Overview of neutrino electromagnetic properties

(theory, laboratory experiments & astrophysical probes)

The Corfu Summer Institute:
Workshop on
the Standard Model
and Beyond
03/09/2020

Alexander Studenikin

Moscow State University
&
JINR -Dubna

Outline

① (short) reminder of ν electromagnetic properties

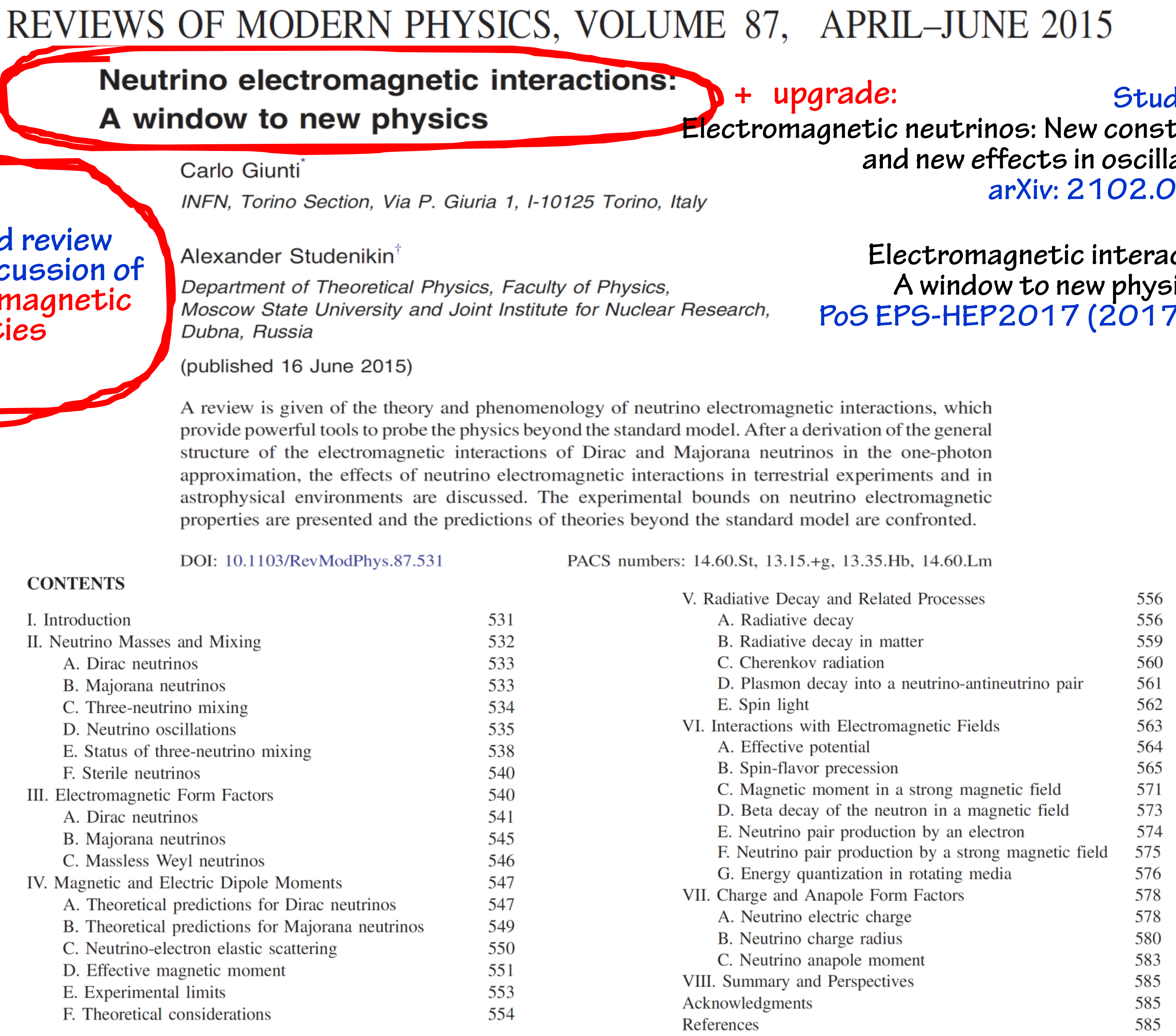
② constraints on μ_ν, d_ν, q_ν and $\langle r_\nu^2 \rangle$ from laboratory experiments

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

. . . two interesting new phenomena in ν spin (flavor) oscillations in moving and polarized mater and magnetic field



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

Neutrino electromagnetic interactions: A window to new physics

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(published 16 June 2015)

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

DOI: 10.1103/RevModPhys.87.531 PACS numbers: 14.60.St, 13.15.+g, 13.35.Hb, 14.60.Lm

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Detailed review
and discussion of
electromagnetic
properties

+ upgrade:

Studenikin,
Electromagnetic neutrinos: New constraints
and new effects in oscillations,
arXiv: 2102.05468

Electromagnetic interactions:
A window to new physics – II,
PoS EPS-HEP2017 (2017) 137

q_ν two very useful papers of the year μ_ν

Hindawi
Advances in High Energy Physics
Volume 2020, Article ID 5908904, 10 pages
https://doi.org/10.1155/2020/5908904

Hindawi

Research Article

Constraints on Neutrino Electric Millicharge from Experiments of Elastic Neutrino-Electron Interaction and Future Experimental Proposals Involving Coherent Elastic Neutrino-Nucleus Scattering

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Received 5 May 2020; Revised 4 July 2020; Accepted 31 October 2020; Published 27 November 2020

Academic Editor: Filipe R. Joaquim

In several extensions of the Standard Model of Particle Physics (SMPP), the neutrinos acquire electromagnetic properties such as the electric millicharge. Theoretical and experimental bounds have been reported in the literature for this parameter. In this work, we first carried out a statistical analysis by using data from reactor neutrino experiments, which include elastic neutrino-electron scattering (ENES) processes, in order to obtain both individual and combined limits on the neutrino electric millicharge (NEM). Then, we performed a similar calculation to show an estimate of the sensitivity of future experiments of reactor neutrinos to the NEM, by involving coherent elastic neutrino-nucleus scattering (CENNS). In the first case, the constraints achieved from the combination of several experiments are $-1.1 \times 10^{-12}e < q_\nu < 9.3 \times 10^{-13}e$ (90% C.L.), and in the second scenario, we obtained the bounds $-1.8 \times 10^{-14}e < q_\nu < 1.8 \times 10^{-14}e$ (90% C.L.). As we will show here, these combined analyses of different experimental data can lead to stronger constraints than those based on individual analysis, where CENNS interactions would stand out as an important alternative to improve the current limits on NEM.

1. Introduction

In the SMPP, the neutrinos are massless, electrically neutral, and only interact weakly with leptons and quarks. Nevertheless, the neutrino oscillation experiments show that neutrinos have mass and are also mixed [1–4]. Hence, the idea of extending the SMPP so as to explain the origin of neutrino mass. Different extensions of SMPP allow the neutrino to have properties such as magnetic and electric dipole moments as well as anapole moment and electric millicharge [5–7]. Even in the Standard Model, it is well-known that the neutrinos also can have nonzero charge radius, as shown in reference [8, 9]. Among these properties, the neutrino magnetic moment (NMM) has been quite studied in several research works, where different experimental constraints to this parameter were obtained, for instance, from reactor neutrino experiments [10–14], solar neutrinos [15, 16], and astrophysical measurements [17, 18]. The limits achieved for the NMM are around $10^{-11}\mu_B$, while the prediction of the simplest extension of the Standard Model, by including right-handed neutrinos, is $3.2 \times 10^{-19}\mu_B$ [19]. Furthermore, considering the representation of three active neutrinos, the magnetic moment is described by a 3×3 matrix whose components are the diagonal and transition magnetic moments. A complete analysis by considering the NMM matrix and using data from solar, reactor, and accelerator experiments was presented in reference [20, 21]. In addition to NMM, the study of the remainder form factors is also important as they are a tool to probe new physics. Among them, the NEM has also been under consideration in the literature, and several constraints have been found mainly from reactor experiments and astrophysical measurements. The most restrictive bound on NEM so far, $q_\nu \lesssim 3.0 \times 10^{-21}e$, was obtained in [18] based on the neutrality of matter. A limit

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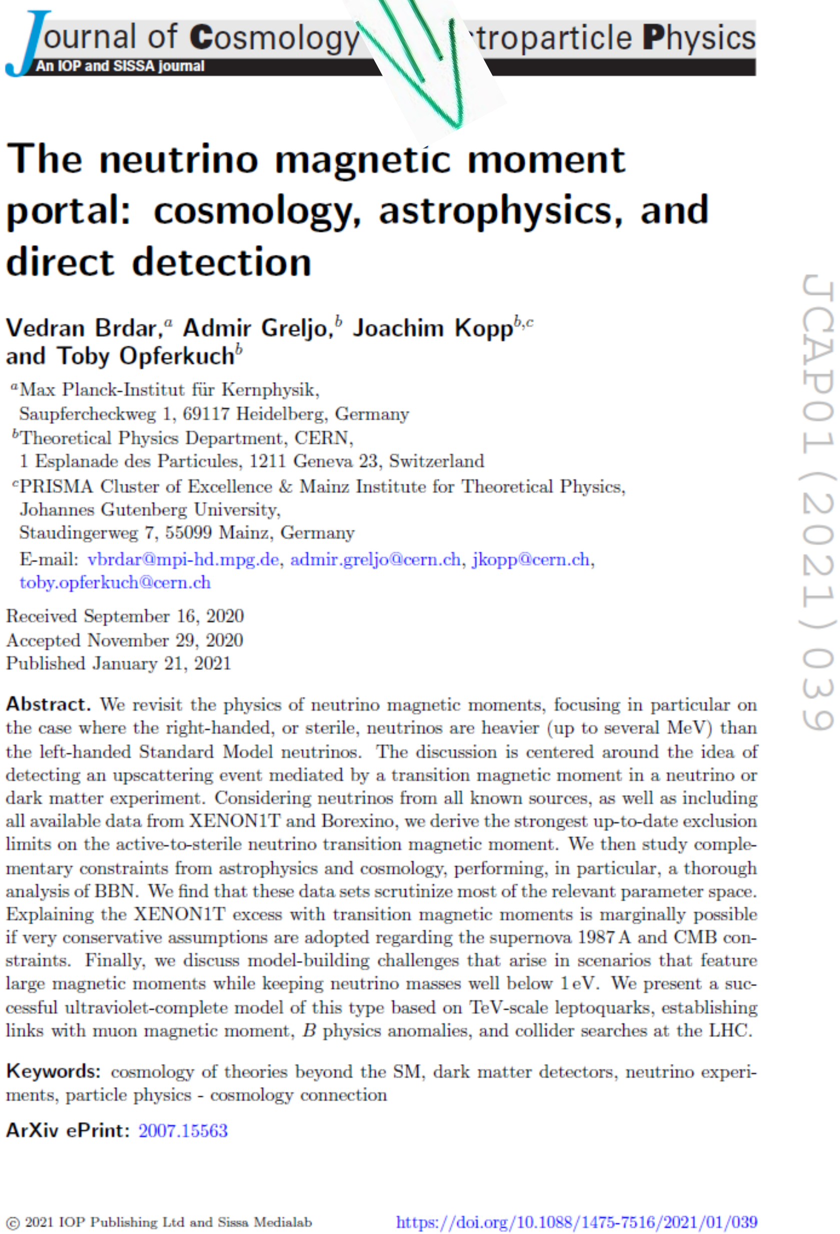

Journal of Cosmology troparticle Physics
An IOP and SISSA journal

The neutrino magnetic moment portal: cosmology, astrophysics, and direct detection

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Received September 16, 2020
Accepted November 29, 2020
Published January 21, 2021

Abstract. We revisit the physics of neutrino magnetic moments, focusing in particular on the case where the right-handed, or sterile, neutrinos are heavier (up to several MeV) than the left-handed Standard Model neutrinos. The discussion is centered around the idea of detecting an upscattering event mediated by a transition magnetic moment in a neutrino or dark matter experiment. Considering neutrinos from all known sources, as well as including all available data from XENON1T and Borexino, we derive the strongest up-to-date exclusion limits on the active-to-sterile neutrino transition magnetic moment. We then study complementary constraints from astrophysics and cosmology, performing, in particular, a thorough analysis of BBN. We find that these data sets scrutinize most of the relevant parameter space. Explaining the XENON1T excess with transition magnetic moments is marginally possible if very conservative assumptions are adopted regarding the supernova 1987 A and CMB constraints. Finally, we discuss model-building challenges that arise in scenarios that feature large magnetic moments while keeping neutrino masses well below 1 eV. We present a successful ultraviolet-complete model of this type based on TeV-scale leptoquarks, establishing links with muon magnetic moment, B physics anomalies, and collider searches at the LHC.

