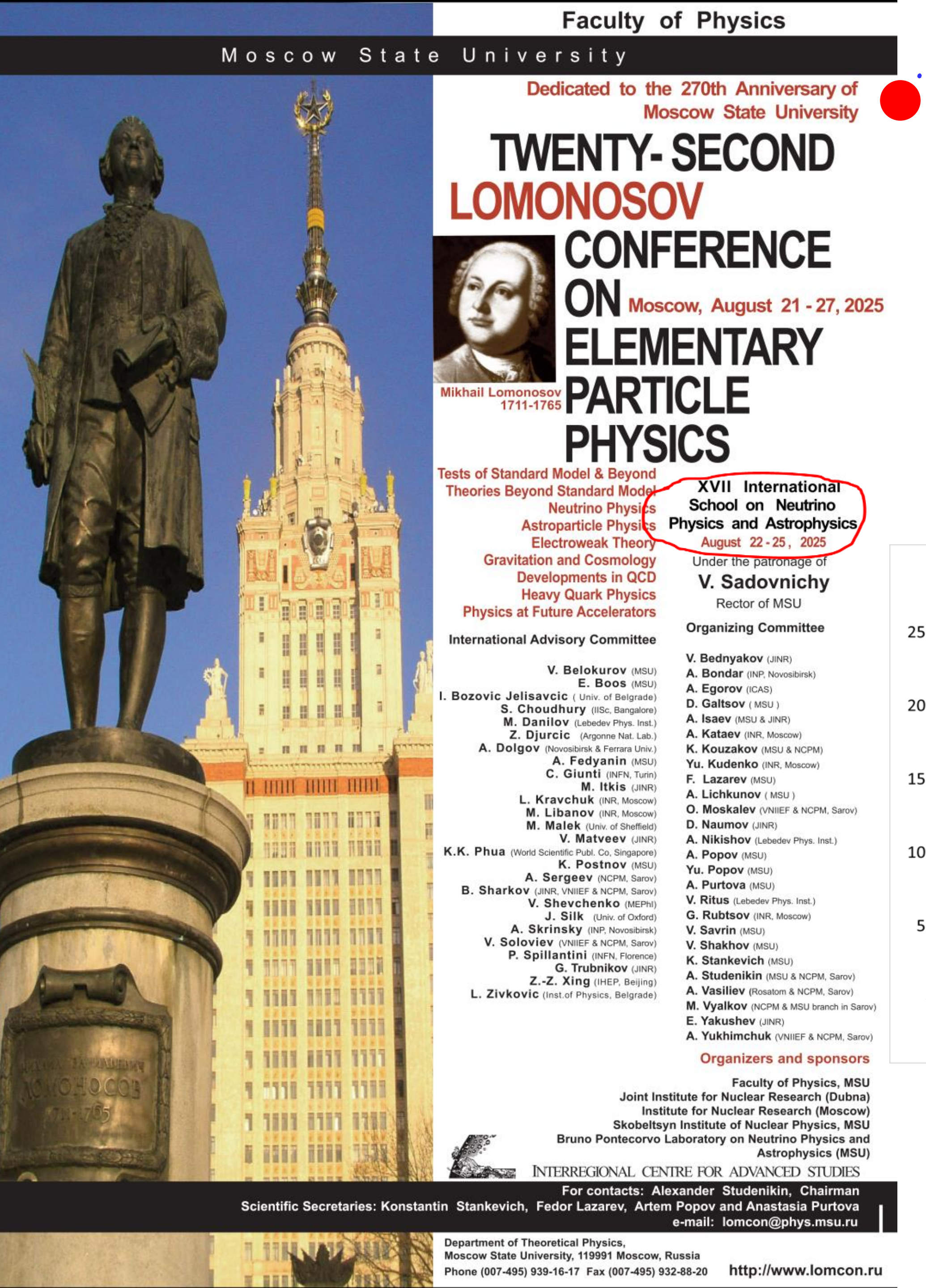
LOBACHEVSKY UNIVERSITY

JOINT INSTITUTE FOR NUCLEAR RESEARCH

IPM RAS

Ioffe Physical-Technical Institute

158



Faculty of Physics

Moscow State University

Dedicated to the 270th Anniversary of
Moscow State University

TWENTY- SECOND LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

Moscow, August 21 - 27, 2025

Mikhail Lomonosov
1711-1765

Tests of Standard Model & Beyond
Theories Beyond Standard Model
Neutrino Physics
Astroparticle Physics
Electroweak Theory
Gravitation and Cosmology
Developments in QCD
Heavy Quark Physics
Physics at Future Accelerators

XVII International
School on Neutrino
Physics and Astrophysics
August 22 - 25, 2025

