Lecture # 2:
Electromagnetic neutrino properties In laboratory experiments and constraints on μ_ν, d_ν, q_ν and $<r^2_\nu>$

The European Consortium for Astroparticle Theory,

Astroneutrino Theory Workshop 2021,
Czech Technical University, Prague
21/09/2020

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Lecture # 1 (20.09.2021)
Introduction to ν electromagnetic properties

- AS, ν flavor and spin oscillations
- Alexey Lichkunov,
  The interplay of ν flavor and spin oscillations in a magnetic field

Lecture # 2 (21.09.2021)
Electromagnetic ν properties In laboratory experiments and constraints on μ_ν, d_ν, q_ν and $< r^2_\nu >$

- Fedor Lazarev, Electromagnetic effects in elastic ν scattering on nucleons and nuclei
- Georgy Donchenko, ν magnetic moments in low-energy ν scattering on atomic and condensed matter systems

Lecture # 3 (22.09.2021)
Electromagnetic ν: New effects in magnetic fields and matter

- Vadim Shakhov, ν spin and flavor oscillations in transversal matter currents
- Artem Popov, Majorana ν oscillations in a magnetic field and CP violation
- Konstantin Stankevich, The effect of quantum decoherence in astrophysical ν oscillations

ν

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:

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

where the Standard Model contribution

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

T is the electron recoil energy and

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

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

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

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

for antineutrinos $g_A \to -g_A$

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

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

ν-γ coupling ... valid for ν scattering on free e

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

with change of helicity, contrary to SM

T is the electron recoil energy: $0 \le T \le \dfrac{2E_\nu^2}{2E_\nu + m_e}$

If neutrino has electric dipole moment,
or electric or magnetic transition moments,
these quantities also contribute to scattering cross section

$$\mu_{\nu_\ell}^2 \simeq \mu_{\bar{\nu}_\ell}^2 \simeq \sum_j \left| \sum_k U_{\ell k}^* (\mu_{jk} - i\epsilon_{jk}) \right|^2$$

effective flavour magnetic moment
for short-baseline experiments

Kouzakov
Studenikin
PRD 2017

Possibility of *distractive interference* between magnetic and electric transition moments of Dirac neutrino
(Majorana neutrino has only magnetic or electric transition moment, but not both if CP is conserved)

Effective ν_e magnetic moment measured in ν-e scattering experiments ?

$$\mu_e^2$$

Two steps:

1) consider ν_e as superposition of mass eigenstates ($i=1,2,3$) at some distance L from the source, and then sum up magnetic moment contributions to ν-e scattering amplitude (of each of mass components) induced by their magnetic moments

$$A_j \sim \sum_i U_{ei} e^{-iE_i L} \mu_{ji}$$

J.Beacom, P.Vogel, 1999

2) amplitudes combine incoherently in total cross section

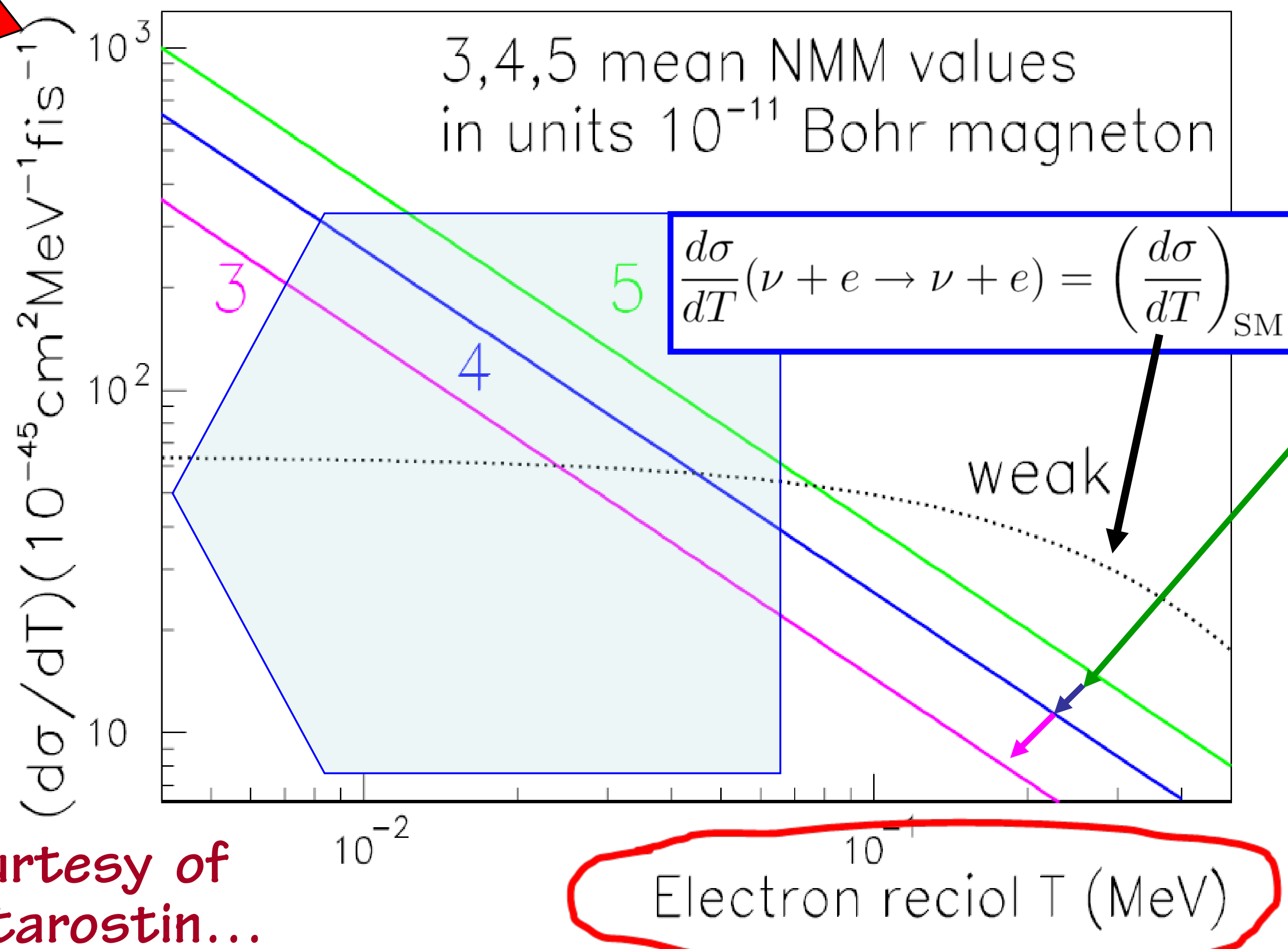
$$\sigma \sim \mu_e^2 = \sum_j \left| \sum_i U_{ei} e^{-iE_i L} \mu_{ji} \right|^2$$

C.Giunti, A.Studenikin, 2009

NB! Summation over $j=1,2,3$ is outside the square because of incoherence of different final mass states contributions to cross section

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

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



… courtesy of A.Starostin…

First and future ν-e scattering experiments

- $$\mu_\nu \leq 2 \div 4 \times 10^{-10} \mu_B$$

  Savannah River (1976), *first observation of ν - e*

  Vogel, Engel, 1989

  Kurchatov, Krasnoyarsk (1992), Rovno (1993) reactors

- $$\mu_\nu \leq \; 1.1 \times 10^{-10} \; \mu_B$$

  Super-Kamiokande (2004)

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

  ...in the future...

