The background of the slide is a photograph of the main building of Moscow State University, a grand, multi-story structure with a central spire topped by a golden orb. The building is light-colored with many windows and is set against a clear blue sky. Some trees are visible in the foreground.

Neutrino magnetic properties:
An overview and new project SATURNE
on study of coherent elastic neutrino
scattering on atom

The XXIII International Seminar
on High-Energy Physics
"Quarks 2026"
18/05/2026
Petrozavodsk, Russia

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

supported by Russian Science Foundation under
grant No. 24-12-00084



Национальный центр
ФИЗИКИ И МАТЕМАТИКИ

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

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



Саровский
тритиевый
нейтринный
эксперимент
= SATURNE

- Sarov Tritium Ultra-Reach Neutrino Experiment = SATURNE
- Sarov Tritium Neutrino Experiment = SATURNE Collaboration

...the 2020-2026 result is a major achievement of our research ...

National Center for Physics and Mathematics

in the 8th direction "Hydrogen Isotope Physics"

«Study of coherent scattering on atoms and nuclei and electromagnetic properties of ν using an intense tritium source of (anti)neutrinos»

- 1) verifying the validity of the Standard Model
- 2) measurement of the magnetic moment with record-breaking accuracy

...two orders of magnitude better than from existing measurements of reactor ν fluxes ...

Studies of (electro)magnetic properties

- ... background
- ... results
- ... prospects
- **SATURNE** project at
National Center for Physics and Mathematics



Neutrino electromagnetic interactions:
A window to new physics

+ upgrade:

Studentikin,

Neutrino magnetic moment: a window to new physics

A. Studentikin*

*Department of Theoretical Physics, Moscow State University, 119991 Moscow, Russia

A short review on a neutrino magnetic moment is presented.

Carlo Giunti*

INFN, Torino Section, Via P. Giuria 1, I-10125 Torino, Italy

Electromagnetic neutrinos: The basic interaction processes and constraints from laboratory experiments and astrophysics, *Int.J.Mod.Phys.E (2024) 2441033*

Alexander Studentikin†

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

(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

CONTENTS

I. Introduction	531
II. Neutrino Masses and Mixing	532
A. Dirac neutrinos	533
B. Majorana neutrinos	533
C. Three-neutrino mixing	534
D. Neutrino oscillations	535
E. Status of three-neutrino mixing	538
F. Sterile neutrinos	540
III. Electromagnetic Form Factors	540
A. Dirac neutrinos	541
B. Majorana neutrinos	545
C. Massless Weyl neutrinos	546
IV. Magnetic and Electric Dipole Moments	547
A. Theoretical predictions for Dirac neutrinos	547
B. Theoretical predictions for Majorana neutrinos	549
C. Neutrino-electron elastic scattering	550
D. Effective magnetic moment	551
E. Experimental limits	553
F. Theoretical considerations	554

Introduction. Experimental and theoretical studies of flavour conversion in solar, atmospheric, reactor and accelerator neutrino fluxes give strong evidence of non-zero neutrino mass. A massive neutrino can have non-trivial electromagnetic properties [1]. For a recent review on neutrino electromagnetic properties see [2].

The neutrino dipole magnetic moment (along with the electric dipole moment) is the most well studied among neutrino electromagnetic properties. The effective Lagrangian, that is in charge of a neutrino coupling to the electromagnetic field, can be written in the form

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

where the magnetic moments μ_{ij} , in the presence of mixing between different neutrino states, are associated with the neutrino mass eigenstates ν_i . The interplay between magnetic moment and neutrino mixing effects is important. Note that electric (transition) moments ϵ_{ij} do also contribute to the coupling.

A Dirac neutrino may have non zero diagonal electric moments in models where CP invariance is violated. For a Majorana neutrino the diagonal magnetic and electric moments are zero. Therefore, neutrino magnetic moments can be used to distinguish Dirac and Majorana neutrinos (see [3] and also [2] for a detailed discussion).