Under the patronage of
V. Sadovnichy
Rector of MSU

International Advisory Committee

V. Belokurov (MSU)
E. Boos (MSU)
I. Bozovic Jelisavcic (Univ. of Belgrade)
S. Choudhury (IISc, Bangalore)
M. Danilov (Lebedev Phys. Inst.)
Z. Djurcic (Argonne Nat. Lab.)
A. Dolgov (Novosibirsk & Ferrara Univ.)
A. Fedyanin (MSU)
C. Giunti (INFN, Turin)
M. Itkis (JINR)
L. Kravchuk (INR, Moscow)
M. Libanov (INR, Moscow)
M. Malek (Univ. of Sheffield)
V. Matveev (JINR)
K.K. Phua (World Scientific Publ. Co, Singapore)
K. Postnov (MSU)
A. Sergeev (NCPM, Sarov)
B. Sharkov (JINR, VNIIEF & NCPM, Sarov)
V. Shevchenko (MEPhI)
J. Silk (Univ. of Oxford)
A. Skrinsky (INP, Novosibirsk)
V. Soloviev (VNIIEF & NCPM, Sarov)
P. Spillantini (INFN, Florence)
G. Trubnikov (JINR)
Z.-Z. Xing (IHEP, Beijing)
L. Zivkovic (Inst.of Physics, Belgrade)

Organizing Committee

V. Bednyakov (JINR)
A. Bondar (INP, Novosibirsk)
A. Egorov (ICAS)
D. Galtsov (MSU)
A. Isaev (MSU & JINR)
A. Kataev (INR, Moscow)
K. Kouzakov (MSU & NCPM)
Yu. Kudenko (INR, Moscow)
F. Lazarev (MSU)
A. Lichkunov (MSU)
O. Moskalev (VNIIEF & NCPM, Sarov)
D. Naumov (JINR)
A. Nikishov (Lebedev Phys. Inst.)
A. Popov (MSU)
Yu. Popov (MSU)
A. Purtova (MSU)
V. Ritus (Lebedev Phys. Inst.)
G. Rubtsov (INR, Moscow)
V. Savrin (MSU)
V. Shakhov (MSU)
K. Stankevich (MSU)
A. Studenikin (MSU & NCPM, Sarov)
A. Vasiliev (Rosatom & NCPM, Sarov)
M. Vyalkov (NCPM & MSU branch in Sarov)
E. Yakushev (JINR)
A. Yukhimchuk (VNIIEF & NCPM, Sarov)

Organizers and sponsors

Faculty of Physics, MSU
Joint Institute for Nuclear Research (Dubna)
Institute for Nuclear Research (Moscow)
Skobeltsyn Institute of Nuclear Physics, MSU
Bruno Pontecorvo Laboratory on Neutrino Physics and Astrophysics (MSU)