  Beta-beams

  McLaughlin, Volpe, 2004

MUNU experiment at Bugey reactor (2005)

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

TEXONO collaboration at Kuo-Sheng power plant (2006)

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

GEMMA (2007)

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

GEMMA I 2005 - 2007

BOREXINO (2008)

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

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

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

based on first release of BOREXINO data

Montanino, Picariello, Pulido, PRD 2008

... attempts to improve bounds

GEMMA (2005 – 2012 - 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

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

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 $T \sim 200 \;\; eV$

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

2021 + few years of data taking ?

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

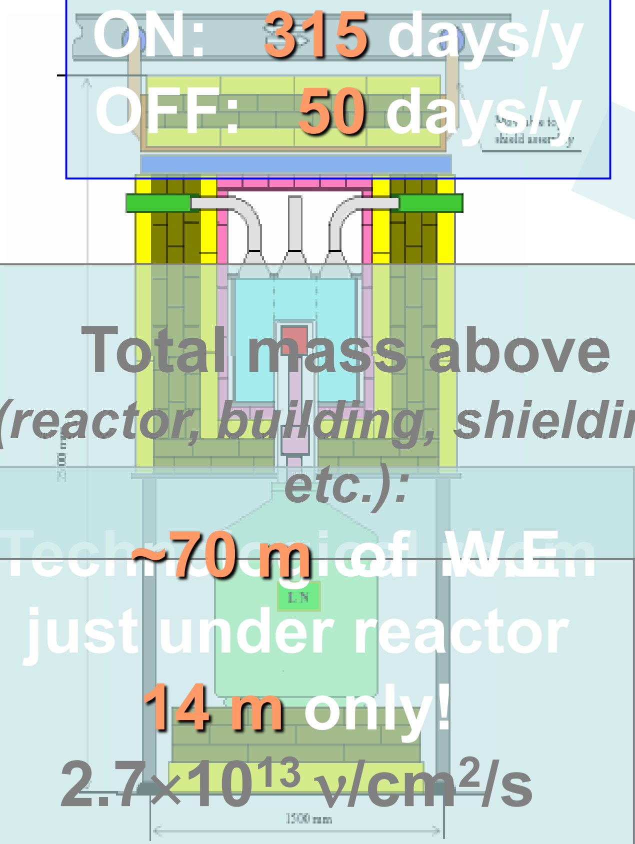
Калининской атомной станции
(Удомля, Тверская область)

Reactor unit #2 of the "Kalinin" Nuclear Power Plant (400 km North from Moscow)

Power: 3 GW

ON: **315** days/y

OFF: **50** days/y



Total mass above

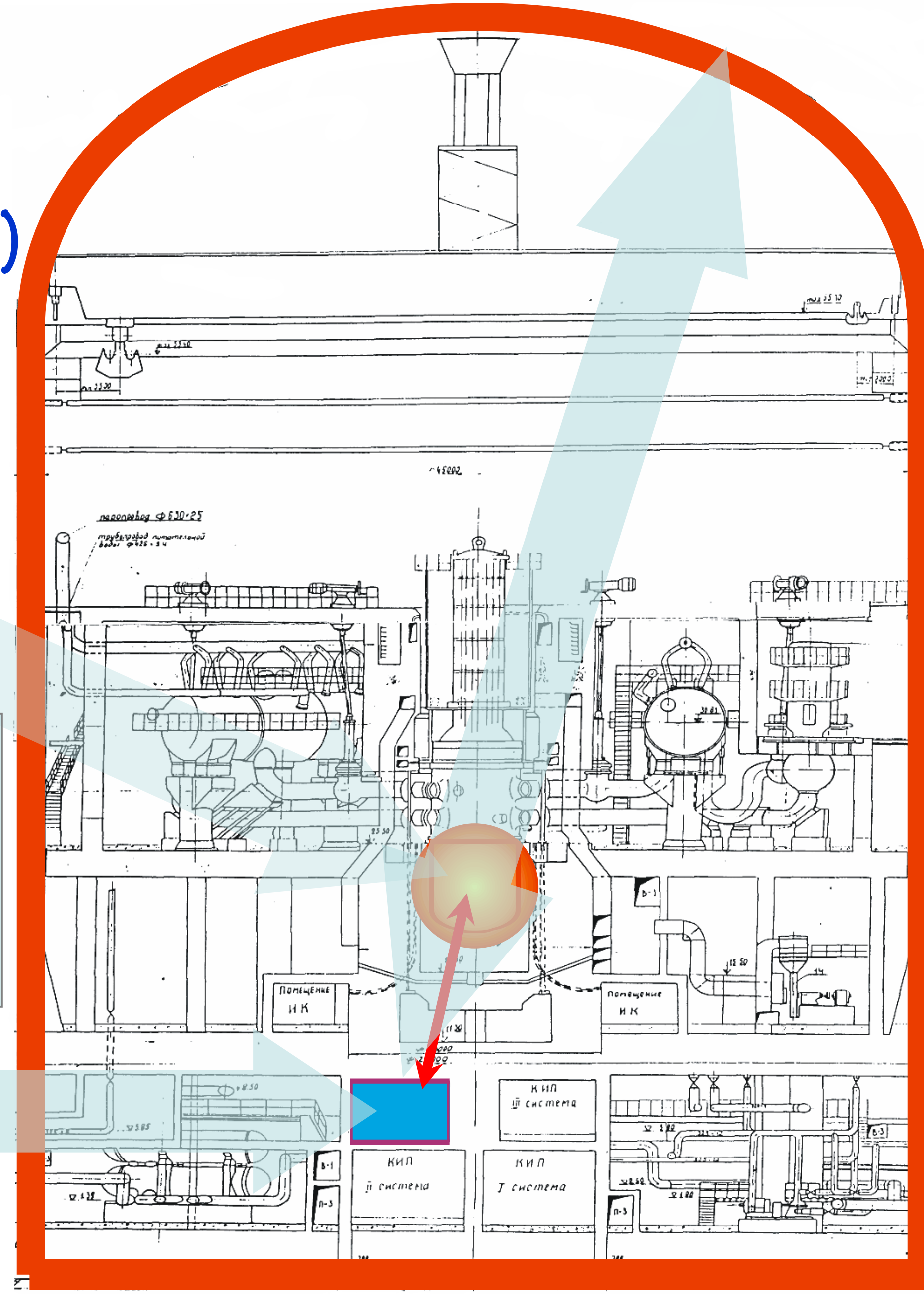
(reactor, building, shielding, etc.):

~70 m of W.E

Technological room just under reactor

14 m only!