Keywords: cosmology of theories beyond the SM, dark matter detectors, neutrino experiments, particle physics - cosmology connection

ArXiv ePrint: 2007.15563

https://doi.org/10.1088/1475-7516/2021/01/039

JCAP01(2021)039

… there are certain advantages in online conferences …

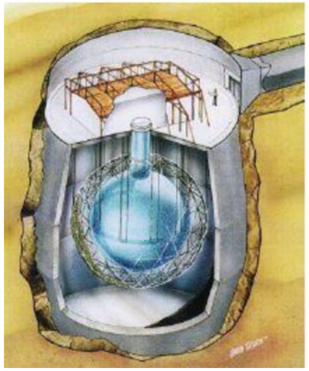
9 presentations at TAUP 2021 dedicated to ν electromagnetic properties and related issues

- 1) A. Studenikin, Electromagnetic neutrino: The theory, laboratory experiments and astrophysical probes, oral presentation # 230
- 2) A.Popov, A.Studenikin, Effects of nonzero Majorana CP phases on oscillations of supernova neutrinos, poster # 231
- 3) K.Stankevich, V.Shakhov, A.Studenikin, Spin and spin-flavor oscillations due to neutrino charge radii interaction with an external environment, poster # 241
- 4) A.Lichkunov, R.Stankevich, A.Studenikin, M.Vialkov, Neutrino quantum decoherence engendered by neutrino decay to photons, familons and gravitons, poster # 242
- 5) V.Shakhov, U.Abdullaeva, A.Studenikin, A.Tsvirov, Dirac and Majorana neutrino oscillations in magnetized moving and polarized matter, poster # 245
- 6) Y.F.Li, Z.Chen, A.Kouzakov, V.Shakhov, K.Stankevich, A.Studenikin, Collective neutrino oscillations in moving and polarized matter, poster # 249
- 7) A.Kouzakov, D.Abeyadira, A.Studenikin, Dirac and Majorana neutrino oscillations in magnetized moving and polarized matter, poster # 266
- 8) G.Donchenko, K.Kouzakov, A.Studenikin, Neutrino magnetic moments in low-energy neutrino scattering on condensed matter systems, poster # 268
- 9) F.Lazarev, K.Kouzakov, A.Studenikin, Electromagnetic effects in elastic neutrino scattering on nucleons and nuclei, poster # 289

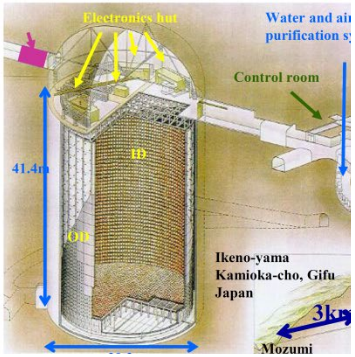
Arthur McDonald

Takaaki Kajita

The Nobel Prize in Physics 2015



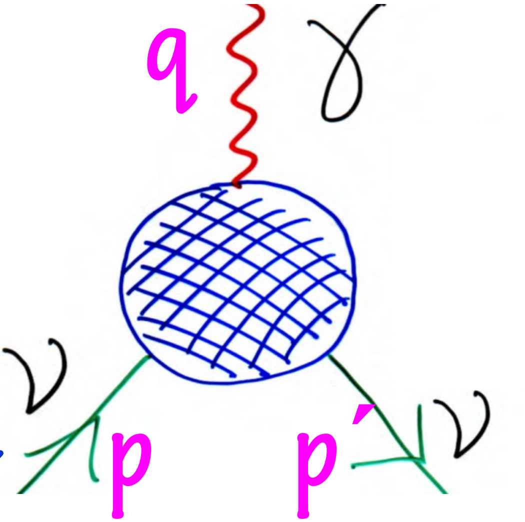
«for the discovery of neutrino oscillations, which shows that neutrinos have mass»



$$m_\nu \neq 0$$

ν electromagnetic properties (flash on theory)

electromagnetic vertex function



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

Matrix element of electromagnetic current is a Lorentz vector

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

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

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

vectors q_μ and l_μ

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

● Lorentz covariance (1) and electromagnetic gauge invariance (2) ⇒

Matrix element of electromagnetic current between neutrino states

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

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 $J_\mu^{\rm EM}$ put constraints on form factors

Dirac ν

1) CP invariance + Hermiticity ⟹ $f_E = 0$,

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

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

!

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_μ^{EM} can be considered between different initial $\psi_i(p)$ and final $\psi_j(p')$ states of different masses

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

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

… beyond SM… ν

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

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

Dipole magnetic $\boxed{f_M(q^2)}$ and electric $\boxed{f_E(q^2)}$ are most well studied and theoretically understood among form factors

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

$\boxed{\mu_\nu = f_M(0)}$ ⟸ ν magnetic moment ●

$\boxed{\epsilon_\nu = f_E(0)}$ ⟸ ν electric moment ???

… Why ν electromagnetic properties are important ?

…Why ν em properties

to new physics ?

… How does it all relate to ν oscillations ?

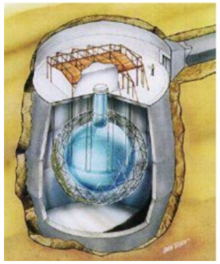
⟹ $m_\nu \neq 0$ ●

magnetic moment $\mu_\nu \neq 0$ ●

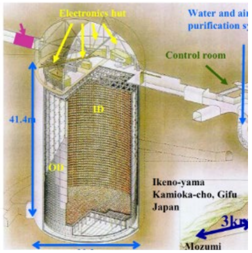
Arthur McDonald

The Nobel Prize in Physics 2015

Takaaki Kajita



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



in Standard Model

● $m_\nu = 0$!!!

In the easiest generalization of SM

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

if $\boxed{m_i \sim 1\ eV}$ $\Longleftarrow$ **KATRIN limit**

then $\boxed{\mu_{ii}^{D} \sim 3.2 \times 10^{-19}\mu_B}$!

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

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} and ν_{SN}) limits
  Borexino 2017

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
- much weaker constraints are imposed by astrophysics

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

magnetic moment   millicharge   charge radius

Particle Data Group
Review of Particle Properties (2014-2020)
update of 2021

… so far there is no any evidence in favour of non-zero ν electromagnetic properties

- either from laboratory experiments
- or from astrophysical observations

ν magnetic moment

… most easily accepted are
dipole magnetic and electric moments

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

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

Cross-section:

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

!

where the Standard Model contribution

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

T is the electron recoil energy and

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

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

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

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

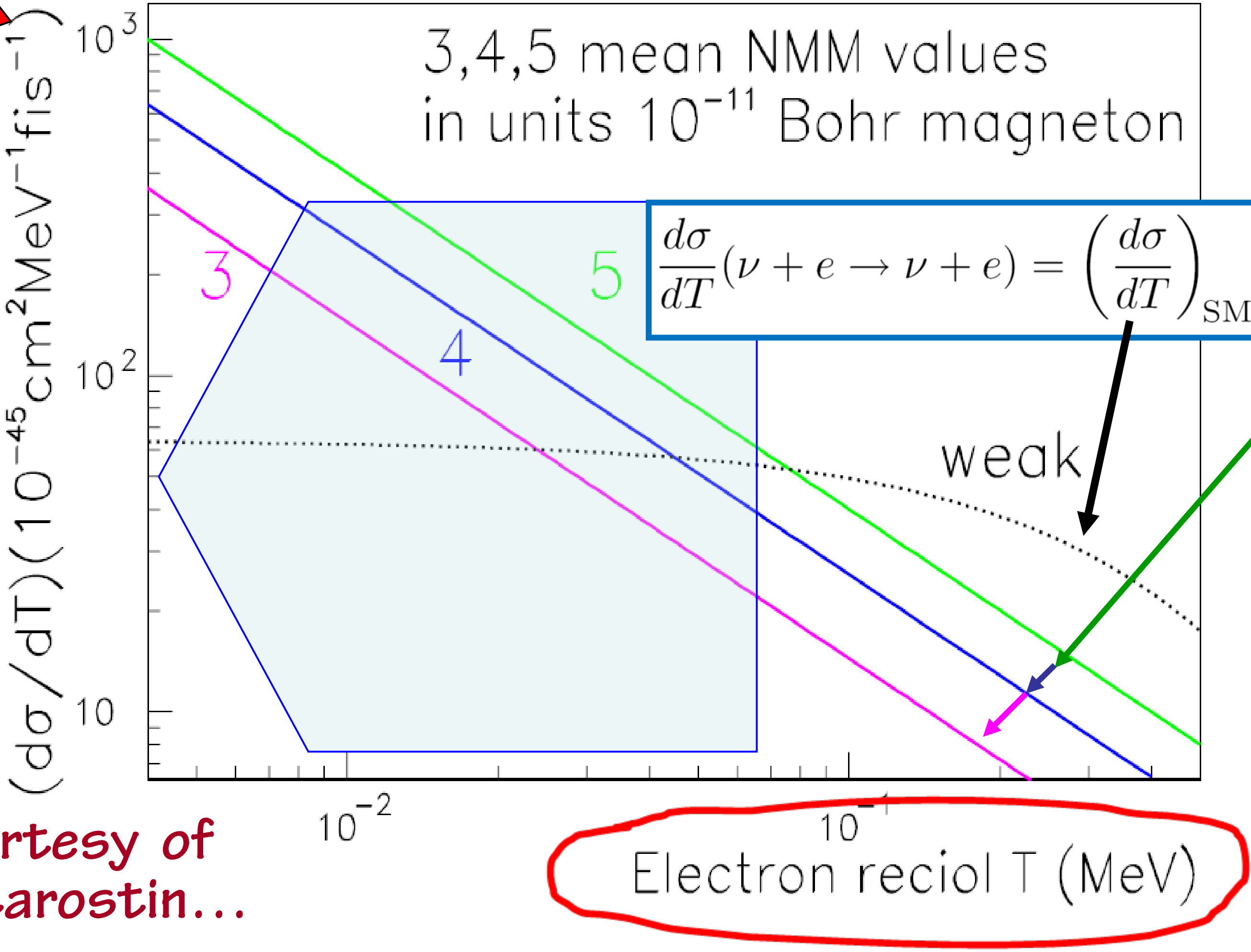
for anti-neutrinos

$$g_A \to -g_A$$

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

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 …



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

… courtesy of
A.Starostin…

GEMMA (2005 – 2012 - running)

Germanium Experiment for Measurement
of Magnetic Moment of Antineutrino

JINR (Dubna) + ITEP (Kurchatov Inst., 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

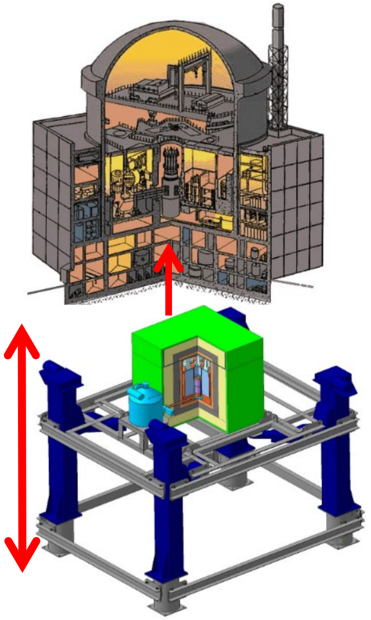
… searching for μ_ν and CEνNS unprecedentedly low threshold $\boxed{T \sim 200 \quad eV}$

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

2021 + few years of data taking ?

… courtesy of Alexey Lobashevsky, first results of νGeN are reported at TAUP 2021…

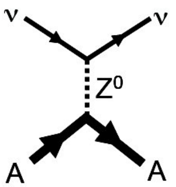
experiment at Kalinin nuclear power plant

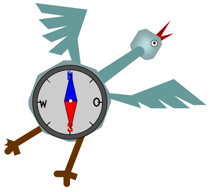


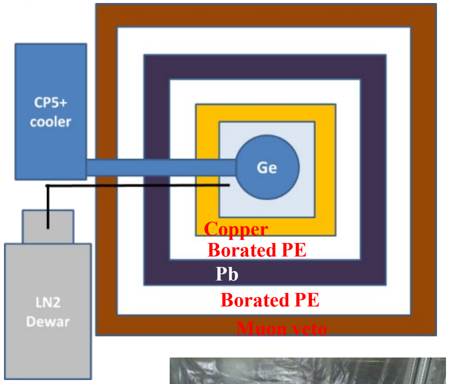
The GEMMA-3/νGeN projects investigate fundamental properties of neutrino at Kalinin Nuclear Power Plant (KNPP) with a low background innovative semiconductor HPGe detectors. In particular, the searches for CEνNS and magnetic moment of neutrino are performed. Such investigations allow us to perform a search for the New Physics using non-standard neutrino interactions, investigation of the nuclear structure, and many other applications, including reactor monitoring.

The setup is been constructing at ~ 10 m from powerful 3.1 GW reactor's core under an enormous antineutrino flux of more than > $5 \cdot 10^{13}$ ν/(s·cm^2). The location also allows to have good shielding against cosmic radiation ~ 50 m w.e. Backgrounds from surrounding and cosmic radiation are suppressed by passive and active shielding.