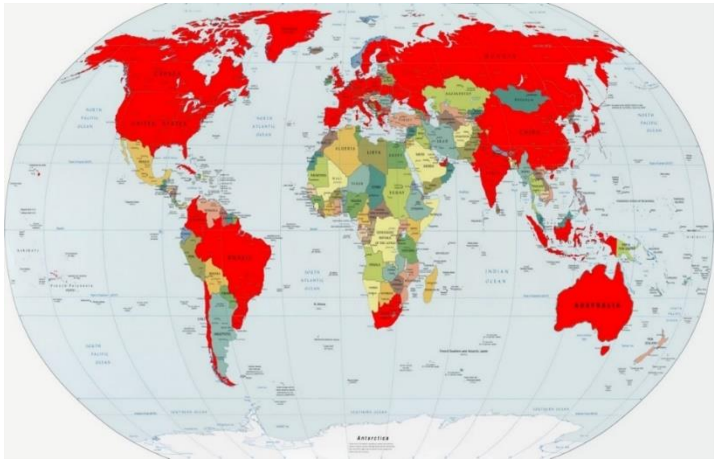
INTERREGIONAL CENTRE FOR ADVANCED STUDIES

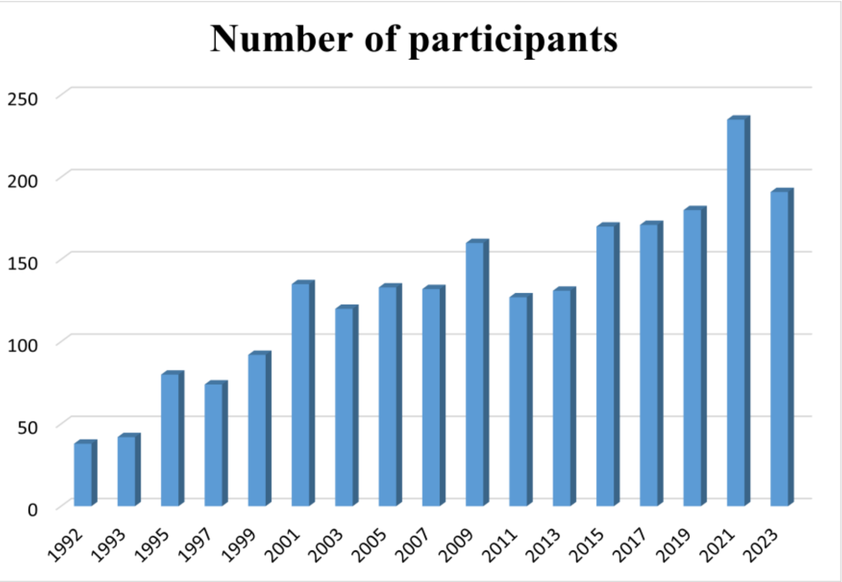
For contacts: Alexander Studenikin, Chairman
Scientific Secretaries: Konstantin Stankevich, Fedor Lazarev, Artem Popov and Anastasia Purtova
e-mail: lomcon@phys.msu.ru

Department of Theoretical Physics,
Moscow State University, 119991 Moscow, Russia
Phone (007-495) 939-16-17 Fax (007-495) 932-88-20

http://www.lomcon.ru

... about 200 speakers and 400 participants





... registration will be opened
in October 2024 ...

http://lomcon.ru

… Thank you …

The SATURNE Collaboration

M. Cadeddu, F. Dordei, C. Giunti, K. Kouzakov, E. Picciau, A. Studenikin,

- Potentialities of a low-energy detector based on 4He evaporation to observe atomic effects in coherent neutrino scattering and physics Perspectives, Phys.Rev.D 100 (2019) 073014

- New process in superfluid 4 He detectors: The coherent elastic neutrino-atom scattering, PoS ICHEP2020 (2021) 211

A.Yukhimchuk, K.Kouzakov, A.Studenikin et al.,

- Physics of hydrogen isotopes, PhysMath J. 1 (2023) p. 5-19, DOI: 10.56304/S2949609823010057

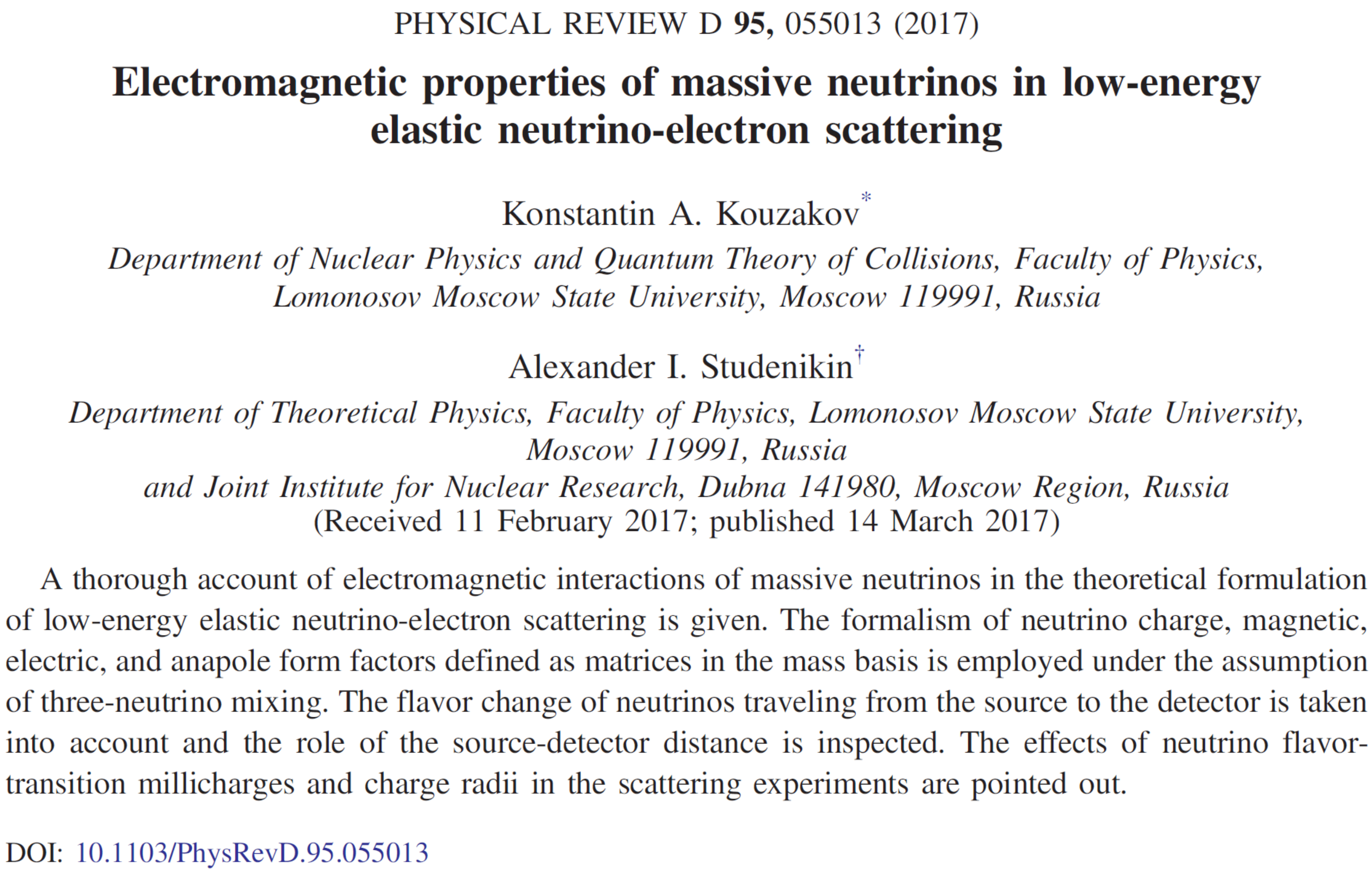
Presentations on behalf of SATURNE Collaboration