2.7×10^{13} ν/cm²/s



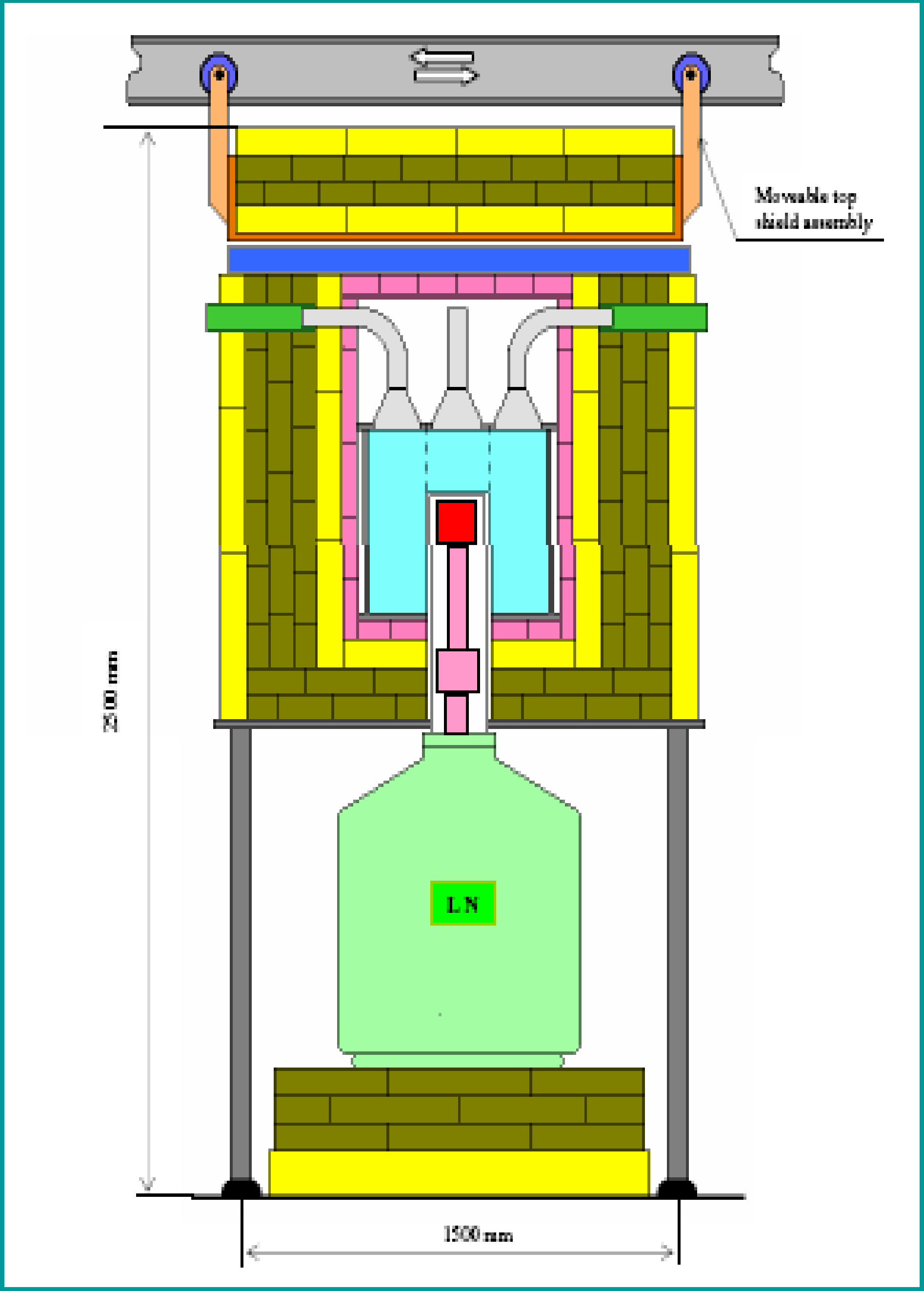
... courtesy of D.Medvedev...

Experiment **GEMMA**

(**G**ermanium **E**xperiment for measurement of **M**agnetic **M**oment of **A**ntineutrino)