Measurements at LSM underground laboratory (Modane, France) proved very good radiopurity of all components. The movable platform allows to suppress systematic uncertainties connected with unknown information about neutrino flux and backgrounds. In November 2019, the first HPGe detector was moved to the experimental room at KNPP and we started commissioning measurements.







… courtesy V. Brudanin and E. Yakushev …

results and plans

The measurements at JINR demonstrated a possibility to acquire signal below 200 eV (with trigger efficiency of about 70%). Energy resolution of the first detector measured with pulse generator is 78.0(3) eV (FWHM).

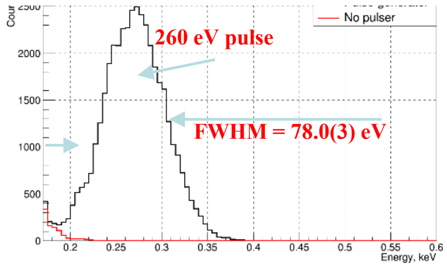
The preliminary background measurements at KNPP showed that all visible lines are from cosmogenic isotopes and decreasing with time. Resolution of cosmogenic lines are: 10.37 keV – 187(3) eV (FWHM), for 1.3 keV – 124(9) eV (FWHM).

Improvement in comparison with GEMMA-I:

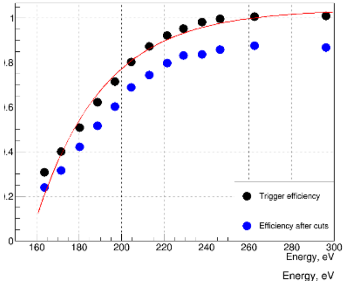
- ✓ **Energy threshold: 2 keV → 200 eV (achived)**
- ✓ **Neutrino flux: $2.6 \cdot 10^{13}\ \nu/(s \cdot cm^2) \rightarrow 5 \cdot 10^{13}\ \nu/(s \cdot cm^2)$ (place is ready)**
- ✓ **Mass: 1.5 kg → 5.5 kg (first detector is at place, waiting for others to be ready)**
- ✓ **$\mu_\nu < 2.9 \cdot 10^{-11} \mu_B$ (world best limit) → $\mu_\nu < (5\text{-}9) \cdot 10^{-12} \mu_B$ (after few years of data taking)**

A good background index has been achieved! Due to the influence of COVID-19, measurements at the KNPP are just restarted. We will continue investigations of the neutrino properties with aim to achieve sensitivity to the detection of CEvNS in a region of full coherence.

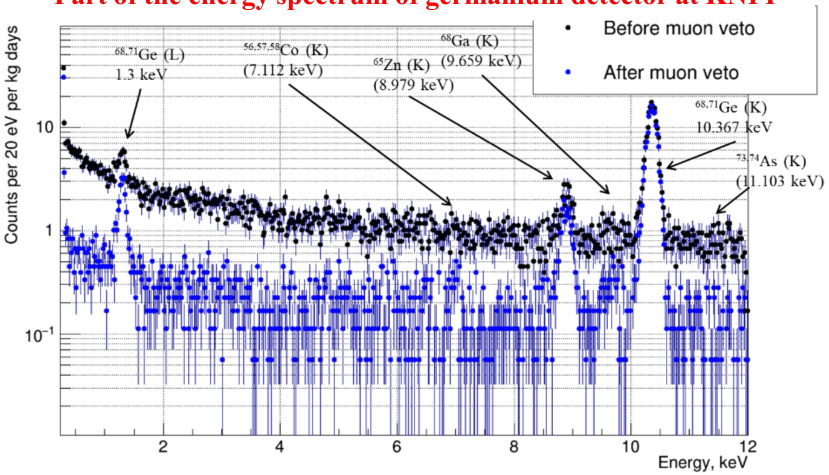
Measurements with pulse generator near energy threshold



Measurements of detector's efficiency



Part of the energy spectrum of germanium detector at KNPP

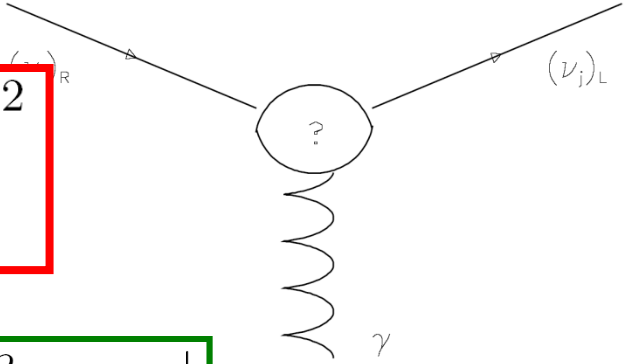


Preliminary! Further Background decrease is expected!

… courtesy V. Brudanin and E. Yakushev …

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**

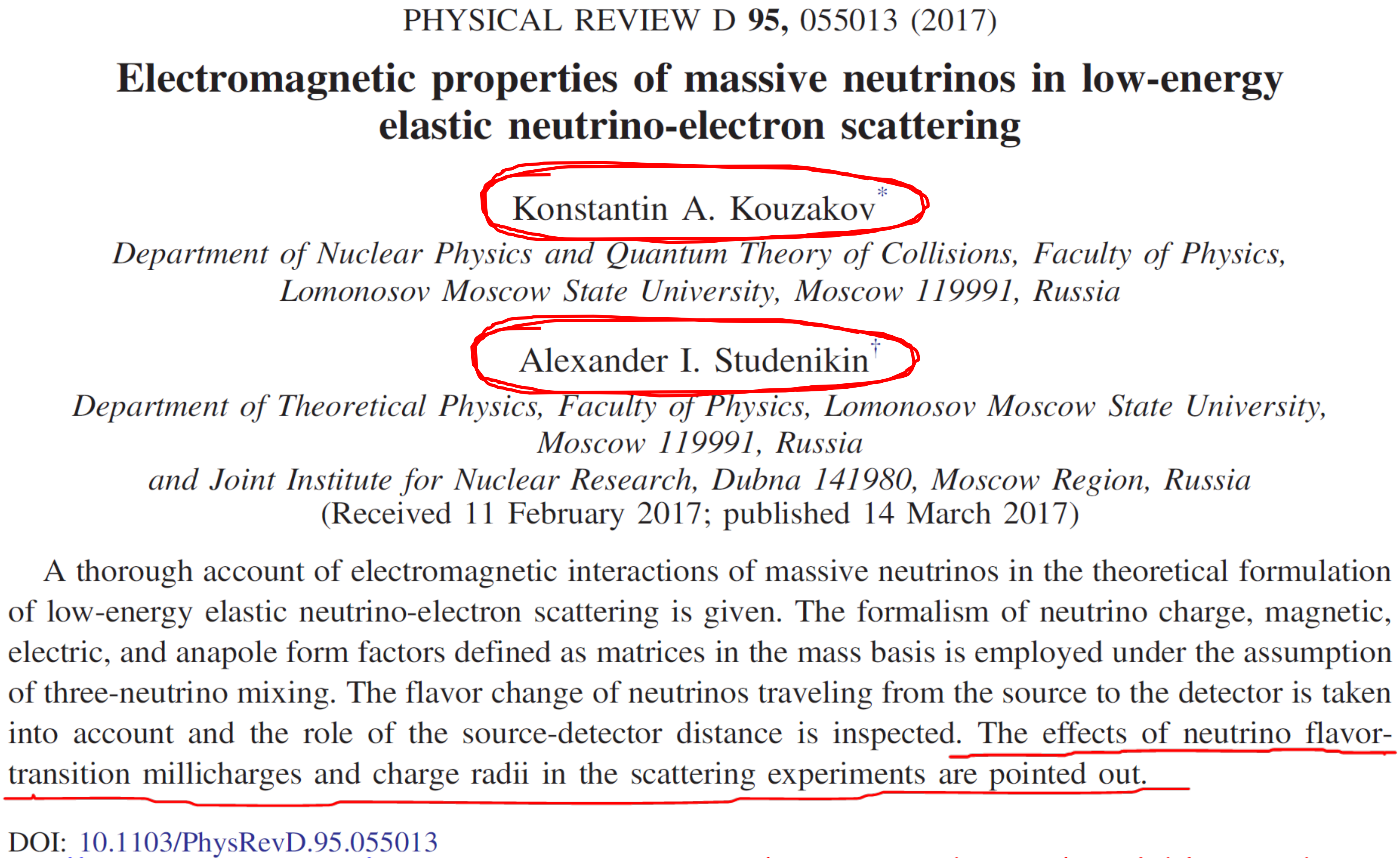
$$\mu_{ij} \equiv |\beta_{ij} - \varepsilon_{ij}|$$

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.

… comprehensive analysis of ν-e scattering …



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

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

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(Received 11 February 2017; published 14 March 2017)

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

DOI: 10.1103/PhysRevD.95.055013

… all experimental constraints on charge radius should be redone

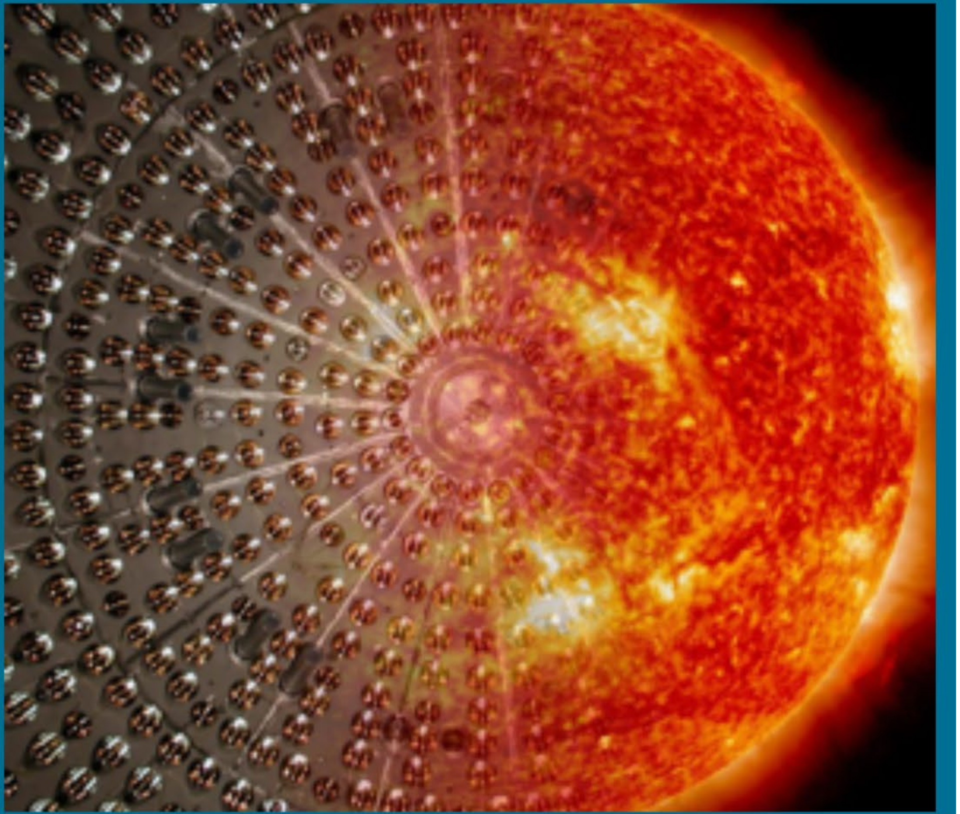
TAUP Topics in Astroparticle and Underground Physics 2017