Neutrino magnetic moment in a minimal extension of Standard Model. The explicit con-

ditionally accounts for $a_i = \frac{m_i^2}{3m_p^2}$ ($l = e, \mu, \tau$), leads the following result [4].

$$\mu_{ij}^D = \frac{eG_F m_i}{8\sqrt{2}\pi^2} \left(1 - \frac{m_i}{m_l}\right) \sum_{\alpha, \beta, \gamma} f(\alpha_i) U_{ij} U_{\alpha\beta}^* \quad (2)$$

$$f(\alpha_i) = \frac{3}{4} \left[1 + \frac{1}{1 - \alpha_i} - \frac{2\alpha_i}{(1 - \alpha_i)^2} - \frac{2\alpha_i^2 \ln \alpha_i}{(1 - \alpha_i)^3} \right],$$

where U_{ij} is the neutrino mixing matrix. The correspondent result in the absence of mixing was confirmed in [5,6]. A Majorana neutrino may also have transition moment of the value $\mu_{ij}^M = 2\mu_{ij}^D$ (see [2] for a detailed discussion and references).

For the diagonal magnetic moment of the Dirac neutrino, from (2) in the limit $\alpha_i \ll 1$ the result [1] can be obtained

$$\mu_{ii}^D = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \left(1 - \frac{1}{2} \sum_{l=e,\mu,\tau} |U_{il}|^2\right) \quad (3)$$

The magnetic moment for hypothetical heavy neutrino was studied in [6]. In particular, it was obtained

$$\mu_{\nu} = \frac{eG_F m_{\nu}}{8\sqrt{2}\pi^2} \left\{ \begin{array}{l} 3 + \frac{3}{4} b, \quad m_l \ll m_{\nu} \ll M_W, \\ 1, \quad m_l \ll M_W \ll m_{\nu}. \end{array} \right. \quad (4)$$

Note that the LEP data set a limit on number of light neutrinos coupled to Z boson.

The numerical value of the Dirac neutrino magnetic moment within a minimal extension of the Standard Model, as it follows from (3), is

V. Radiative Decay and Related Processes	556
A. Radiative decay	556
B. Radiative decay in matter	559
C. Cherenkov radiation	560
D. Plasmon decay into a neutrino-antineutrino pair	561
E. Spin light	562
VI. Interactions with Electromagnetic Fields	563
A. Effective potential	564
B. Spin-flavor precession	565
C. Magnetic moment in a strong magnetic field	571
D. Beta decay of the neutron in a magnetic field	573
E. Neutrino pair production by an electron	574
F. Neutrino pair production by a strong magnetic field	575
G. Energy quantization in rotating media	576
VII. Charge and Anapole Form Factors	578
A. Neutrino electric charge	578
B. Neutrino charge radius	580
C. Neutrino anapole moment	583
VIII. Summary and Perspectives	585
Acknowledgments	585
References	585

Electromagnetic neutrinos: The basic interaction processes and constraints from laboratory experiments and astrophysics

Alexander Studenikin
*Department of Theoretical Physics,
Faculty of Physics,
Lomonosov Moscow State University,
Moscow 119991, Russia
studenik@srd.sinp.msu.ru*

Received 8 October 2024
Revised 20 November 2024
Accepted 26 November 2024
Published

After a brief historical background on the first steps and the latest achievements in the study of the electromagnetic properties of neutrinos, the flavor, spin and spin-flavor oscillations of neutrinos in a magnetic field and moving matter are discussed in detail.

Keywords: Neutrino electromagnetic properties; neutrino oscillations.