*[Phys. of At. Nucl.,**67**(2004)1948]*

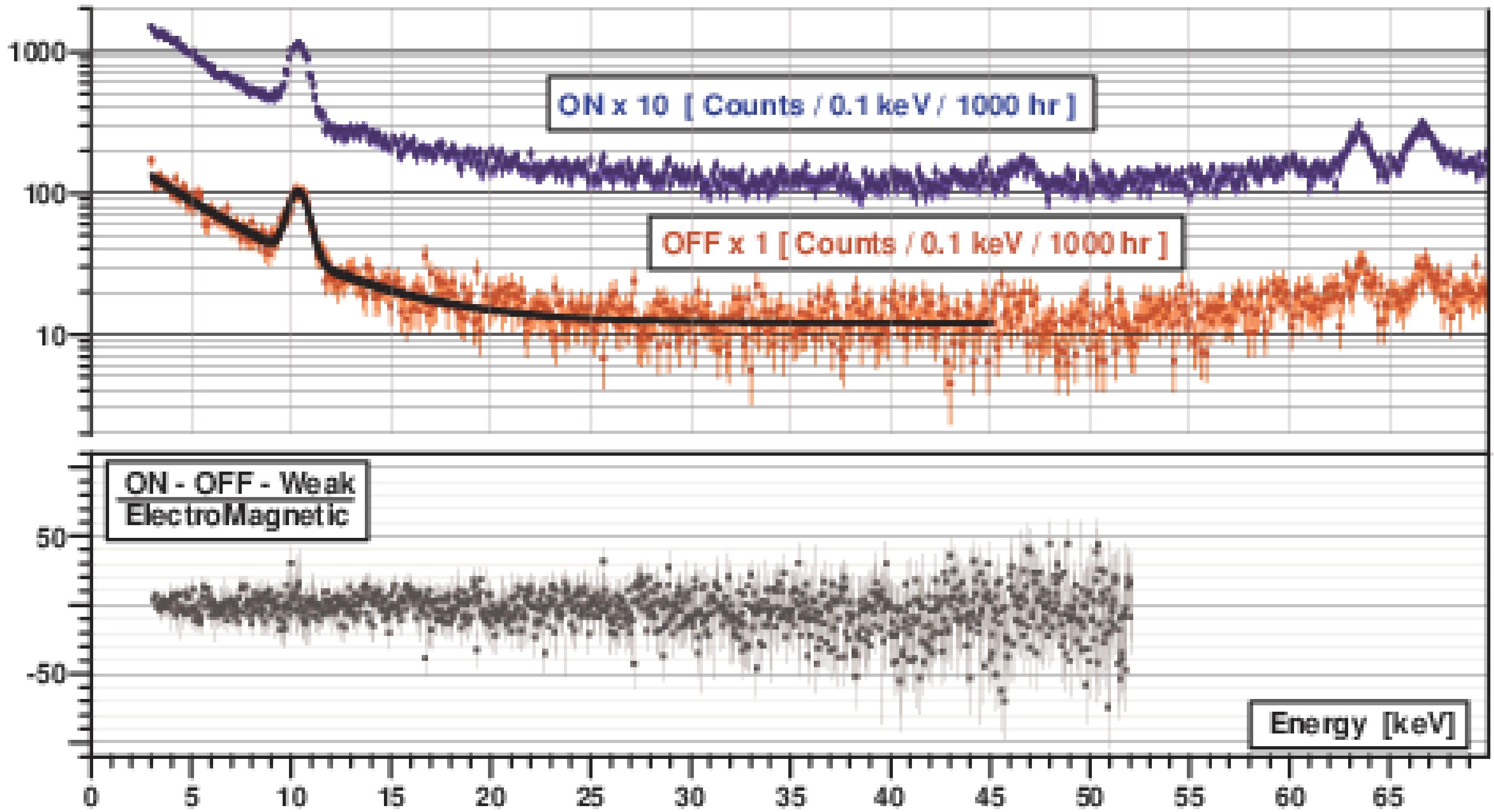
- Spectrometer includes a HPGe detector of 1.5 kg installed within NaI active shielding.
- HPGe + NaI are surrounded with multi-layer passive shielding : electrolytic copper, borated polyethylene and lead.



GEMMA background conditions

- **γ-rays** were measured with Ge detector. The main sources are: **^{137}Cs , ^{60}Co, ^{134}Cs.**
- **Neutron** background was measured with ^{3}He counters, i.e., thermal neutrons were counted. Their flux at the facility site turned out to be **30 times lower** than in the outside laboratory room.
- **Charged** component of the cosmic radiation (**muons**) was measured to be **5 times lower** than outside.

Final spectra



Experimental sensitivity

$$\mu_\nu \propto \frac{1}{\sqrt{N_\nu}}\left(\frac{B}{mt}\right)^{\frac{1}{4}}$$

- N_ν : number of signal events expected
- B : background level in the ROI
- m : target (=detector) mass
- t : measurement time

$N_\nu \sim \varphi_\nu$ (~ *Power* / r^2)

$\sim (T_{max} - T_{min} / T_{max} * T_{min})^{1/2}$

GEMMA I

φ_ν ~ 2.7 ×10^{13} ν / cm^2 / s
t ~ 4 years
B ~ 2.5 keV^{-1} kg^{-1} day^{-1}
m ~ 1.5 kg
T_{th} ~ 2.8 keV

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

Data Set

- I phase – 5184 h ON, 1853 h OFF

$$\mu_\nu < 5.8*10^{-11}\mu_B$$

- II phase – 6798 h ON, 1021 h OFF
- I+II – 11982 h ON, 2874 h OFF

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

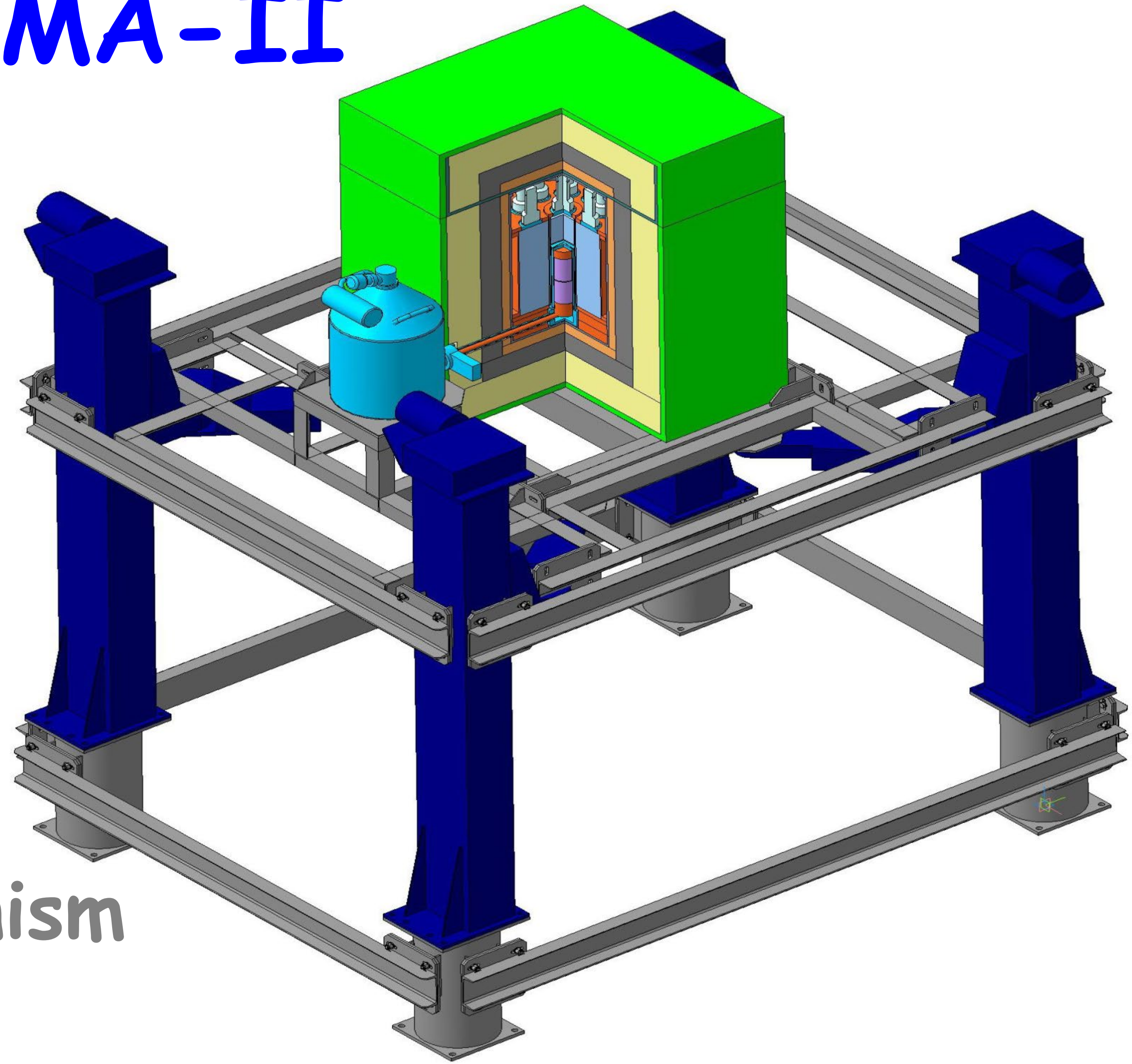
- III phase – 6152 h ON, 1613 h OFF
- I+II+III – 18134 h ON, 4487 h OFF