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

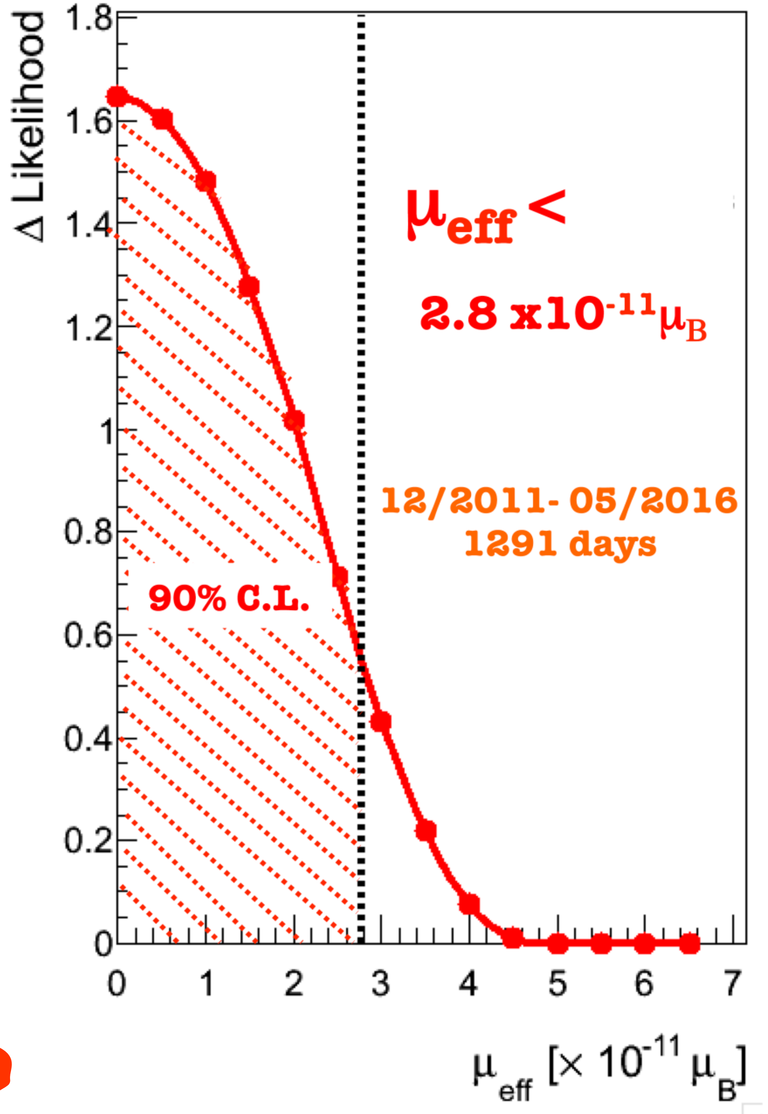
NMM results from Phase 2

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

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

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

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

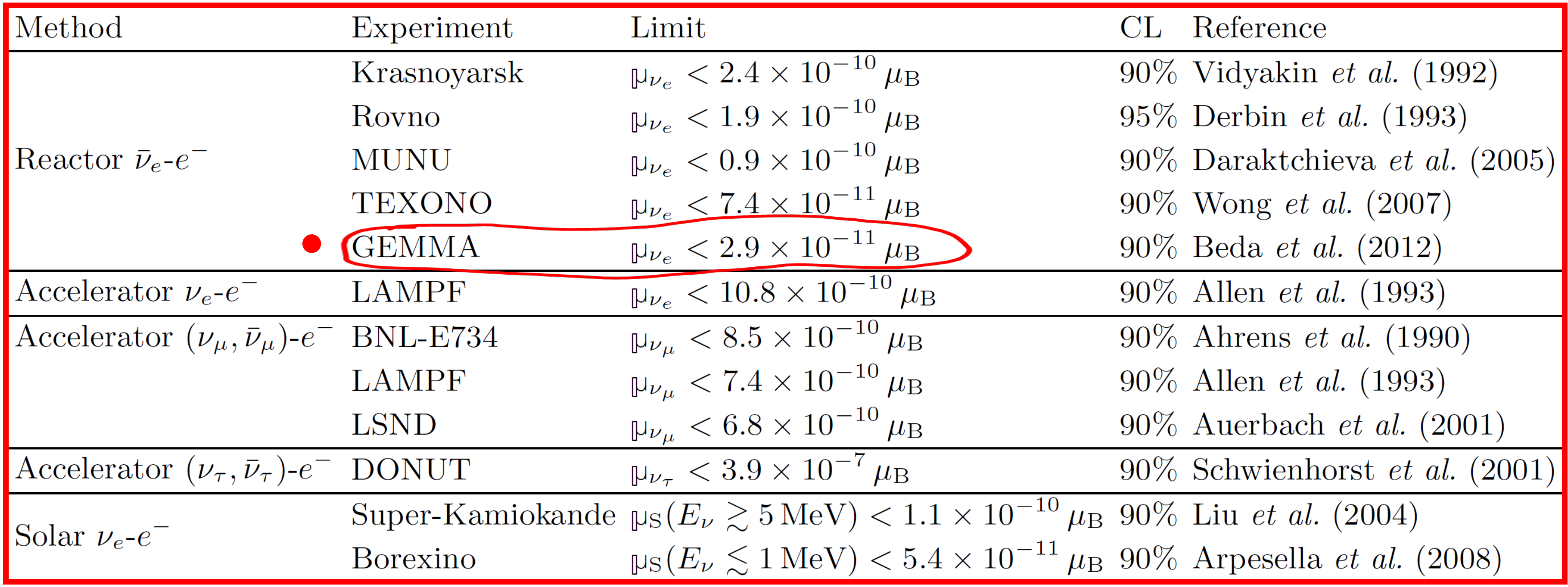


μ_{eff} <
2.8 x$10^{-11}\mu_B$

12/2011- 05/2016
1291 days

90% C.L.

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, 2014-2020 and update of 2021

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

ν neutrality $Q=0$ is attributed to

gauge invariance
+
anomaly cancellation constraints

imposed in SM of electroweak interactions

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

- …General proof:

In SM :

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

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

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

$\boxed{Q=0}$

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

Bardeen, Gastmans, Lautrup, 1972;
Cabral-Rosetti, Bernabeu, Vidal, Zepeda, 2000;
Beg, Marciano, Ruderman, 1978;
Marciano, Sirlin, 1980; Sakakibara, 1981;
- 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

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, 2016-2020
and update of 2021

Expected new constraints from GEMMA:

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

!

$\boxed{\text{2021 + few years data taking}}$

νGeN experiment

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

… low threshold …

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

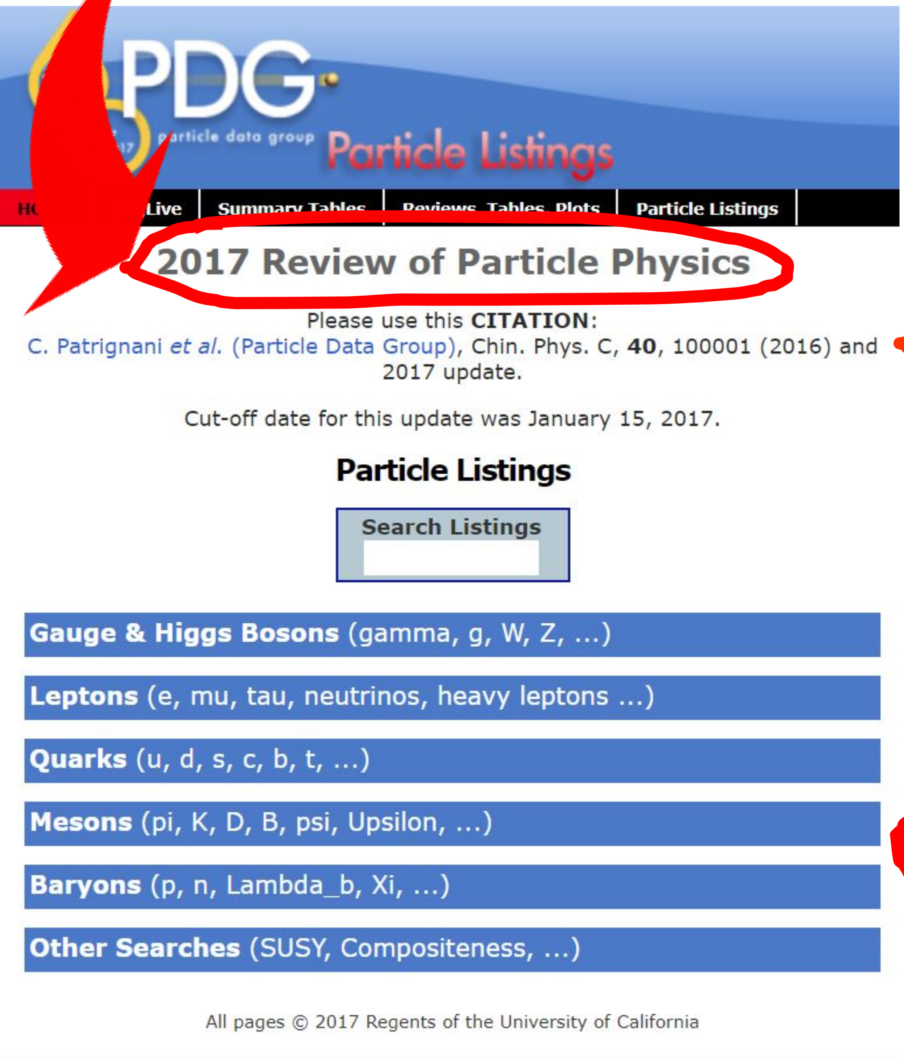
Constraints on q_ν !

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

in ν Table of Particle Data Group
since 2016 !

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

Particle Data Group collaboration 2016 – 2020 and 2021 update



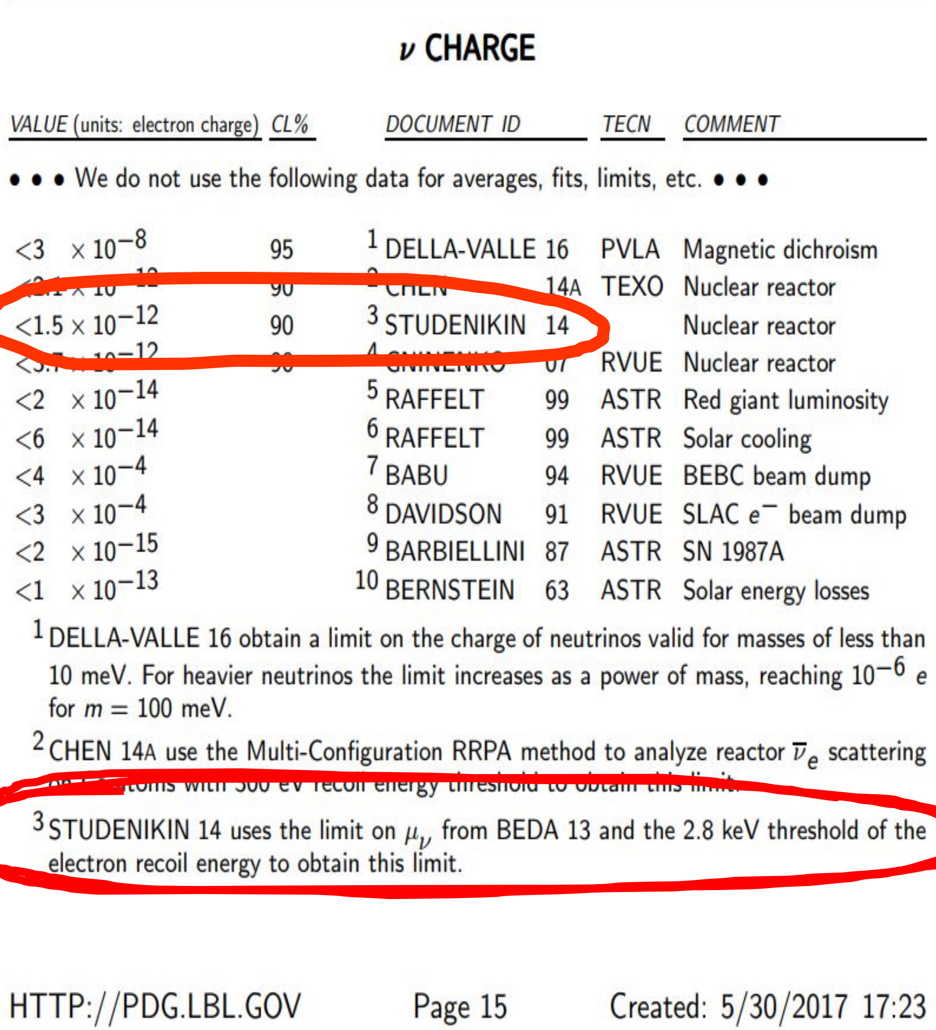
2017 Review of Particle Physics

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, ...)



ν CHARGE

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units: electron charge)	CL%	DOCUMENT ID	TECN	COMMENT
$<3 \times 10^{-8}$	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 Ge 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 ???