- XXI Lomonosov Conference on Elementary Particle Physics, August 2023, Moscow
- First African Conference on High Energy Physics, October 2023, Rabat, Marocco
- XXII International Seminar on High-Energy Physics "Quarks 2024", May 2024, Pereslavl Zalessky, Russia
- LXXIV International Conference "Nucleus-2024", July 2024, Dubna

Supported by the Russian Science Foundation project #24-12-00084

… Backup slides …

… comprehensive analysis of ν-e scattering …



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

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

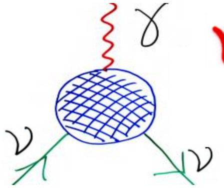
Konstantin A. Kouzakov[*]
Department of Nuclear Physics and Quantum Theory of Collisions, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia

Alexander I. Studenikin[†]
Department of Theoretical Physics, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
and Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia

(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



ν electromagnetic interactions

mass states ν_j , $m_j \ (j=1,2,3)$

$q = p_j - p_k$

$$\mathcal{H}_{\text{em}}^{(\nu)} = j_\lambda^{(\nu)} A^\lambda = \sum_{j,k=1}^{3} \overline{\nu}_j \Lambda_\lambda^{jk} \nu_k A^\lambda$$

$$\Lambda_\lambda(q) = \left(\gamma_\lambda - \frac{q_\lambda \not{q}}{q^2}\right) \left[f_Q(q^2) + f_A(q^2) q^2 \gamma^5\right] - i\sigma_{\lambda\rho} q^\rho \left[f_M(q^2) + i f_E(q^2)\gamma^5\right]$$

Elastic neutrino-electron scattering

at energy-momentum transfer $q = (T, \mathbf{q})$

$$\nu_l(L) + e^- \rightarrow \nu_j + e^-$$

flavour state $|\nu_\ell\rangle$ in the source arrives to the detector as

$$|\nu_\ell(L)\rangle = \sum_{k=1}^{3} U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}L} |\nu_k\rangle$$

Matrix element of weak interactions

$$\mathcal{M}_j^{(w)} = \frac{G_F}{\sqrt{2}} \sum_{k=1}^{3} U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}L} \left[(g_V')_{jk} \bar{u}_j \gamma_\lambda (1-\gamma^5) u_k J_V^\lambda(q) - (g_A')_{jk} \bar{u}_j \gamma_\lambda (1-\gamma^5) u_k J_A^\lambda(q)\right]$$

$$(g_V')_{jk} = \delta_{jk} g_V + U_{ej}^* U_{ek} \quad (g_A')_{jk} = \delta_{jk} g_A + U_{ej}^* U_{ek} \quad g_V = 2\sin^2\theta_W - 1/2, \; g_A = -1/2$$

Electron transition V and A currents in detector

$|i\rangle$ and $|f\rangle$

states of detector

$$J_V^\lambda(q) = \langle f | \sum_d e^{i\mathbf{q}\cdot\mathbf{r}_d} \gamma_d^0 \gamma_d^\lambda | i \rangle$$

$$J_A^\lambda(q) = \langle f | \sum_d e^{i\mathbf{q}\cdot\mathbf{r}_d} \gamma_d^0 \gamma_d^\lambda \gamma_d^5 | i \rangle$$

over all electrons of detector

$$\mathcal{E}_f - \mathcal{E}_i = T$$

energy transfer

Matrix element of electromagnetic interactions

$$\boxed{\mathcal{M}_j^{(\gamma)} = \mathcal{M}_j^{(Q)} + \mathcal{M}_j^{(\mu)}}$$