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

***Beda A.G. et al.* // Advances in High Energy Physics. 2012. V. 2012, Article ID 350150.**
***Beda A.G. et al.* // Physics of Particles and Nuclei Letters, 2013, V. 10, №2, pp. 139–143.**


#2: 14 m
#3: 10 m
KNPP
Udomlya
Russia

GEMMA-II



Lifting mechanism

Sensitivity of future experiments

B = 0.2 1/keV/kg/day (background level in ROI)

Mass, kg	Threshold, keV	Sensitivity, $10^{-12}\mu_B$
4.5	0.4	5.8
10	0.4	4.7
20	0.4	4.0
4.5	0.3	5.6
10	0.3	4.6
20	0.3	3.9

… claim that

ν-e cross section

should be increased by

Atomic Ionization effect:

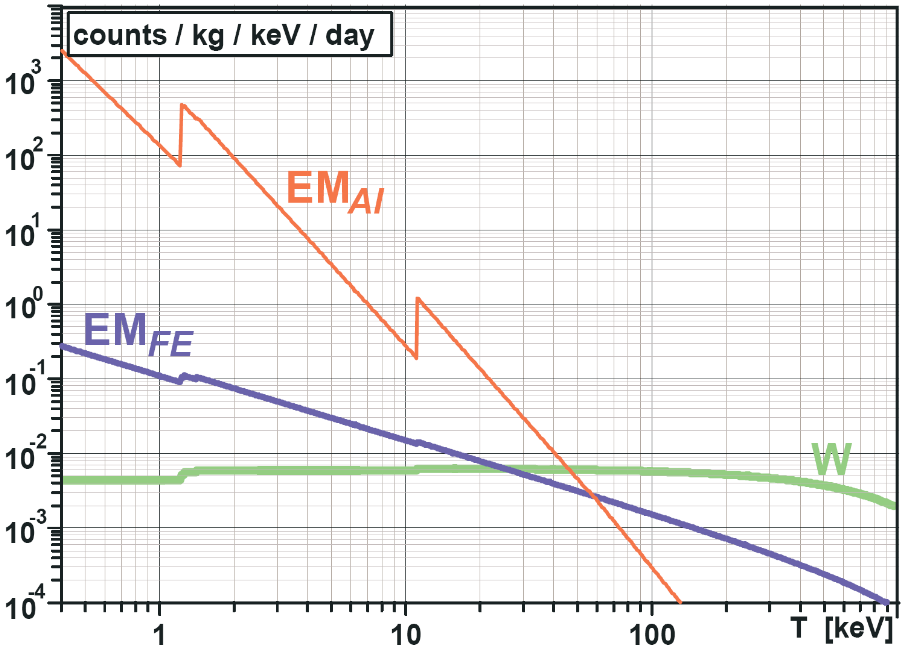
$$\nu + (A,Z) \longrightarrow \nu' + (A,Z)^+ + e^-$$
$$\downarrow \text{recombination}$$
$$(A,Z) \quad + \gamma$$

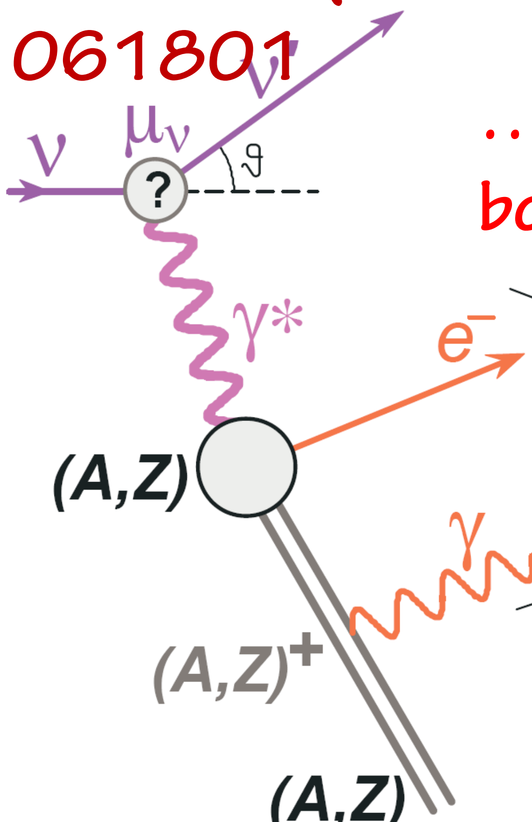
?

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 ...

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

... atomic ionization effect accounted for ...

H.Wong et al., (TEXONO Coll.), arXiv: 1001.2074, 13 Jan 2010, PRL 105 (2010) 061801

Neutrino 2010 Conference, Athens

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

... however ..

... atomic ionization effect accounted for ...

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

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

... 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

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).

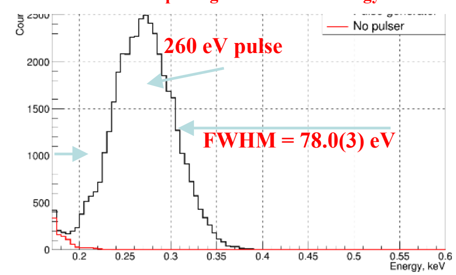
The preliminary background measurements at KNPP showed that all visible lines are from cosmogenic isotopes and decreasing with time. Resolution of cosmogenic lines are: 10.37 keV – 187(3) eV (FWHM), for 1.3 keV – 124(9) eV (FWHM).

Improvement in comparison with GEMMA-I:

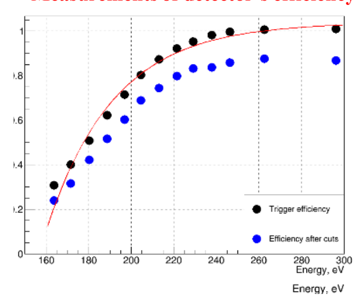
- ✓ Energy threshold: 2 keV → 200 eV (achived)
- ✓ Neutrino flux: $2.6\cdot10^{13}$ ν/(s·cm²) → $5\cdot10^{13}$ ν/(s·cm²) (place is ready)
- ✓ Mass: 1.5 kg → 5.5 kg (first detector is at place, waiting for others to be ready)
- ✓ $\mu_\nu < 2.9\cdot10^{-11}\mu_B$ (world best limit) → $\mu_\nu < (5\text{-}9)\cdot10^{-12}\mu_B$ (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.