ν charge radius and anapole moment

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

1. electric

dipole

2. magnetic

3. electric

4. anapole

Although it is usually assumed that ν are electrically neutral (charge quantization implies $Q \sim \frac{1}{3}e$),

ν can dissociates into charged particles so that $f_Q(q^2) \neq 0 \;\; for \;\; q^2 \neq 0$

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

where the massive ν charge radius

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

For massless ν

anapole moment →

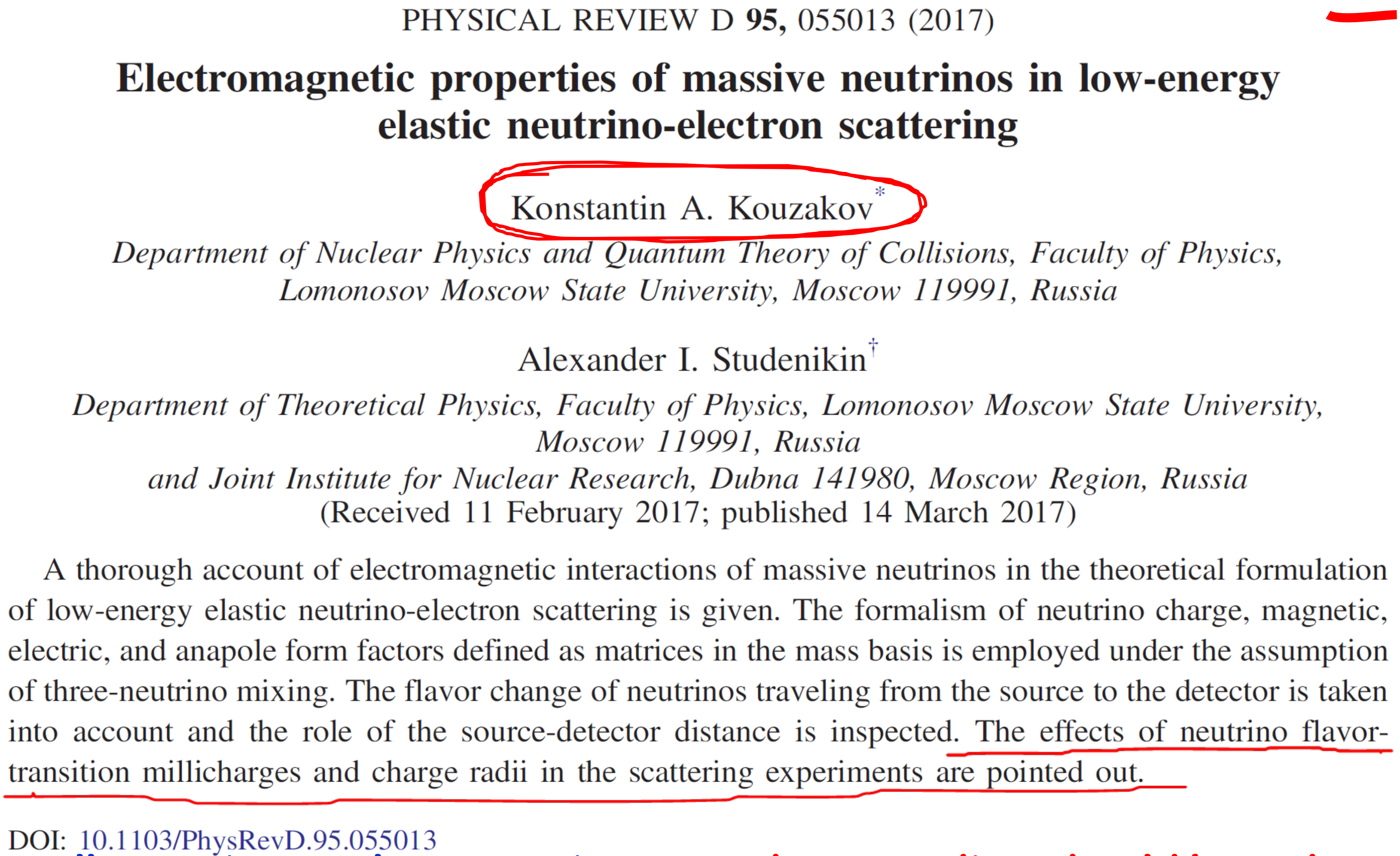
$$\boxed{a_\nu = f_A(q^2) = \frac{1}{6}\langle r_\nu^2 \rangle}$$

Interpretation of charge radius as an observable is rather delicate issue: $\langle r_\nu^2 \rangle$ represents a correction to tree-level electroweak scattering amplitude between ν and charged particles, which receives radiative corrections from several diagrams (including γ exchange) to be considered simultaneously ⟹ calculated CR is infinite and gauge dependent quantity. For massless ν, a_ν and $\langle r_\nu^2 \rangle$ can be defined (finite and gauge independent) from scattering cross section.

? ? ? For massive ν ? ? ?

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

… comprehensive analysis of ν-e scattering …



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

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

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(Received 11 February 2017; published 14 March 2017)

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

DOI: 10.1103/PhysRevD.95.055013

… all experimental constraints on charge radius should be redone

Concluding remarks

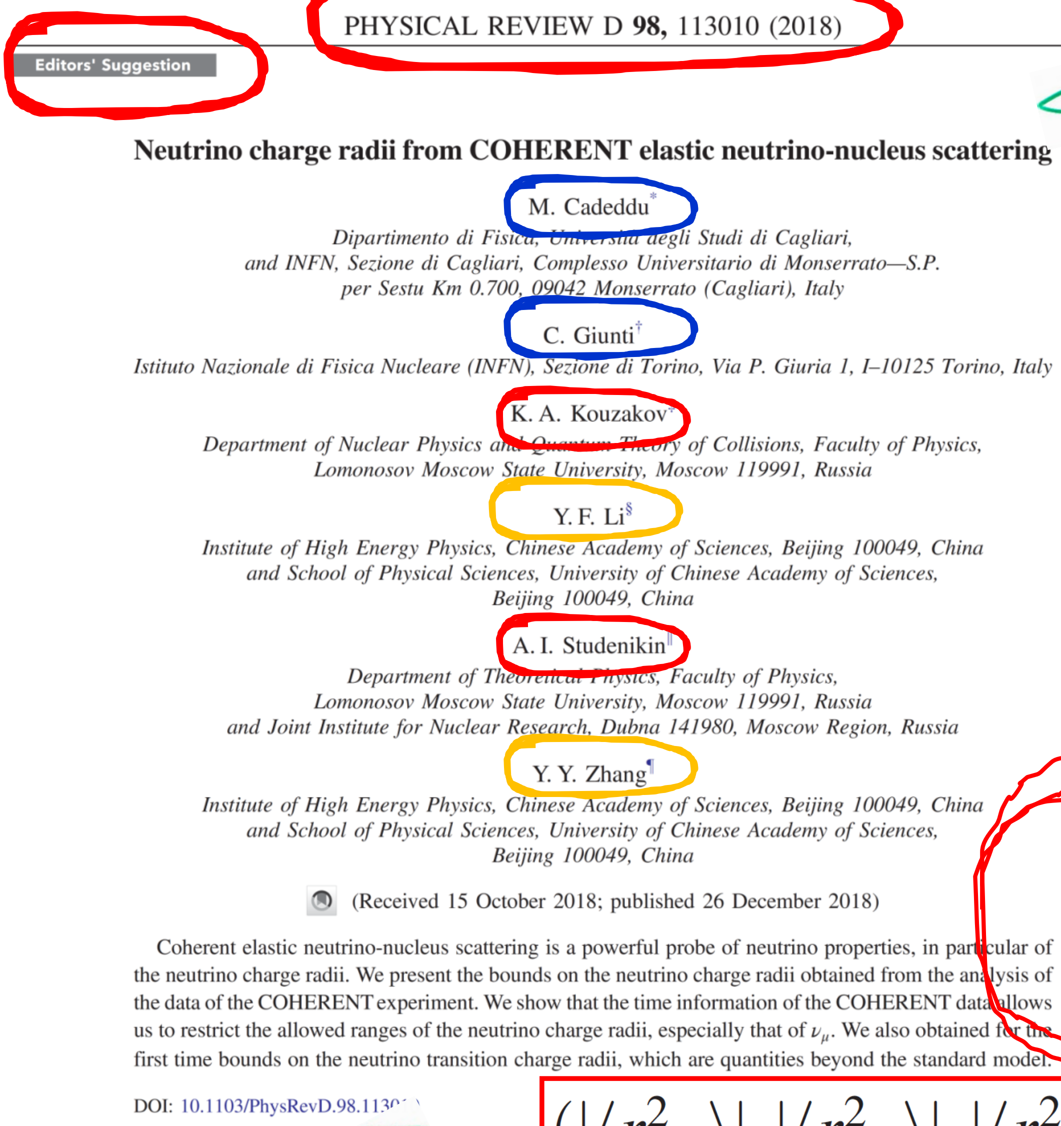
Kouzakov, Studenikin
Phys. Rev. D 95 (2017) 055013

- 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 $g_V \rightarrow g_V + \boxed{\frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2 \theta_W}$, there are also contributions from flavor-transition charge radii !

Ch – It – Ru collaboration



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

Editors' Suggestion

Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering

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per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy

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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.98.1130

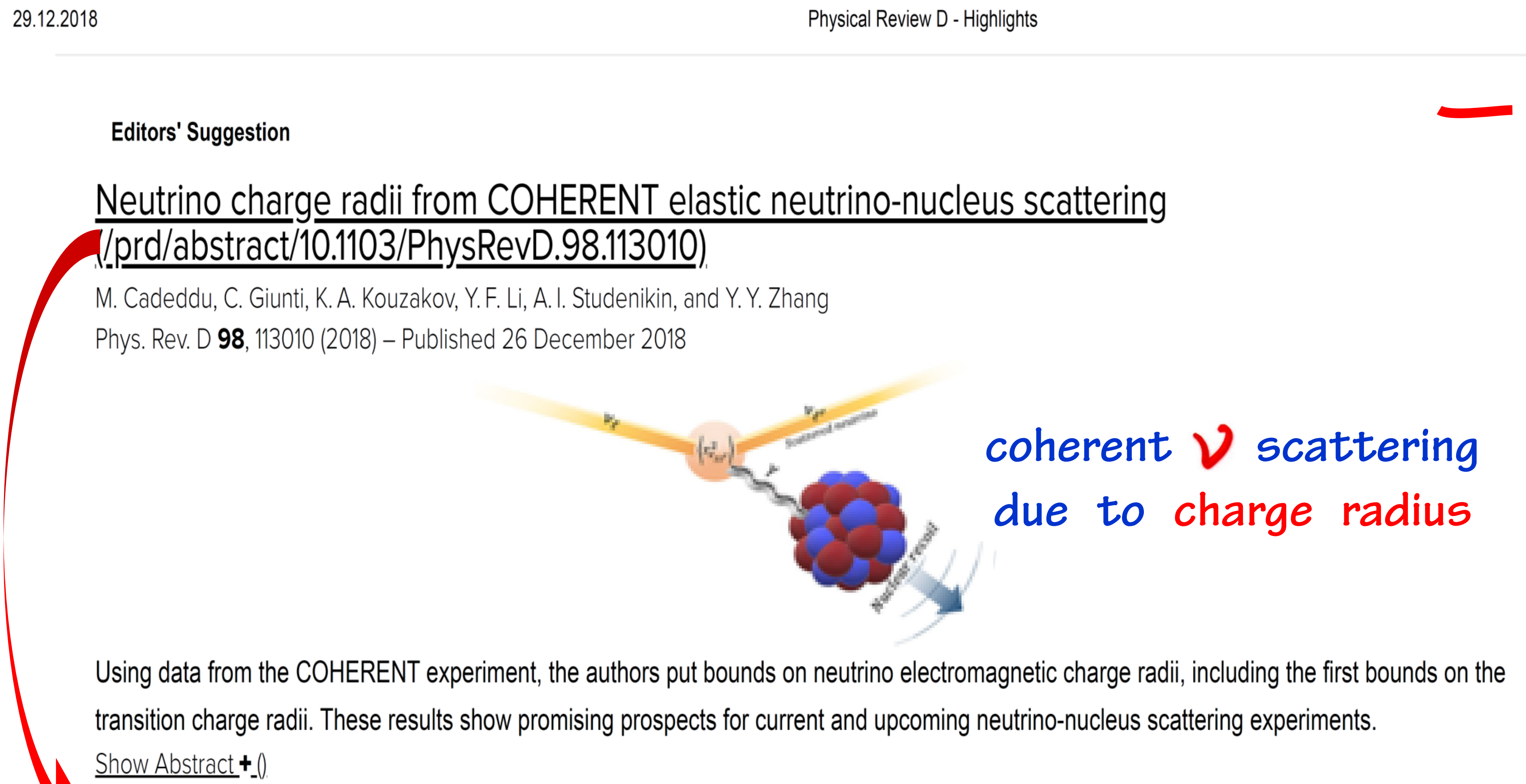
Physical Review D
– Highlights 2018 –
Editors' Suggestion