- $$\boxed{\mathcal{M}_j^{(Q)} = \frac{4\pi\alpha}{q^2} \sum_{k=1}^{3} U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}L} \bar{u}_j \left(\gamma_\lambda - \frac{q_\lambda \not{q}}{q^2}\right) \left[(e_\nu)_{jk} + \frac{q^2}{6}\langle r_\nu^2\rangle_{jk}\right] u_k J_V^\lambda(q)}$$

millicharge $\boxed{(e_\nu)_{jk} = e_{jk}}$ charge radius and anapole moment $\boxed{\langle r_\nu^2\rangle_{jk} = \langle r^2\rangle_{jk} + 6\gamma^5 a_{jk}}$

- $$\boxed{\mathcal{M}_j^{(\mu)} = -i\frac{2\pi\alpha}{m_e q^2} \sum_{k=1}^{3} U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}L} \bar{u}_j \sigma_{\lambda\rho} q^\rho (\mu_\nu)_{jk} u_k J_V^\lambda(q)}$$

$\boxed{(\mu_\nu)_{jk} = \mu_{jk} + i\gamma^5\varepsilon_{jk}}$

magnetic & electric dipole moments

nonmoving matter !!!

Helicity-conserving amplitudes

$$\mathcal{M}_j^{(w,Q)} = \mathcal{M}_j^{(w)} + \mathcal{M}_j^{(Q)}$$

$$= \frac{G_F}{\sqrt{2}} \sum_{k=1}^{3} U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}L} \Big\{ \left[(g_V')_{jk} + \tilde{Q}_{jk}\right] \bar{u}_j \gamma_\lambda (1-\gamma^5) u_k J_V^\lambda(q)$$

$$- (g_A')_{jk} \bar{u}_j \gamma_\lambda (1-\gamma^5) u_k J_A^\lambda(q) \Big\}$$

$$\tilde{Q}_{jk} = \frac{2\sqrt{2}\pi\alpha}{G_F} \left[\frac{(e_\nu)_{jk}}{q^2} + \frac{1}{6}\langle r_\nu^2\rangle_{jk}\right]$$

Differential cross section measured in scattering experiment

the final massive state is not resolved in experiment

$$\boxed{\frac{d\sigma}{dT}=\frac{1}{32\pi^2}\int\limits_{T^2}^{(2E_\nu-T)^2}\frac{d\mathbf{q}^2}{E_\nu^2}\int\limits_0^{2\pi}d\varphi_{\mathbf{q}}\,|\mathcal{M}_{fi}|^2\,\delta(T-\mathcal{E}_f+\mathcal{E}_i)}$$

1) ν masses are neglected
2) $p_j=p' \qquad p_k=p$
3) averaging (summation) over initial (final) spin polariz.
4) $\varphi_{\mathbf{q}}$ is azimutal angle

$$\left|\mathcal{M}_{fi}^{(w,Q)}\right|^2=\sum_{j=1}^{3}\left|\tilde{\mathcal{M}}_j^{(w,Q)}\right|^2 \qquad \boxed{|\mathcal{M}_{fi}|^2=\sum_{j=1}^{3}\left\{\left|\mathcal{M}_j^{(w,Q)}\right|^2+\left|\mathcal{M}_j^{(\mu)}\right|^2\right\}}$$

$$\begin{aligned}=4G_F^2\Big\{&C_1\left[2|p\cdot J_V(q)|^2-(p\cdot p')J_V(q)\cdot J_V^*(q)-i\varepsilon_{\lambda\rho\lambda'\rho'}p'^{\rho}p^{\rho'}J_V^{\lambda}(q)J_V^{\lambda'*}(q)\right]\\
&+C_2\Big[\left(p\cdot J_A(q)\right)\left(p'\cdot J_A^*(q)\right)+\left(p'\cdot J_A(q)\right)\left(p\cdot J_A^*(q)\right)-(p\cdot p')J_A(q)\cdot J_A^*(q)\\
&-i\varepsilon_{\lambda\rho\lambda'\rho'}p'^{\rho}p^{\rho'}J_A^{\lambda}(q)J_A^{\lambda'*}(q)\Big]+2\mathrm{Re}\Big\{C_3\Big[\left(p\cdot J_V(q)\right)\left(p'\cdot J_A^*(q)\right)\\
&+\left(p'\cdot J_A(q)\right)\left(p\cdot J_V^*(q)\right)-(p\cdot p')J_V(q)\cdot J_A^*(q)-i\varepsilon_{\lambda\rho\lambda'\rho'}p'^{\rho}p^{\rho'}J_V^{\lambda}(q)J_A^{\lambda'*}(q)\Big]\Big\}\Big\}\end{aligned}$$