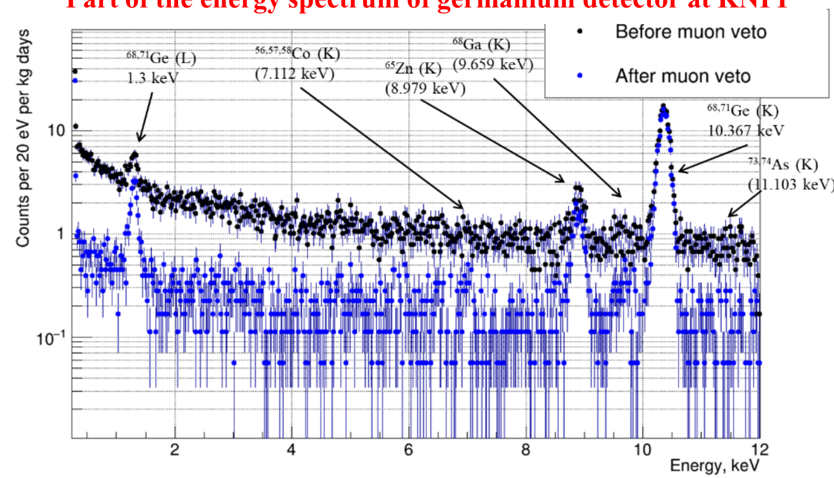
Measurements with pulse generator near energy threshold



Measurements of detector's efficiency



Part of the energy spectrum of germanium detector at KNPP



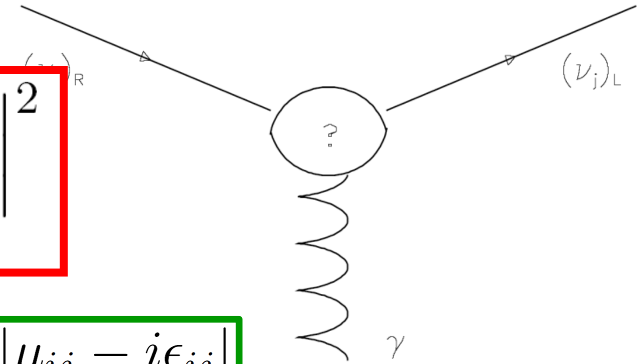
Preliminary! Further Background decrease is expected!

... 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

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

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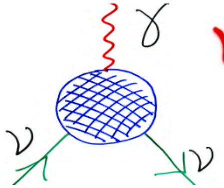
A thorough account of electromagnetic interactions of massive neutrinos in the theoretical formulation of low-energy elastic neutrino-electron scattering is given. The formalism of neutrino charge, magnetic, electric, and anapole form factors defined as matrices in the mass basis is employed under the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



ν electromagnetic interactions

mass states ν_j , m_j $(j=1,2,3)$

$q = p_j - p_k$

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

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

Elastic neutrino-electron scattering

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

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

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

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

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

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

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

$(\mu_\nu)_{jk} = \mu_{jk} + i\gamma^5\varepsilon_{jk}$ magnetic & electric dipole moments

nonmoving matter !!!

Helicity-conserving amplitudes

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

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

$$\left. -(g'_A)_{jk}\bar{u}_j\gamma_\lambda(1-\gamma^5)u_k J_A^\lambda(q)\right\}$$

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

Differential cross section measured in scattering experiment

the final massive state is not resolved in experiment

$$\frac{d\sigma}{dT} = \frac{1}{32\pi^2} \int_{T^2}^{(2E_\nu - T)^2} \frac{d\mathbf{q}^2}{E_\nu^2} \int_0^{2\pi} d\varphi_{\mathbf{q}} \, |\mathcal{M}_{fi}|^2 \, \delta(T - \mathcal{E}_f + \mathcal{E}_i)$$

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

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

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

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

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

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

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

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

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

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

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

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

... it is usually claimed ...

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

Magnetic moment part of cross section

$$\frac{d\sigma}{dT} = \frac{1}{32\pi^2} \int_{T^2}^{(2E_\nu - T)^2} \frac{d\mathbf{q}^2}{E_\nu^2} \int_0^{2\pi} d\varphi_{\mathbf{q}} \, |\mathcal{M}_{fi}|^2 \, \delta(T - \mathcal{E}_f + \mathcal{E}_i)$$

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

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

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

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 (T)

electron binding energy in detector (E_b)

ν-e scattering cross section (free e)

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

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

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

$$E_e' = m_e + T$$

final electron energy

Finally cross section (free e)

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

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

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

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 and probability

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

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

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

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

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

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

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

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

where

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

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

millicharge

in ν flavour basis

charge radius

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

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

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

- for GEMMA experiment ...

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

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 $|\mu_\nu(L, E_\nu)|^2 = \sum_{j,k=1}^{3} |U_{\ell k}|^2 \, |(\mu_\nu)_{jk}|^2$ is independent of *L* and *E*

- for Borexino experiment …

Mitglied der Helmholtz-Gemeinschaft

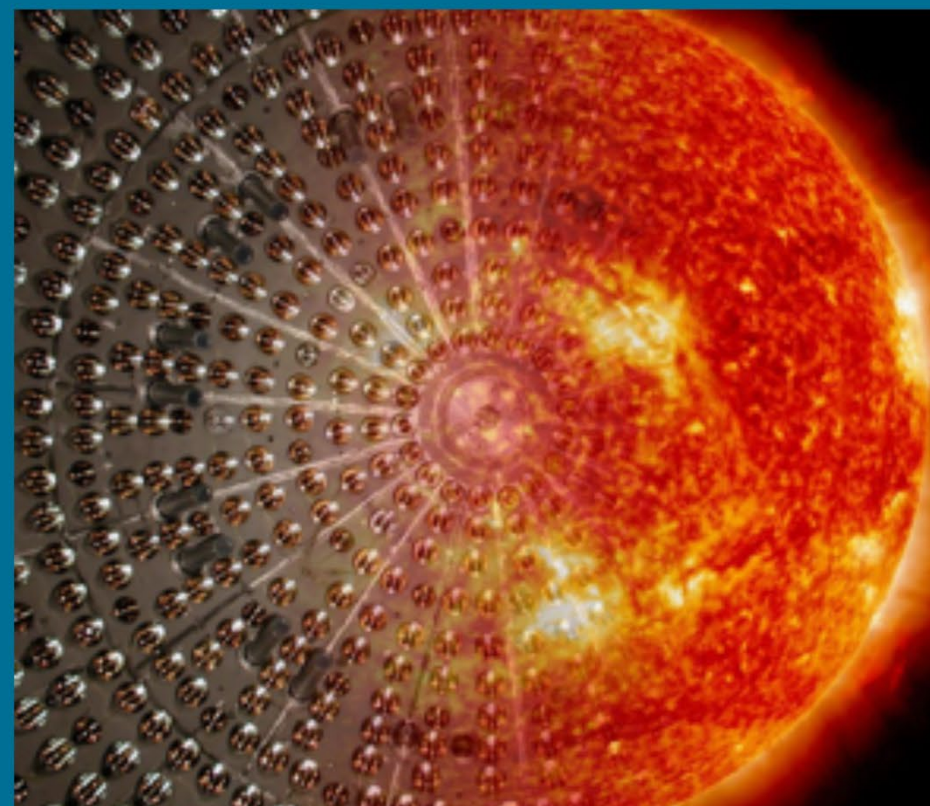
TAUP 2017
Topics in Astroparticle and Underground Physics