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

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

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

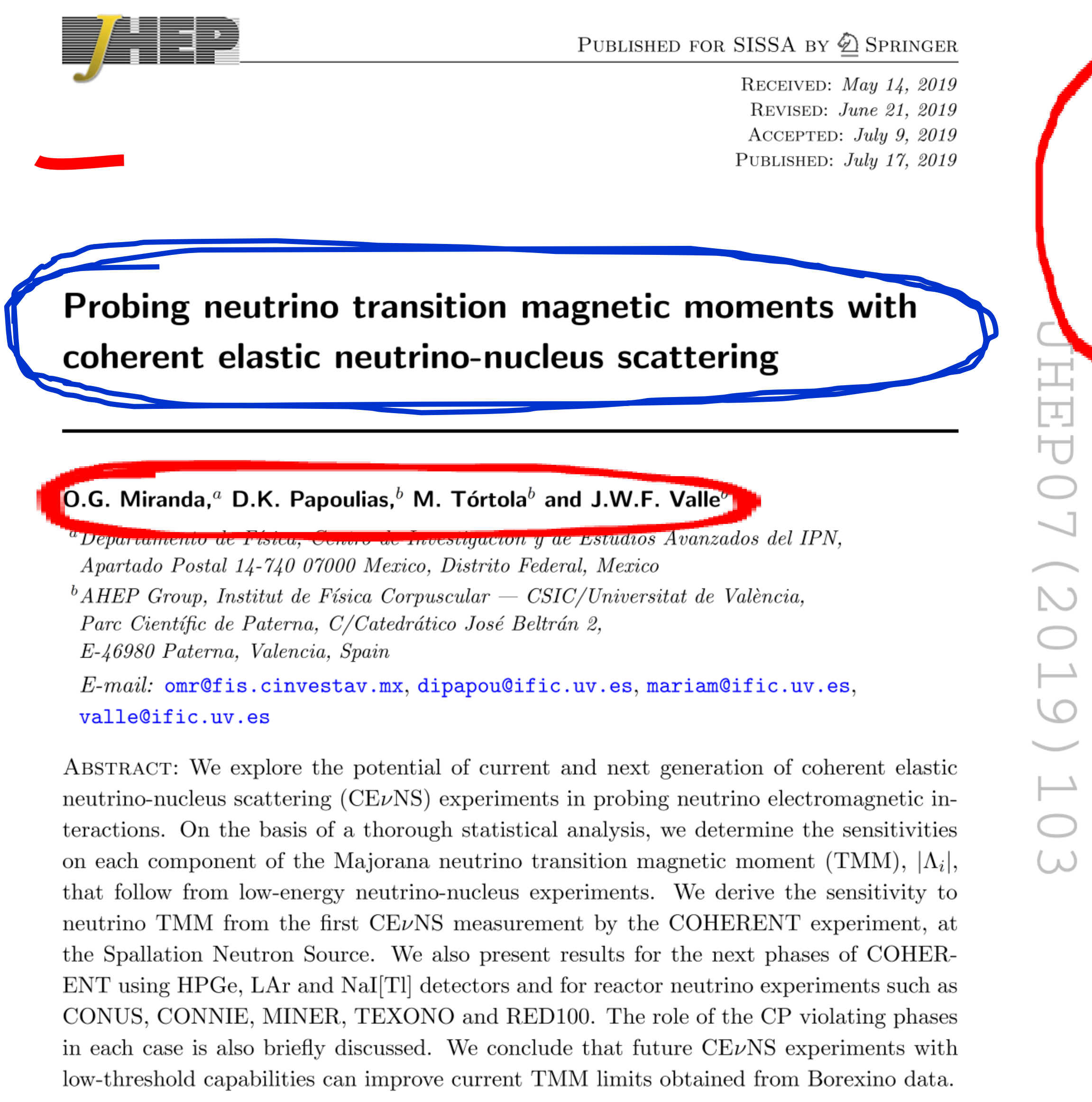
Phys. Rev. D **98**, 113010 (2018) – Published 26 December 2018

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 Properties (2018-2020),
update of 2021



JHEP
PUBLISHED FOR SISSA BY SPRINGER
RECEIVED: May 14, 2019
REVISED: June 21, 2019
ACCEPTED: July 9, 2019
PUBLISHED: July 17, 2019

Probing neutrino transition magnetic moments with coherent elastic neutrino-nucleus scattering

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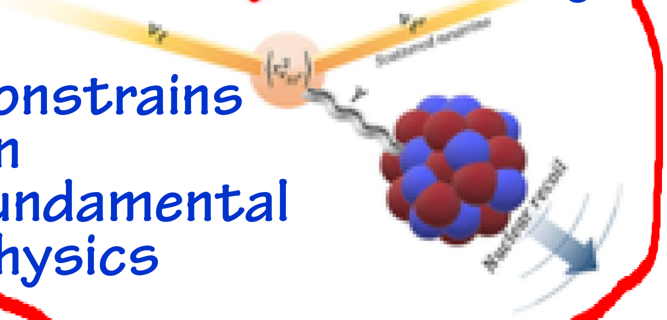
ABSTRACT: We explore the potential of current and next generation of coherent elastic neutrino-nucleus scattering (CEνNS) experiments in probing neutrino electromagnetic interactions. On the basis of a thorough statistical analysis, we determine the sensitivities on each component of the Majorana neutrino transition magnetic moment (TMM), $|\Lambda_i|$, that follow from low-energy neutrino-nucleus experiments. We derive the sensitivity to neutrino TMM from the first CEνNS measurement by the COHERENT experiment, at the Spallation Neutron Source. We also present results for the next phases of COHERENT using HPGe, LAr and NaI[Tl] detectors and for reactor neutrino experiments such as CONUS, CONNIE, MINER, TEXONO and RED100. The role of the CP violating phases in each case is also briefly discussed. We conclude that future CEνNS experiments with low-threshold capabilities can improve current TMM limits obtained from Borexino data.

- Neutrino, electroweak, and nuclear physics from COHERENT … with refined quenching factor ,
  Cadeddu, Dordei, Giunti, Li, Zhang, PRD 2020

coherent ν scattering



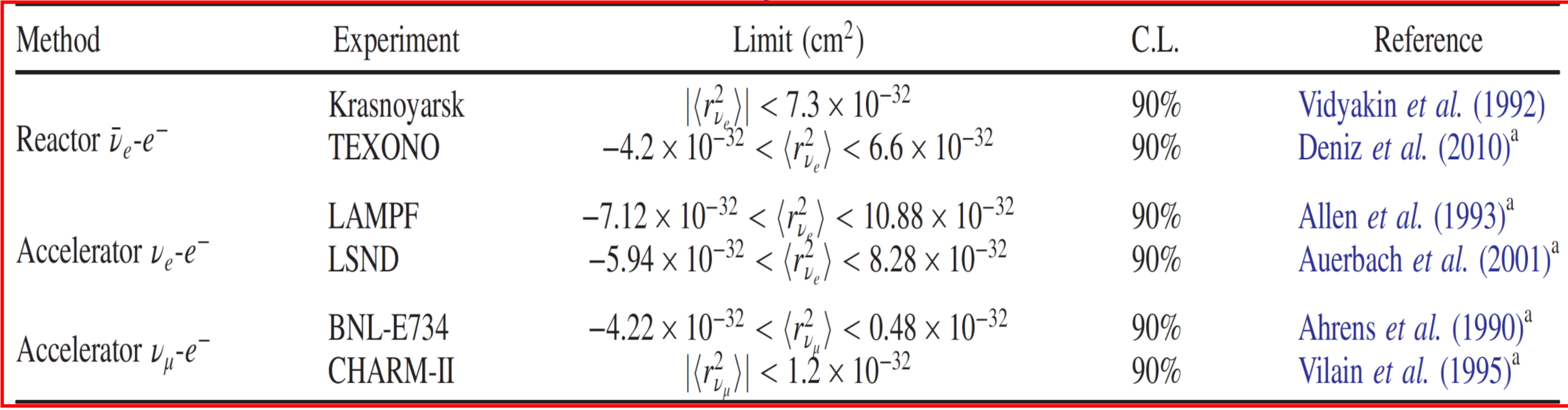
constrains on fundamental physics

COHERENT data have been used for different purposes:

- nuclear neutron distributions
  Cadeddu, Giunti, Li, Zhang
  PRL 2018
- weak mixing angle
  Cadeddu & Dordei, PRD 2019
  Huang & Chen 2019
- ν electromagnetic properties
  Papoulias & Kosmas PRD 2018
- ν non-standard interactions
  Coloma, Gonzalez-Garcia,
  Maltoni, Schwetz PRD 2017
  Liao & Marfatia PLB 2017

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

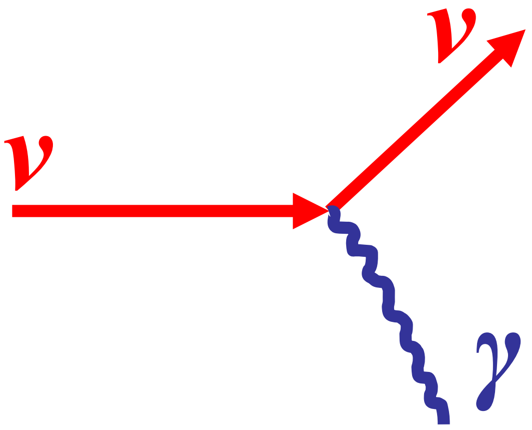
… updated by the recent constraints
(effects of physics Beyond Standard Model)

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

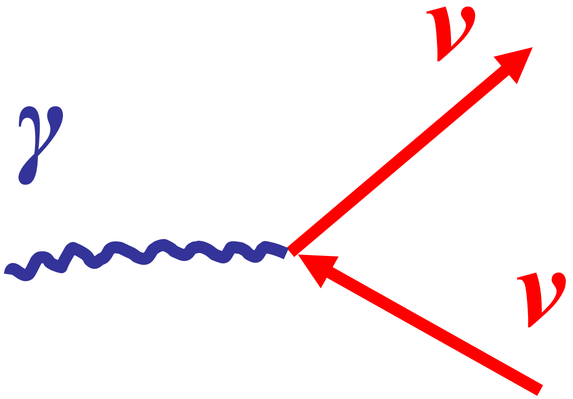
M.Cadeddu, C. Giunti, K.Kouzakov,
Yu-Feng Li, A. Studenikin, Y.Y.Zhang,
Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering, Phys.Rev.D 98 (2018) 113010

Electromagnetic ν in astrophycis and bounds on μ_ν and q_ν

ν electromagnetic interactions

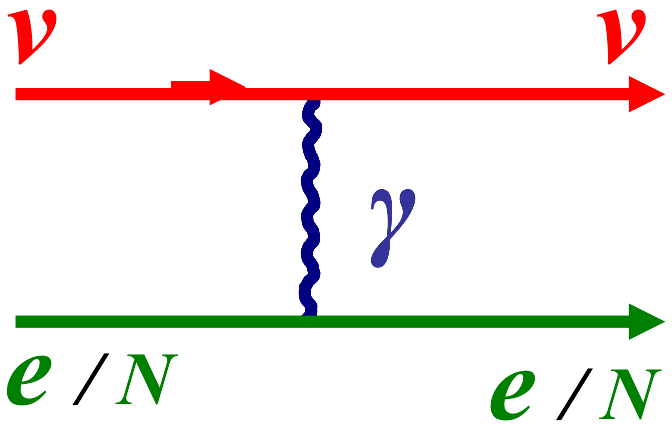


ν decay, Cherenkov radiation,
ν spin-light (SL ν)

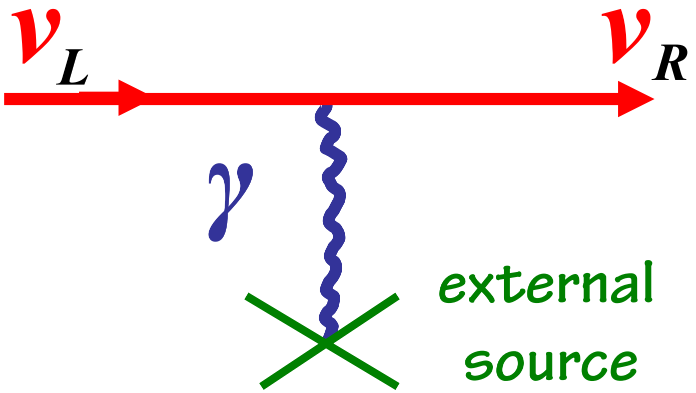


γ decay in plasma

!!!