… complicated intersection of weak and electromagnetic interactions with effects of mixing …

$$C_1=\sum_{j,k,k'=1}^{3}U_{\ell k}^*U_{\ell k'}e^{-i\frac{\delta m_{kk'}^2}{2E_\nu}L}\left[(g_V')_{jk}+\tilde{Q}_{jk}\right]\left[(g_V')_{jk'}^*+\tilde{Q}_{jk'}^*\right]$$

$$C_2=\sum_{j,k,k'=1}^{3}U_{\ell k}^*U_{\ell k'}e^{-i\frac{\delta m_{kk'}^2}{2E_\nu}L}(g_A')_{jk}(g_A')_{jk'}^*$$

$$C_3=\sum_{j,k,k'=1}^{3}U_{\ell k}^*U_{\ell k'}e^{-i\frac{\delta m_{kk'}^2}{2E_\nu}L}\left[(g_V')_{jk}+\tilde{Q}_{jk}\right](g_A')_{jk'}^*$$

$$\boxed{\tilde{Q}_{jk}=\frac{2\sqrt{2}\pi\alpha}{G_F}\left[\frac{(e_\nu)_{jk}}{q^2}+\frac{1}{6}\langle r_\nu^2\rangle_{jk}\right]}$$

$$\boxed{(g_V')_{jk}=\delta_{jk}g_V+U_{ej}^*U_{ek}}$$

$$\boxed{(g_A')_{jk}=\delta_{jk}g_A+U_{ej}^*U_{ek}}$$

$$\delta m_{kk'}^2=m_k^2-m_{k'}^2$$

… it is usually claimed …

$$g_V\to g_V+\boxed{\tfrac{2}{3}M_W^2\langle r^2\rangle\sin^2\theta_W}$$

Magnetic moment part of cross section

$$\frac{d\sigma}{dT} = \frac{1}{32\pi^2} \int\limits_{T^2}^{(2E_\nu - T)^2} \frac{d\mathbf{q}^2}{E_\nu^2} \int\limits_0^{2\pi} d\varphi_{\mathbf{q}} \, |\mathcal{M}_{fi}|^2 \, \delta(T - \mathcal{E}_f + \mathcal{E}_i)$$

$$|\mathcal{M}_{fi}|^2 = \sum_{j=1}^{3} \left\{ \left| \mathcal{M}_j^{(w,Q)} \right|^2 + \left| \mathcal{M}_j^{(\mu)} \right|^2 \right\}$$

$$\left| \mathcal{M}_{fi}^{(\mu)} \right|^2 = \sum_{j=1}^{3} \left| \mathcal{M}_j^{(\mu)} \right|^2 = \frac{32\pi^2\alpha^2}{m_e^2 |q^2|} |\mu_\nu(L, E_\nu)|^2 |p \cdot J_V(q)|^2$$

$$|\mu_\nu(L, E_\nu)|^2 = \sum_{j=1}^{3} \left| \sum_{k=1}^{3} U_{\ell k}^* e^{-i \frac{m_k^2}{2E_\nu} L} (\mu_\nu)_{jk} \right|^2$$

Giunti, Studenikin,
Rev. Mod. Phys. 2015

For Dirac antineutrinos

$$(e_\nu)_{jk} \to (e_{\bar\nu})_{jk} = -e_{kj} \qquad (\mu_\nu)_{jk} \to (\mu_{\bar\nu})_{jk} = -\mu_{kj} - i\gamma^5 \varepsilon_{kj} \qquad \langle r_\nu^2 \rangle_{jk} \to \langle r_{\bar\nu}^2 \rangle_{jk} = -\langle r^2 \rangle_{kj} + 6\gamma^5 a_{kj}$$

$$(g'_V)_{jk} \to -(g'_V)^*_{jk} \qquad (g'_A)_{jk} \to -(g'_A)^*_{jk} \qquad \varepsilon_{\lambda\rho\lambda'\rho'} \to -\varepsilon_{\lambda\rho\lambda'\rho'} \qquad U_{\ell k} \to U^*_{\ell k}$$

Free-electron approximation $T \gg E_b$

electrons are free and at rest

energy transfer

electron binding energy in detector

ν-e scattering cross section (free e)

$$\boxed{\frac{d\sigma}{dT} = \frac{1}{32\pi^2} \int\limits_{T^2}^{(2E_\nu - T)^2} \frac{d\mathbf{q}^2}{E_\nu^2} \int\limits_0^{2\pi} d\varphi_{\mathbf{q}} \left|\mathcal{M}_{fi}\right|^2 \delta\left(T - \sqrt{\mathbf{q}^2 + m_e^2} + m_e\right)}$$

$$J_A^\lambda(q) = \frac{1}{2\sqrt{E_e' m_e}} \bar{u}_e' \gamma^\lambda \gamma^5 u_e$$

$$J_V^\lambda(q) = \frac{1}{2\sqrt{E_e' m_e}} \bar{u}_e' \gamma^\lambda u_e$$

$$E_e' = m_e + T$$

final electron energy

Finally cross section (free e)