Neutrino Electromagnetic Properties

Carlo Giunti,¹ Konstantin Kouzakov,²
Yu-Feng Li,³ and Alexander Studenikin⁴

¹Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino,
Via P. Giuria 1, 10125 Torino, Italy; email: carlo.giunti@to.infn.it

²Faculty of Physics, Lomonosov Moscow State University, Leninskie Gory,
Moscow 119991, Russia; email: kouzakov@gmail.com

³Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049,
China; School of Physical Sciences, University of Chinese Academy of Sciences,
Beijing 100049, China; email: liyufeng@ihep.ac.cn

⁴Faculty of Physics, Lomonosov Moscow State University, Leninskie Gory,
Moscow 119991, Russia; email: studenik@srd.sinp.msu.ru

Contents

1. Introduction	2
2. Neutrino mixing and oscillations	3
3. Electromagnetic properties of massive Dirac and Majorana neutrinos	4
4. Neutrino magnetic moment	6
5. Neutrino charge radius	13
6. Neutrino electric charge	15
7. Astrophysical neutrino electromagnetic processes	18
7.1. Neutrino radiative decay	19
7.2. Neutrino Cherenkov radiation and related processes	19
7.3. Plasmon decay into a neutrino-antineutrino pair	20
7.4. Spin light of neutrino	20
7.5. Neutrino spin and spin-flavor oscillations in magnetic fields and moving matter	21
8. Neutrino magnetic moment portal	22
9. Conclusions and future prospects	24

Keywords

neutrino, neutrino magnetic moment, neutrino charge, neutrino charge radius, beyond standard model

Abstract

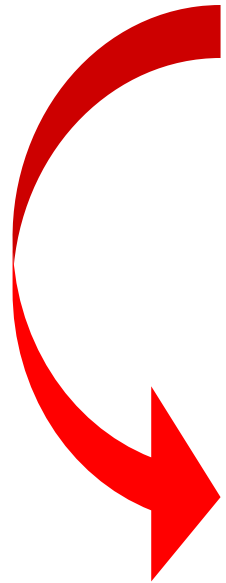
Neutrinos are neutral in the Standard Model, but they have tiny charge radii generated by radiative corrections. In theories Beyond the Standard Model, neutrinos can also have magnetic and electric moments and small electric charges (millicharges). We review the general theory of neutrino electromagnetic form factors, which reduce, for ultrarelativistic neutrinos and small momentum transfers, to the neutrino charges, effective charge radii, and effective magnetic moments. We discuss the phenomenology of these electromagnetic neutrino properties and we review the existing experimental bounds. We briefly review also the electromagnetic processes of astrophysical neutrinos and the neutrino magnetic moment portal in the presence of sterile neutrinos.

Annu. Rev. Nucl. Part. Sci. 2025. 75:1–29

<https://doi.org/10.1146/annurev-nucl-102122-023242>

Copyright © 2025 by the author(s).
All rights reserved

- *background ...*



modern studies of ν
magnetic moment μ_ν

✓ exhibits unexpected properties (puzzles)

W. Pauli, 1930

neutral "neutron" \Rightarrow



E. Fermi
1933

- probably $m_\nu \neq 0$! ?

Pauli himself wrote to Baade:

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

MATHEMATICAL
PROCEEDINGS

of the
Cambridge Philosophical Society

VOLUME 136 PART 3

May 1935



CAMBRIDGE
UNIVERSITY PRESS

M.E. Nahmias,

An attempt to detect the neutrino,

Math. Proc. Cambridge Phil. Soc. 31 (1935)

... earlier years of ν ...

99

AN ATTEMPT TO DETECT THE NEUTRINO

By M. E. NAHMIAS, PH.D. (VICT.)

[Communicated by MR P. M. S. BLACKETT]

[Received 5 December, read 10 December 1934]

... > 90 years ago...

I. EXPERIMENTS WITH A SOURCE OF RADIUM D AND E

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

An attempt to detect the neutrino

101

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

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

> 70 years ago ...

C. L. Cowan, F. Reines and F. B. Harrison,

- Upper limit on the **neutrino magnetic moment**,
Phys. Rev. 96 (1954) 1294

✓ electromagnetic properties

and possibility of measuring μ_ν

raised before experimental discovery of ✓



F. Reines and C. Cowan (1956)

1995



... problem and puzzle ...