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

NMM results from Phase 2

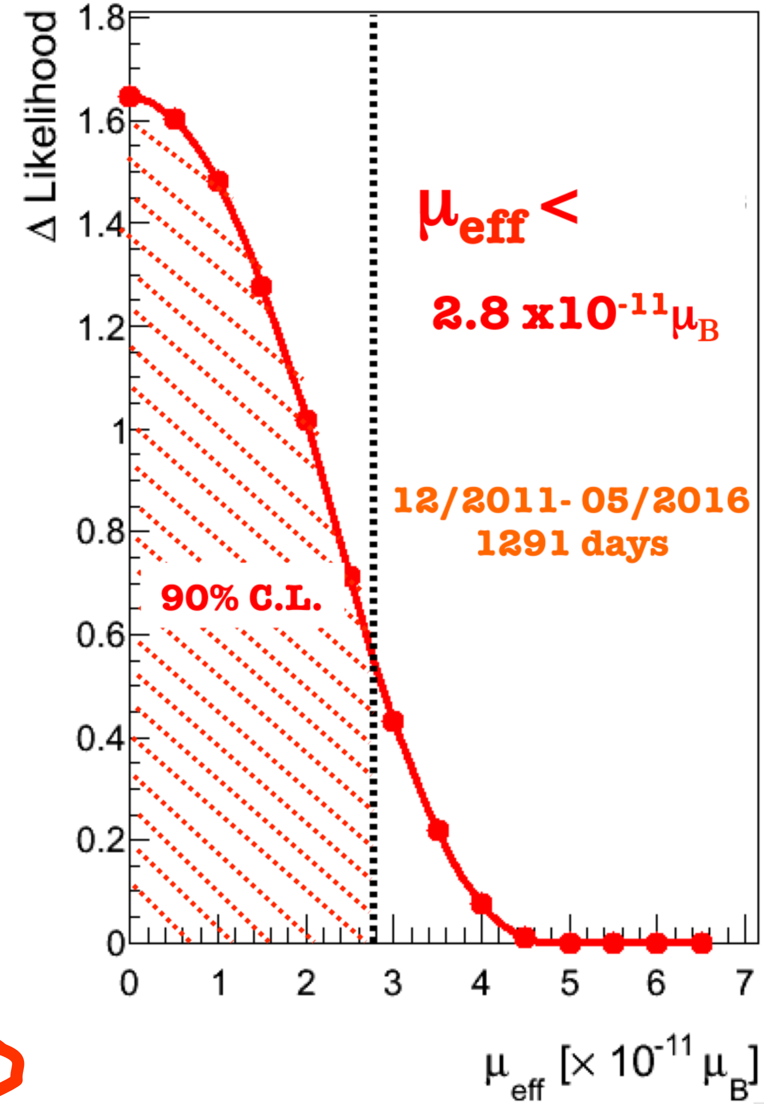
JÜLICH FORSCHUNGSZENTRUM

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

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

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

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



Experimental limits for different effective μ_ν

Method	Experiment	Limit	CL	Reference
Reactor $\bar{\nu}_e$-e^-	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}\,\mu_B$	90%	Vidyakin *et al.* (1992)
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}\,\mu_B$	95%	Derbin *et al.* (1993)
	MUNU	$\mu_{\nu_e} < 0.9 \times 10^{-10}\,\mu_B$	90%	Daraktchieva *et al.* (2005)
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}\,\mu_B$	90%	Wong *et al.* (2007)
	• GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}\,\mu_B$	90%	Beda *et al.* (2012)
Accelerator ν_e-e^-	LAMPF	$\mu_{\nu_e} < 10.8 \times 10^{-10}\,\mu_B$	90%	Allen *et al.* (1993)
Accelerator $(\nu_\mu, \bar{\nu}_\mu)$-e^-	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}\,\mu_B$	90%	Ahrens *et al.* (1990)
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}\,\mu_B$	90%	Allen *et al.* (1993)
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}\,\mu_B$	90%	Auerbach *et al.* (2001)
Accelerator $(\nu_\tau, \bar{\nu}_\tau)$-$e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}\,\mu_B$	90%	Schwienhorst *et al.* (2001)
Solar ν_e-e^-	Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5\,\text{MeV}) < 1.1 \times 10^{-10}\,\mu_B$	90%	Liu *et al.* (2004)
	Borexino	$\mu_S(E_\nu \lesssim 1\,\text{MeV}) < 5.4 \times 10^{-11}\,\mu_B$	90%	Arpesella *et al.* (2008)

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

- new 2017 Borexino PRD : $\mu_\nu^{eff} < 2.8 \cdot 10^{-11}\ \mu_B$ at 90% c.l.

- Particle Data Group, 2014-2020 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: $SU(2)_L \times U(1)_Y$

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

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

$Q=0$

- $Q=0$ 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

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

Bounds on q_ν from … unobserved effects of New Physics

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

!

Studenikin, Europhys. Lett. 107 (2014) 210011

Particle Data Group, 2016-2020 and update of 2021

Expected new constraints from GEMMA:

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

2021 + 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 !