$$\boxed{\frac{d\sigma^{\mathrm{FE}}}{dT} = \frac{d\sigma^{\mathrm{FE}}_{(w,Q)}}{dT} + \frac{d\sigma^{\mathrm{FE}}_{(\mu)}}{dT}}$$

where

$$\frac{d\sigma^{\mathrm{FE}}_{(\mu)}}{dT} = \frac{\pi\alpha^2}{m_e^2} \left|\mu_\nu(L, E_\nu)\right|^2 \left(\frac{1}{T} - \frac{1}{E_\nu}\right)$$

and

$$\frac{d\sigma^{\mathrm{FE}}_{(w,Q)}}{dT} = \frac{G_F^2 m_e}{2\pi} \left[C_1 + C_2 - 2\mathrm{Re}\left\{C_3\right\} + \left(C_1 + C_2 + 2\mathrm{Re}\left\{C_3\right\}\right)\left(1 - \frac{T}{E_\nu}\right) + \left(C_2 - C_1\right)\frac{T m_e}{E_\nu^2}\right]$$

The role of ν flavor oscillations

- Manifestation of ν electromagnetic properties depends on ν state $\nu_\ell(L)$ in the detector
- The obtained cross section depends on flavor transition amplitude

$$\mathcal{A}_{\nu_\ell \to \nu_{\ell'}}(L, E_\nu) = \langle \nu_{\ell'} | \nu_\ell(L) \rangle = \sum_{k=1}^{3} U_{\ell k}^* U_{\ell' k} e^{-i\frac{m_k^2}{2E_\nu}L}$$

and probability

$$P_{\nu_\ell \to \nu_{\ell'}}(L, E_\nu) = |\mathcal{A}_{\nu_\ell \to \nu_{\ell'}}(L, E_\nu)|^2$$

$$\frac{d\sigma_{(w,Q)}^{\mathrm{FE}}}{dT} = \frac{G_F^2 m_e}{2\pi}\left[C_1 + C_2 - 2\mathrm{Re}\{C_3\} + (C_1 + C_2 + 2\mathrm{Re}\{C_3\})\left(1 - \frac{T}{E_\nu}\right) + (C_2 - C_1)\frac{T m_e}{E_\nu^2}\right]$$

$$C_1 = g_V^2 + 2g_V P_{\nu_\ell \to \nu_e}(L, E_\nu) + P_{\nu_\ell \to \nu_e}(L, E_\nu) + 2g_V \sum_{\ell', \ell'' = e,\mu,\tau} \mathcal{A}_{\nu_\ell \to \nu_{\ell'}}(L, E_\nu) \mathcal{A}_{\nu_\ell \to \nu_{\ell''}}^*(L, E_\nu) \tilde{Q}_{\ell'' \ell'}$$
$$+ 2\mathrm{Re}\left\{\mathcal{A}_{\nu_\ell \to \nu_e}^*(L, E_\nu) \sum_{\ell' = e,\mu,\tau} \mathcal{A}_{\nu_\ell \to \nu_{\ell'}}(L, E_\nu) \tilde{Q}_{e\ell'}\right\} + \sum_{\ell', \ell'', \ell''' = e,\mu,\tau} \mathcal{A}_{\nu_\ell \to \nu_{\ell'}}(L, E_\nu) \mathcal{A}_{\nu_\ell \to \nu_{\ell''}}^*(L, E_\nu) \tilde{Q}_{\ell'' \ell'''} \tilde{Q}_{\ell''' \ell'}$$

$$C_2 = g_A^2 + 2g_A P_{\nu_\ell \to \nu_e}(L, E_\nu) + P_{\nu_\ell \to \nu_e}(L, E_\nu)$$

$$C_3 = g_V g_A + (g_V + g_A + 1) P_{\nu_\ell \to \nu_e}(L, E_\nu) + g_A \sum_{\ell', \ell'' = e,\mu,\tau} \mathcal{A}_{\nu_\ell \to \nu_{\ell'}}(L, E_\nu) \mathcal{A}_{\nu_\ell \to \nu_{\ell''}}^*(L, E_\nu) \tilde{Q}_{\ell'' \ell'}$$
$$+ \mathcal{A}_{\nu_\ell \to \nu_e}^*(L, E_\nu) \sum_{\ell' = e,\mu,\tau} \mathcal{A}_{\nu_\ell \to \nu_{\ell'}}(L, E_\nu) \tilde{Q}_{e\ell'}$$

Generalized ν charge

Up to now we have used $\tilde{Q}_{jk} = \frac{2\sqrt{2}\pi\alpha}{G_F}\left[\frac{(e_\nu)_{jk}}{q^2} + \frac{1}{6}\langle r_\nu^2\rangle_{jk}\right]$ in mass basis