✓ electromagnetic properties
up to now nothing has been seen

... in spite of reasonable efforts ...

- results of terrestrial lab experiments on μ_0 (and ✓ EM properties in general)
- as well as data from astrophysics and cosmology
- are in agreement with “ZERO” ✓ EM properties

... However, in course of recent development of knowledge on ✓ mixing and oscillations,

... Why ν electromagnetic properties are important ?

... Why ν em properties

to new physics ?



... How does it all relate to ν oscillations ?



$m_\nu \neq 0$

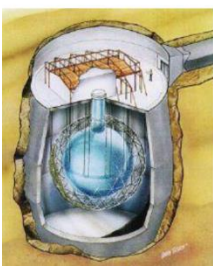
magnetic moment $\mu_\nu \neq 0$



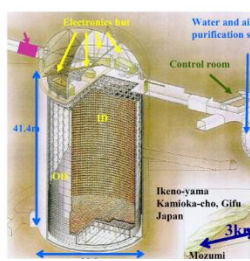
Arthur McDonald

The Nobel Prize in Physics 2015

Takaaki Kajita



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




in Standard Model
 $m_\nu = 0 !!!$

✓ electromagnetic properties

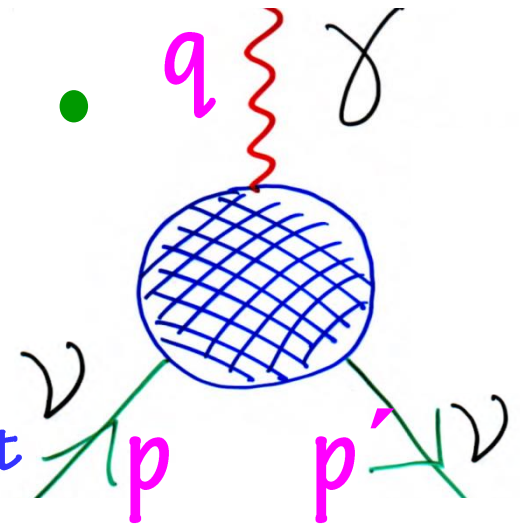


... a window to new physics

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

✓ electromagnetic vertex function

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



Matrix element of electromagnetic current is a Lorentz vector

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

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

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

vectors q_μ and l_μ

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

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



Matrix element of electromagnetic current between neutrino states

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

where vertex function generally contains 4 form factors

$$\Lambda_\mu(q) = f_Q(q^2) \gamma_\mu + f_M(q^2) i \sigma_{\mu\nu} q^\nu - f_E(q^2) \sigma_{\mu\nu} q^\nu \gamma_5$$

1. electric

dipole

2. magnetic

3. electric

$$+ f_A(q^2) (q^2 \gamma_\mu - q_\mu \not{q}) \gamma_5$$

4. anapole

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

Dirac ✓

1) CP invariance + Hermiticity $\Rightarrow f_E = 0$,

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

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

Majorana ✓

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

$$f_Q = f_M = f_E = 0$$

...as early as 1939, W. Pauli...

EM properties \Rightarrow a way to distinguish Dirac and Majorana ✓

form factors at $q = 0$: $f_M(0) \Rightarrow \mu_\nu$ magnetic moment

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

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

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

... beyond SM...

and

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



form factors are matrices in mass eigenstates space.



Dirac



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

Majorana



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

1) CP invariance + hermiticity

2) CP invariance + Hermiticity

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

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

$f_Q(q^2), f_M(q^2), f_E(q^2), f_A(q^2)$ are relatively real (no relative phases).

... quite different EM properties ...