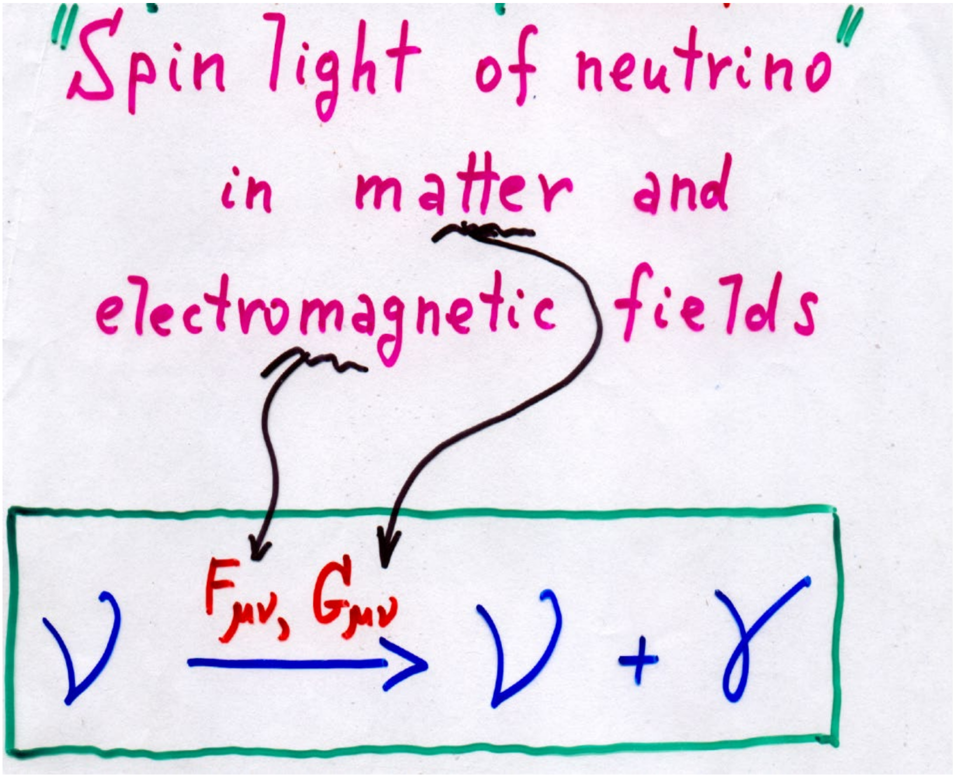
Scattering



Spin precession

New mechanism of electromagnetic radiation

$SL\nu$



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

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Spin light of neutrino in astrophysical environments

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

JCAP11(2017)024

Astrophysical bounds on μ_ν

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

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

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

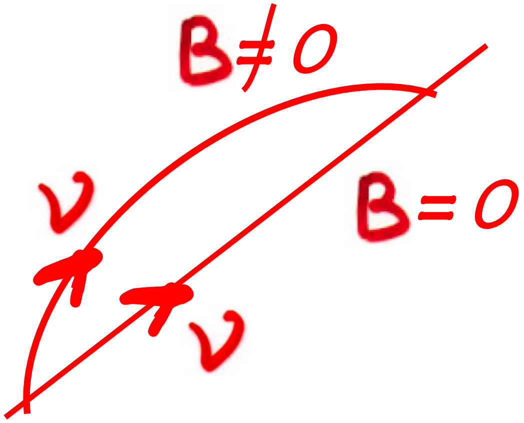
electric dipole moment

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

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



Astrophysics bounds on μ_ν

… example 4 …

1) SN 1987A provides energy-loss limit on μ_ν (also d_ν and transition moments)
related to observed duration of ν signal
…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

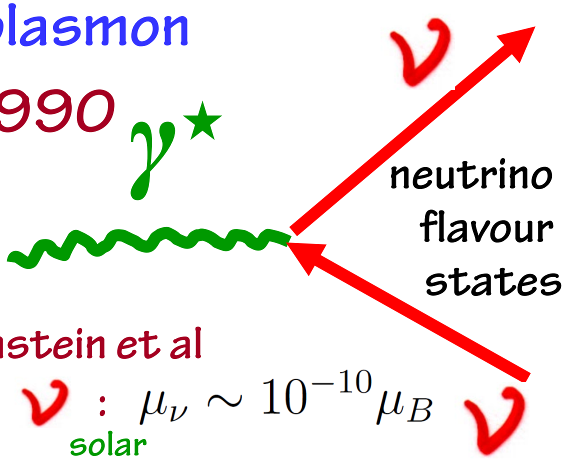
$$\Downarrow$$

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

② Astrophysical bound on μ_ν

… example 6…

comes from cooling of **red giant** stars by plasmon decay $\gamma^\star \longrightarrow \nu\nu$ G.Raffelt, PRL 1990



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

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 $\omega^2 - k^2 = \omega^2_{pl}$

Energy-loss rate per unit volume

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

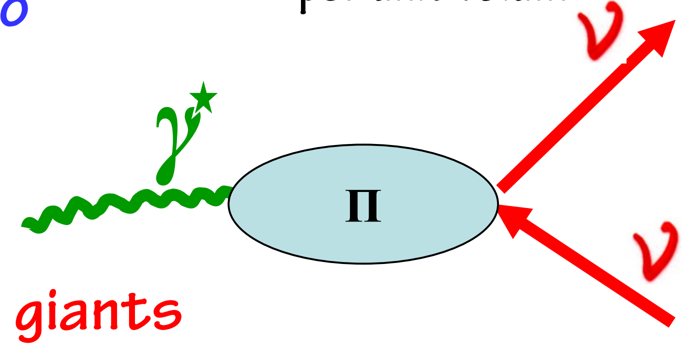
$$\mu^2 \to \sum_{a,b}\left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2\right)$$

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…

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

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

G.Raffelt, PRL 1990

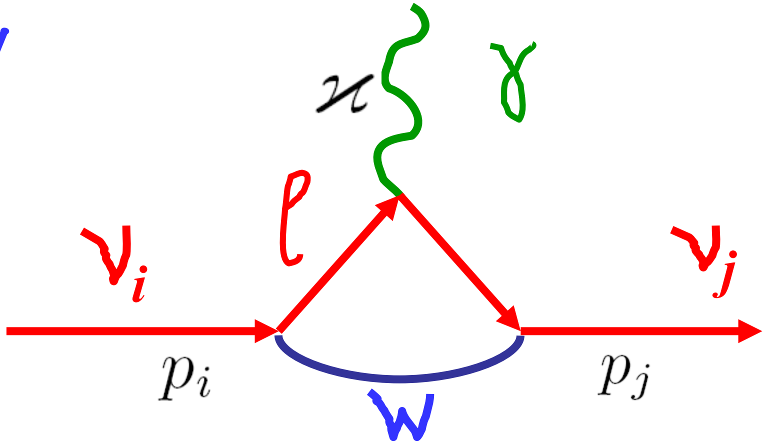
D+M

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

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

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

- 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

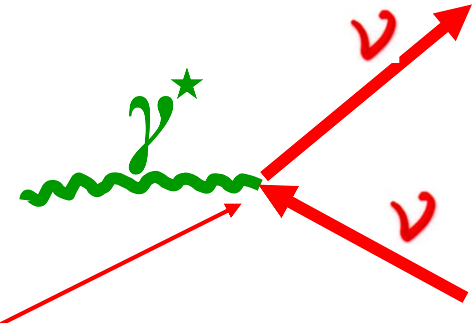
Raffelt 1999

Kolb, Turner 1990;
Ressell, Turner 1990

Astrophysical bounds on q_ν

Constraints on neutrino millicharge from red giants cooling

- **Plasma process** (photon decay) $\gamma^\star \rightarrow \nu\nu$



Interaction Lagrangian $\boxed{L_{int} = -i q_\nu \bar{\psi}_\nu \gamma^\mu \psi_\nu A^\mu}$

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

- $\boxed{q_\nu \leq 2 \times 10^{-14} e}$ ...to avoid delay of helium ignition in low-mass red giants

Halt, Raffelt,
Weiss, PRL1994

- $\boxed{q_\nu \leq 3 \times 10^{-17} e}$ ... absence of anomalous energy-dependent dispersion of SN1987A ν signal, most model independent
- $\boxed{q_\nu \leq 3 \times 10^{-21} e}$ ... 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

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

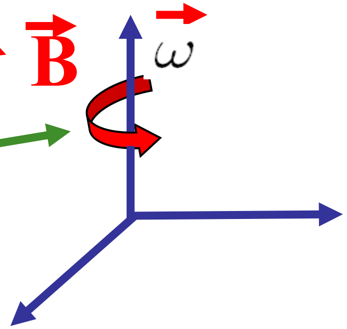
external magnetic field

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

matter potential

rotating matter

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



rotation angular frequency

ν energy is quantized in rotating and magnetized star

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

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

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

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

integer number

matter rotation frequency

millicharge

scalar potential of electric field

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

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

In quasi-classical approach

ν quantum states in rotating matter

ν motion in circular orbits

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

due to effective Lorentz force

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

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

$$q_{eff}\mathbf{E}_{eff}=q_m\mathbf{E}_m+q_0\mathbf{E} \qquad q_{eff}\mathbf{B}_{eff}=|q_mB_m+q_0B|\mathbf{e}_z$$

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

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

- # ν Star Turning mechanism (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

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

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

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

.. best astrophysical bound ...

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

② inherent interplay of ν spin and flavour oscillations in B

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

① ν

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

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

oscillations engendered

by transversal matter currents $j_\perp$

~~$(\mu_\nu B)$~~

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

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

ELEMENTARY PARTICLES AND FIELDS

Theory

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

Neutrino in Electromagnetic Fields and Moving Media

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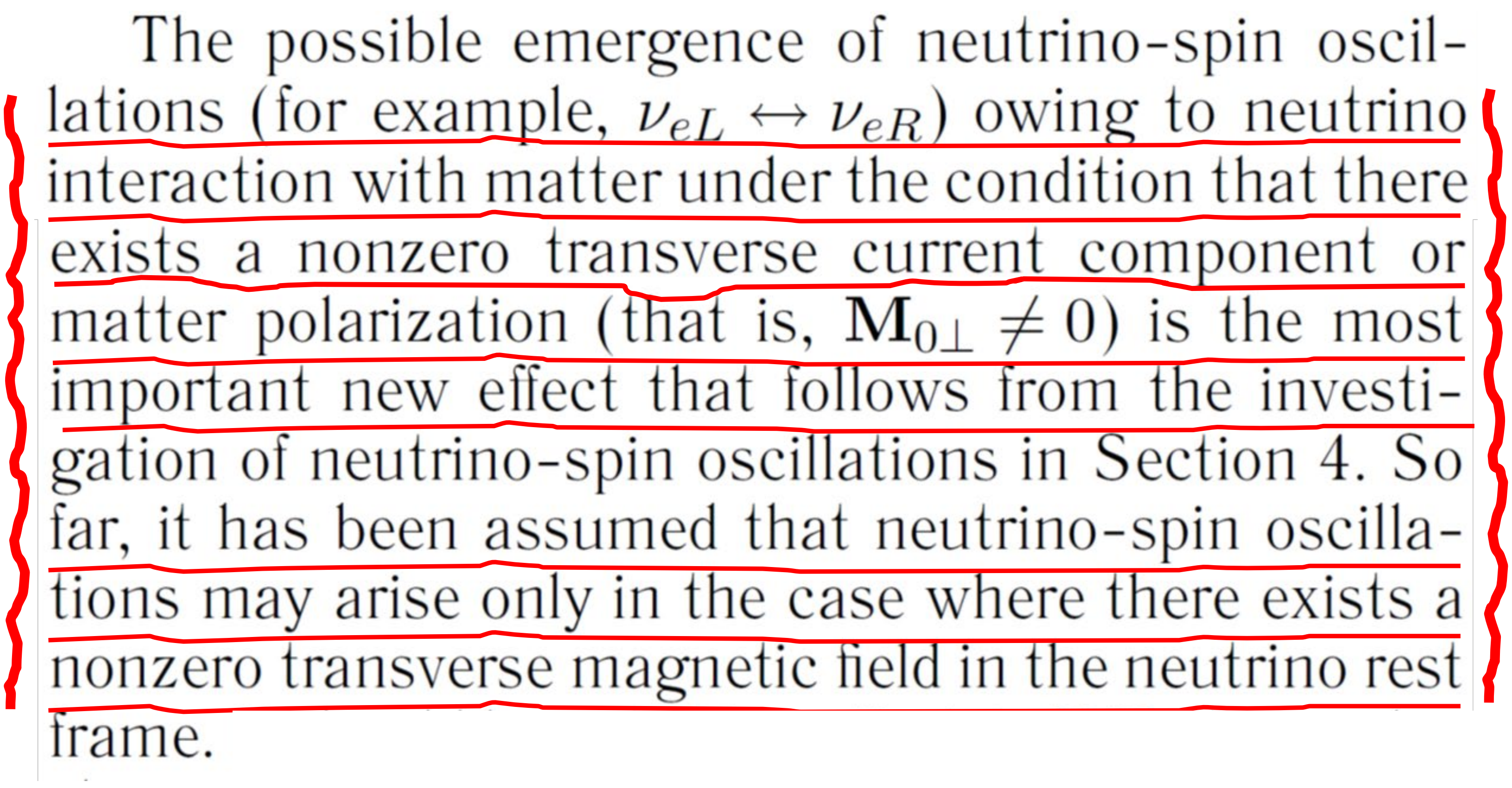
Received March 26, 2003; in final form, August 12, 2003



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

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

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

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

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

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

- transversal current $j_\perp$

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

matter density

$\parallel$

$\perp$

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

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

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

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

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

$l = e, \; or \; \mu$
$i = 1, \; 2$

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

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

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

ν flavour
and
mass states

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

ν (2 flavours x 2 helicities) evolution equation

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

vacuum

matter at rest

moving matter

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

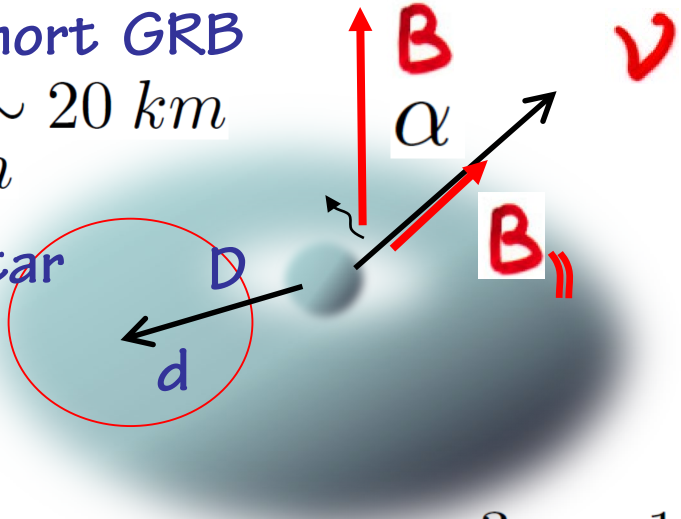
P. Pustoshny, A. Studenikin, Phys. Rev. D98 (2018) 113009