Finally we have in flavour basis

$$\boxed{\tilde{Q}_{\ell'\ell} = \sum_{j,k=1}^{3} U_{\ell' j} U_{\ell k}^{*} \tilde{Q}_{jk} = \frac{2\sqrt{2}\pi\alpha}{G_F}\left[\frac{(e_\nu)_{\ell'\ell}}{q^2} + \frac{1}{6}\langle r_\nu^2\rangle_{\ell'\ell}\right]}$$

where

$$\boxed{(e_\nu)_{\ell'\ell} = \sum_{j,k=1}^{3} U_{\ell' j} U_{\ell k}^{*} (e_\nu)_{jk}}$$

$$\boxed{\langle r_\nu^2\rangle_{\ell'\ell} = \sum_{j,k=1}^{3} U_{\ell' j} U_{\ell k}^{*} \langle r_\nu^2\rangle_{jk}}$$

millicharge

in ν flavour basis

charge radius

- **Short-baselin case** $\boxed{L \ll L_{kk'} = 2E_\nu/|\delta m^2_{kk'}|}$ → $\boxed{e^{-i(\delta m^2_{kk'}/2E_\nu)L} = 1}$

- $P_{\nu_\ell \to \nu_e}(L, E_\nu) = \delta_{\ell e}$ $\qquad$ $\mathcal{A}_{\nu_\ell \to \nu_{\ell'}}(L, E_\nu)\mathcal{A}^*_{\nu_\ell \to \nu_{\ell''}}(L, E_\nu) = \delta_{\ell\ell'}\delta_{\ell\ell''}$

effect of ν flavor change is insignificant
($\nu_\ell(L)$ is as in the source)

$$C_1 = (g_V + \delta_{\ell e} + \tilde{Q}_{\ell\ell})^2 + \sum_{\ell'=e,\mu,\tau} (1 - \delta_{\ell'\ell}) \left|\tilde{Q}_{\ell'\ell}\right|^2 \qquad C_2 = (g_A + \delta_{\ell e})^2$$

$$C_3 = (g_V + \delta_{\ell e})(g_A + \delta_{\ell e}) + (g_A + \delta_{\ell e})\tilde{Q}_{\ell\ell}$$

weak-electromagnetic interference term contains only
flavour-diagonal millicharges and charge radii

- **Effective magnetic moment**

$$|\mu_\nu(L, E_\nu)|^2 = \sum_{j=1}^{3} \sum_{k,k'=1}^{3} U^*_{\ell k} U_{\ell k'} (\mu_\nu)_{jk} (\mu_\nu)^*_{jk'} = \sum_{\ell'=e,\mu,\tau} |(\mu_\nu)_{\ell'\ell}|^2$$ where

$$(\mu_\nu)_{\ell'\ell} = \sum_{j,k=1}^{3} U^*_{\ell k} U_{\ell' j} (\mu_\nu)_{jk}$$ is the effective magnetic moment in flavor basis

- Long-baselin case $\boxed{L \gg L_{kj} = 2E_\nu/|\delta m^2_{kk'}|} \longrightarrow \boxed{\exp(-i\delta m^2_{kk'}/2E_\nu) \; = \; \delta_{kk'}}$

effect of decoherence

$$C_1 = g_V^2 + 2g_V P_{\nu_\ell \to \nu_e} + P_{\nu_\ell \to \nu_e} + \sum_{j,k=1}^{3} |U_{\ell k}|^2 \left|\tilde{Q}_{jk}\right|^2 + 2g_V \sum_{j=1}^{3} |U_{\ell j}|^2 \tilde{Q}_{jj} + 2 \sum_{j,k=1}^{3} |U_{\ell k}|^2 \mathrm{Re}\left\{U_{ej} U_{ek}^* \tilde{Q}_{jk}\right\}$$

$$C_2 = g_A^2 + 2g_A P_{\nu_\ell \to \nu_e} + P_{\nu_\ell \to \nu_e}$$

$$C_3 = g_V g_A + (g_V + g_A + 1) P_{\nu_\ell \to \nu_e} + g_A \sum_{j=1}^{3} |U_{\ell j}|^2 \tilde{Q}_{jj} + 2 \sum_{j,k=1}^{3} |U_{\ell k}|^2 U_{ej} U_{ek}^* \tilde{Q}_{jk}$$

where the flavour transition probability $P_{\nu_\ell \to \nu_e} = \sum_{k=1}^{3} |U_{\ell k}|^2 |U_{ek}|^2$ does not depend on source-detector distance and ν energy

- Effective magnetic moment $|\mu_\nu(L, E_\nu)|^2 = \sum_{j,k=1}^{3} |U_{\ell k}|^2 \left|(\mu_\nu)_{jk}\right|^2$ is independent of *L* and *E*