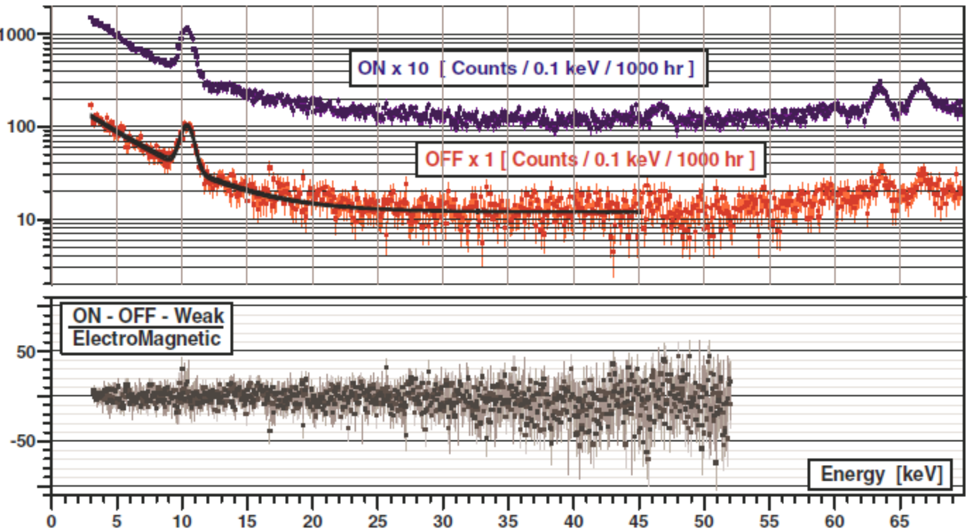
- $|q_\nu| < 1.1 \times 10^{-13} e_0$

... the obtained constraint on neutrino millicharge q_ν

- rough order-of-magnitude estimation,
- exact values should be evaluated using the corresponding statistical procedures

this is because limits on neutrino μ_ν are derived from GEMMA experiment data taken over an extended energy range 2.8 keV - 55 keV, rather than at a single electron energy-bin at threshold

A.Studenikin New bounds on neutrino electric millicharge from limits on neutrino magnetic moment
Eur.Phys.Lett. 107 (2014) 2100, arXiv:1302.1168



Difference between reactor on and off electron recoil energy spectra (with account for weak interaction contribution) normalized by theoretical electromagnetic spectra

A. Beda et al, Adv. High Energy Phys. 2012(2012) 350150

- Limit evaluated using statistical procedures is of the same order as previously discussed

- $$| q_\nu | < 2.7 \times 10^{-12} e_0 \ (90\% \text{ C.L.})$$

A.Studenikin : "New bounds on neutrino electric millicharge from limits on neutrino magnetic moment", Eur.Phys.Lett. 107 (2014) 2100, arXiv:1302.1168

- V.Brudanin, D.Medvedev, A.Starostin, A.Studenikin : "New bounds on neutrino electric millicharge from GEMMA experiment on neutrino magnetic moment", arXiv: 1411.2279

Particle Data Group collaboration 2016 – 2020 and 2021 update

PDG particle data group **Particle Listings**

Home | PDG Live | Summary Tables | Reviews, Tables, Plots | Particle Listings

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

Search 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

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 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.

- 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

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

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

$$f_Q(q^2) = f_Q(0) + q^2 \frac{df_Q}{dq^2}(0) + \cdots,$$ 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 $\langle r_\nu^2 \rangle = +6 \frac{df_Q}{dq^2}(0)$

- ... it is often claimed for SM massless ν anapole moment $a_\nu = f_A(q^2) = \frac{1}{6}\langle r_\nu^2 \rangle$? ? ?

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

to be correct ⟹

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

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

Giunti, Studenikin Rev.Mod.Phys.2015

... 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 ? ? ?

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

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

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

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

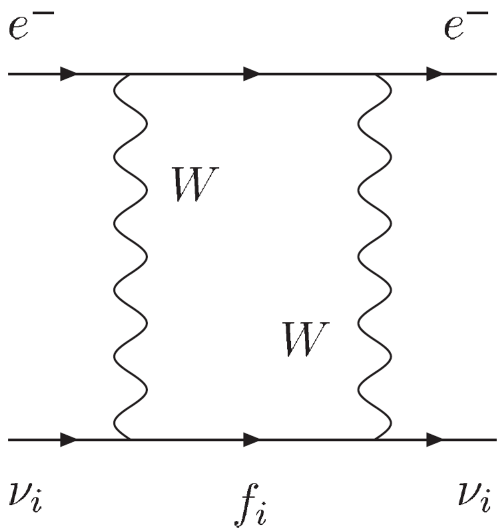
Therefore, the neutrino charge radius (in fact, it is the charge radius squared) is usually defined by

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

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



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

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

Contribution of box diagram to

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

…contribution to ν - e scattering experiments through

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

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

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

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

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

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

DOI: 10.1103/PhysRevD.95.055013

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

Lecture # 2 concluding remarks

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

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

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

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

!

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

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

where

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

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

millicharge — in ν flavour basis — charge radius

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

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

Editors' Suggestion

Ch – It – Ru collaboration

Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering

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(Received 15 October 2018; published 26 December 2018)

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

DOI: 10.1103/PhysRevD.98.113010

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"

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

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

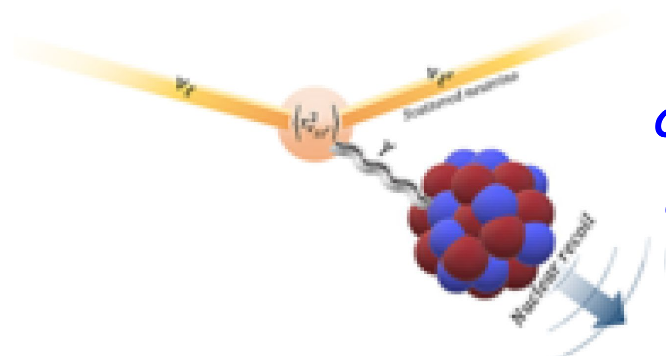
Physical Review D – Highlights 2018 – Editors' Suggestion

Editors' Suggestion

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

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

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



coherent ν scattering
due to charge radius

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

Show Abstract + ()

Particle Data Group,
Review of Particle Properties (2018-2020),
update of 2021

JHEP

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

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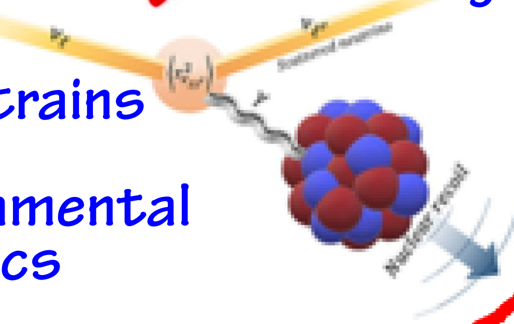
Abstract: We explore the potential of current and next generation of coherent elastic neutrino-nucleus scattering (CEνNS) experiments in probing neutrino electromagnetic interactions. On the basis of a thorough statistical analysis, we determine the sensitivities on each component of the Majorana neutrino 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.

JHEP07(2019)103

- 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)

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

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

for Lecture # 3

22.09.2021

The end of Lecture # 2