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

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

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

- transversal velocity of matter

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

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

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

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

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

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

resonance condition

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

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

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

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

Criterion – oscillations are important:

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

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

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

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

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

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

$$\Delta m^2 = 7.37 \times 10^{-5} \ eV^2$$
$$\sin^2 \theta = 0.297$$
$$p_0^\nu = 10^6 \ eV$$

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

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

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

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

②

ν

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

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

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

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

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

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

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

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

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

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

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

"bra-ket" products

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

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

- ν energy spectrum

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

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

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

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

flavour

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

spin

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

spin-flavour

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

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

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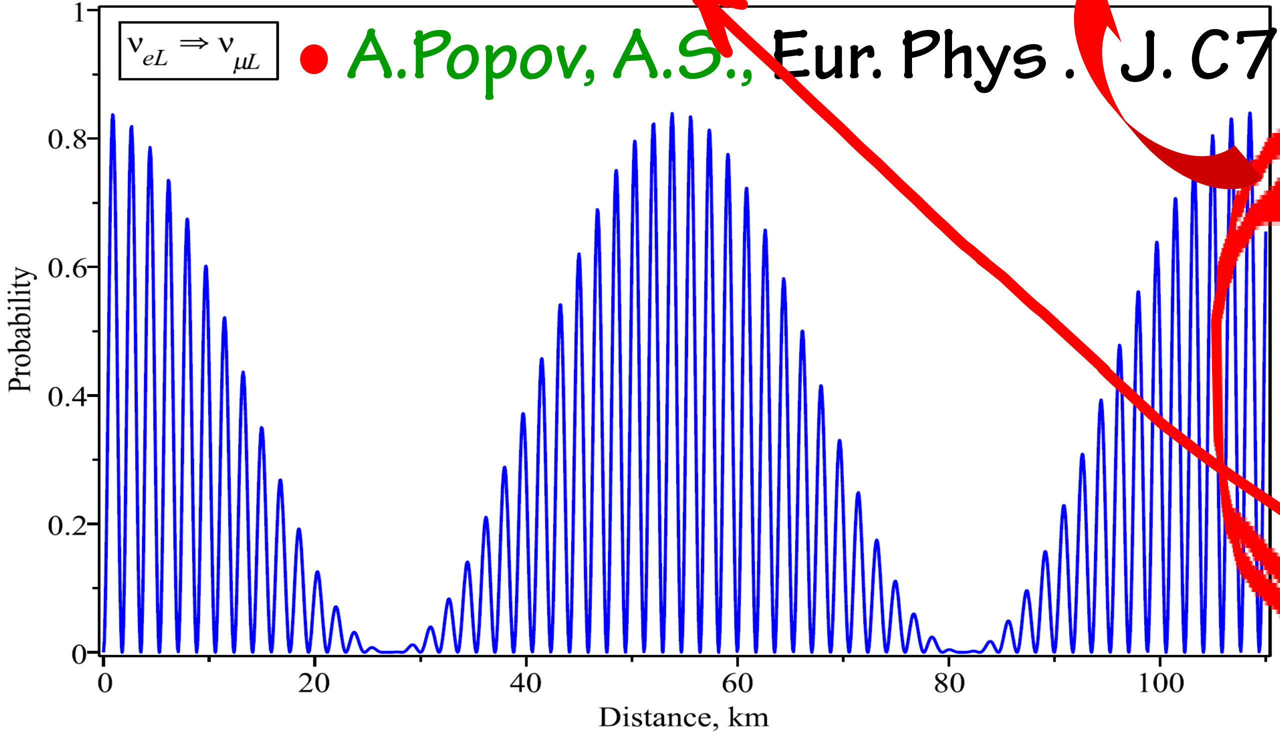
- For the case $\mu_1 = \mu_2$: probability of flavour oscillations

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

flavour

no spin oscillations

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



… 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 $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

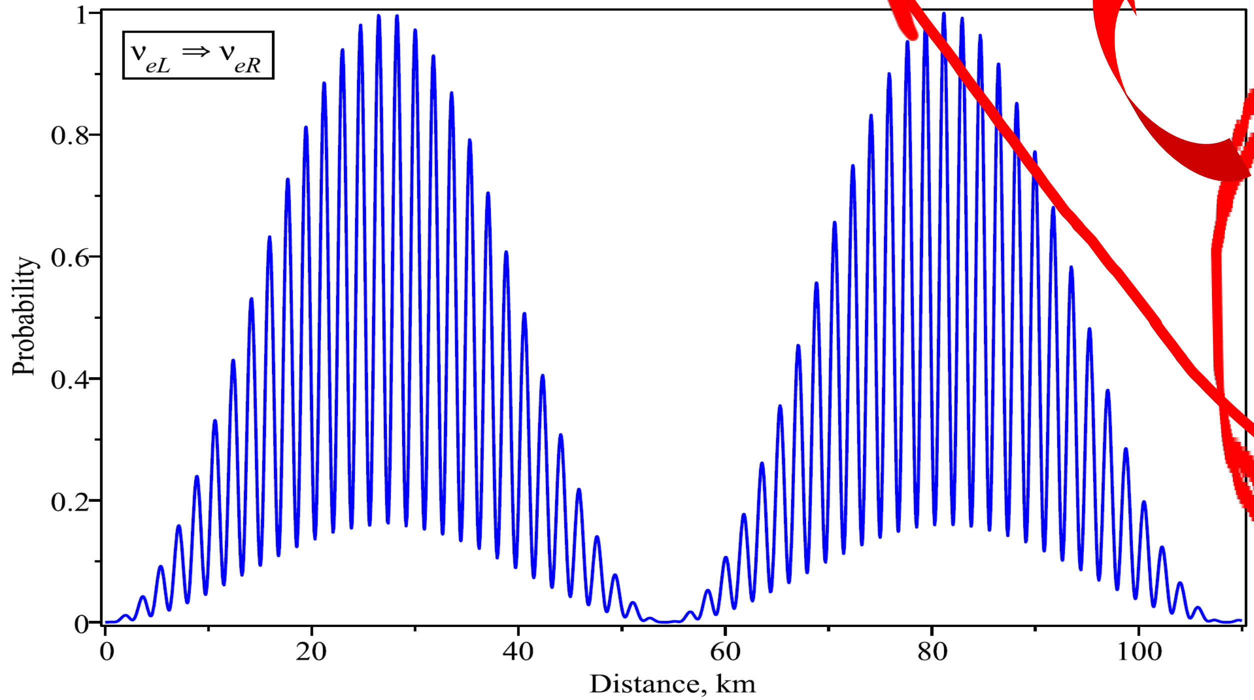
Chotorlishvili, Kouzakov, Kurashvili, Studenikin, Spin-flavor oscillations of ultrahigh-energy cosmic neutrinos in interstellar space: The role of neutrino magnetic moments, Phys. Rev. D96 (2017) 103017

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

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



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

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, $\Delta m^2 = 7\times10^{-5}$ eV^2 and magnetic moments $\mu_1 = \mu_2 = 10^{-20}\mu_B$.

A.Popov, A.S.,
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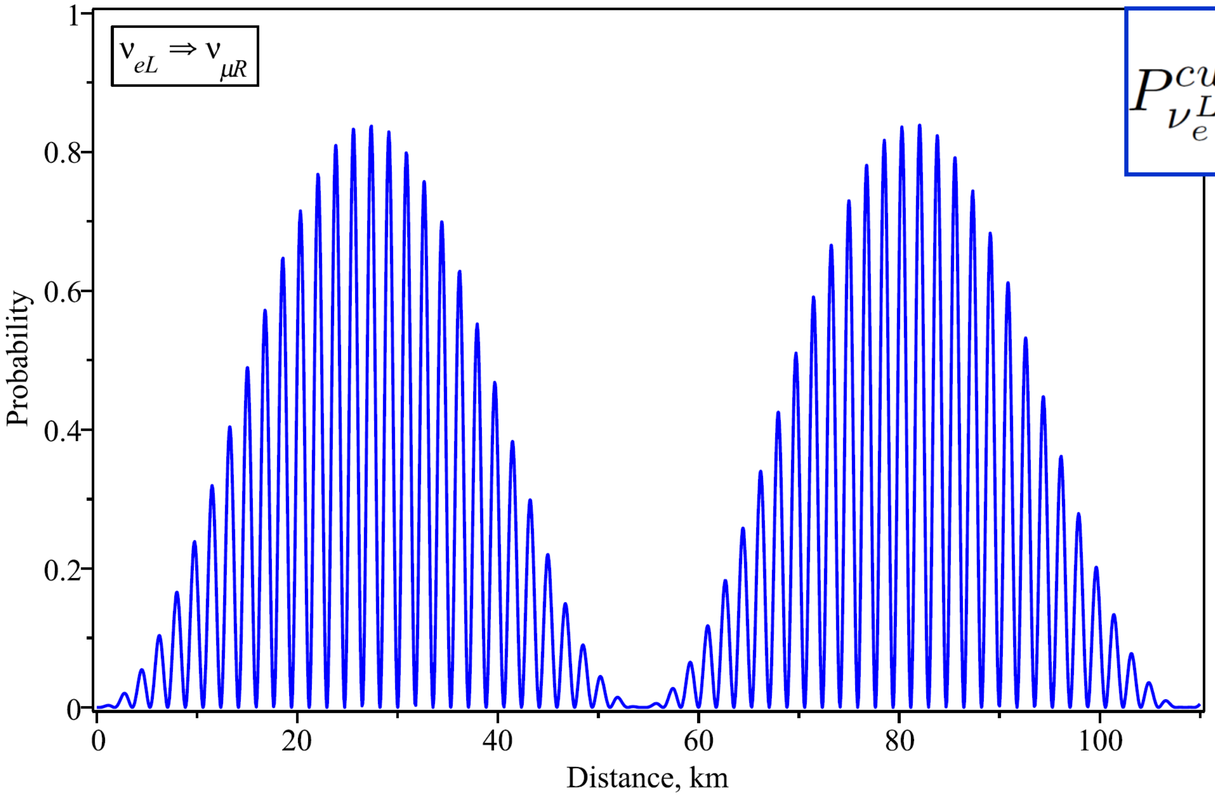
79 (2019) 144

- 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



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

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

… interplay of oscillations

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

and

on magnetic $\boxed{\omega_B = \mu B_\perp}$

frequencies

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

… in literature:

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

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

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

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

… depends on μ_ν and B

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

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

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

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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, Nuovo Cim. C42 (2019) n.6;
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

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

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

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

probability of spin survival
(not spin flip)

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

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

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

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

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

… is modulated by
two "matter"
frequencies …

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

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

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

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Phys.Rev.D 103 (2021) 115027

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

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

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(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 $\mathcal{J}_{\mathrm{CKM}} = (3.18 \pm 0.15) \times 10^{-5}$ [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

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… 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

Conclusions

① ② ③

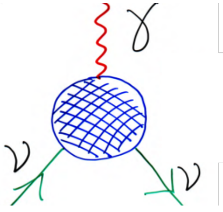
① Electromagnetic Properties of ν

Alexander Studenikin MSU JINR

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

A.Studenikin,
"Electromagnetic ν properties: New constraints and new effects",
arXiv: 2102.05468

① νEP theory - ν vertex function



matrices in ν mass eigenstates space

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

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

CPT + charge concervation

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

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

Fujikawa & Shrock, 1980

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

③ 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

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

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 ⟹ $\boxed{\mu_\nu \in (1.4,\ 2.9)\times 10^{-11}\ \mu_B}$

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 ⟹ $\boxed{\mu_\nu < 2.2 \times 10^{-12} \mu_B}$

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 ⟹ upper limit

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

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

③ ν electromagnetic properties: Future prospects

- liquid xenon (LXe) detectors set limits on ν electromagnetic properties, including millicharge

⇒ XMASS Coll. limits on q_ν :

- in case 3ν have common q_ν $$\boxed{q_\nu < 5.4 \times 10^{-12} e_0}$$
- for individual ν flavours $$\boxed{(q_{\nu_{e,\mu}}; \quad q_{\nu_\tau}) < (1.1; \quad 0.7) \times 10^{-11} e_0}$$

K.Abe et al, XMASS Coll.,
Search for exotic neutrino-electron Interactions using solar neutrinos in XMASS-I,
Phys. Lett.B 809 (2020) 135741

… studies of ν electromagnetic properties are important ⇒

- investigation of properties of an elementary particle
- it provides an important inside to fundamentals of particle physics

Thank you