In the easiest generalization of SM

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

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

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

then $\mu_{ii}^D \sim 1.8 \times 10^{-19} \mu_B$! •

many orders of magnitude smaller than present experimental limits:

• $\mu_\nu \sim 10^{-11} \mu_B$ **reactor ν limits** GEMMA 2012

• $\mu_\nu \sim 10^{-11} \div 10^{-12} \mu_B$ **Astrophysical (ν_{solar} , ν_{SN} , DM) limits**
Borexino 2017 - XENONnT 2023, LUX-ZEPLIN 2023

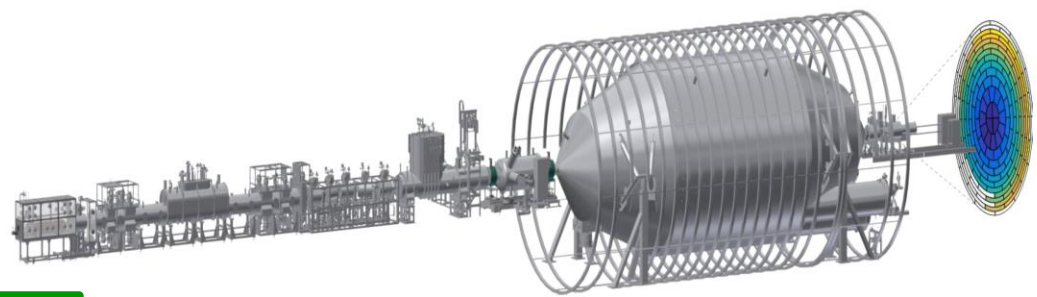
• μ_ν is no less extravagant than possibility of $q_\nu \neq 0$

• limitations imposed by general principles of any theory are very strict

• $q_\nu \leq 3 \times 10^{-21} e$ from neutrality of hydrogen atom

• slightly weaker constraints are imposed by **astrophysics**

Studenikin, Tokarev, NPB, 2014 $q_\nu \leq 1.3 \times 10^{-19} e_0$



$$m_\nu \leq 0.45 \text{ eV}$$



new KATRIN limit arrive: 2406.13516, 19 Jun 2024

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



XXXI International Conference on Neutrino Physics and Astrophysics

Milano (Italy) - June 16-22, 2024

Alexey Lokhov
on behalf of the
KATRIN collaboration

Karlsruhe Institute
of Technology,
Germany

- **Experimental constraints**

(from studies of terrestrial and astrophysical ν fluxes)

on

μ_ν , q_ν

and

$\langle r_\nu^2 \rangle$

magnetic moment

millicharge

charge radius

Particle Data Group
Review of Particle Physics 2024, update 2025

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

... next addition July 2026



Experimental (laboratory) constraints on the magnetic moment of neutrinos

from elastic neutrino scattering on target particles

- on electrons

Elastic Neutrino-Electron Scattering

EVES

- on atomic nuclei

Coherent Elastic Neutrino-Nucleus Scattering

CEvNS

- on atoms

Coherent Elastic Neutrino-Atom Scattering

CEvAS

SATURNE project !

GEMMA (2005 – 2012 - running)
Germanium Experiment for Measurement
of Magnetic Moment of Antineutrino
JINR (Dubna) + ITEP (Kurchatov Inst., Moscow)
at Kalinin Nuclear Power Plant

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

Studies of ν - e scattering

- most sensitive method for experimental investigation of μ_ν

Cross-section:

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

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

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

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

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

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

for anti-neutrinos
 $g_A \rightarrow -g_A$

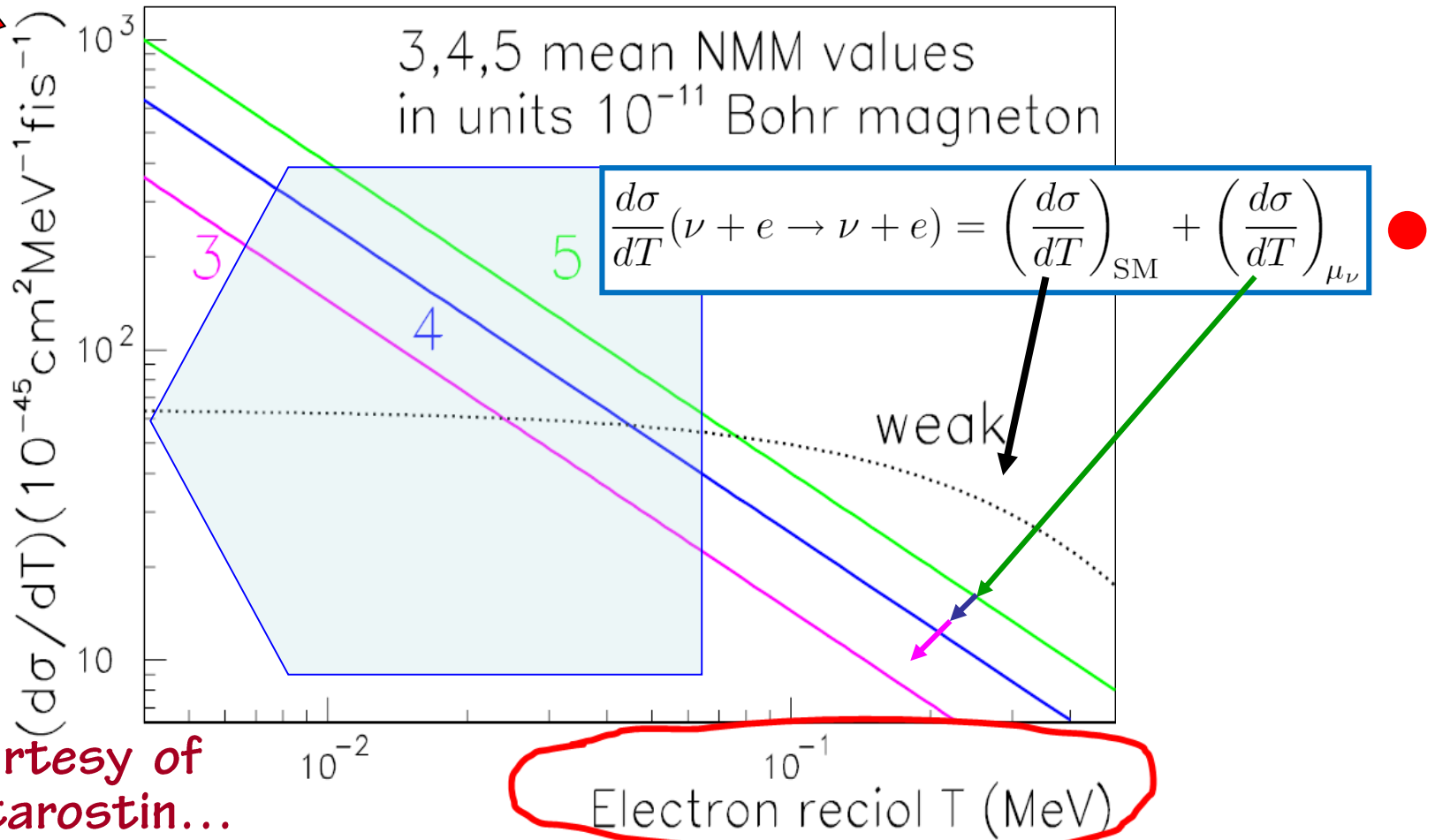
to incorporate charge radius: $g_V \rightarrow g_V + \frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2 \theta_W$????

Magnetic moment contribution dominates at low electron recoil energies when

recoil energies when $\left(\frac{d\sigma}{dT}\right)_{\mu\nu} > \left(\frac{d\sigma}{dT}\right)_{SM}$ and

$$\frac{T}{m_e} < \frac{\pi^2 \alpha_{em}}{G_F^2 m_e^4} \mu_\nu^2$$

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



... courtesy of A.Starostin...

GEMMA (2005 – 2012 - 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 / ν GeN experiment ●

... searching for μ_ν and CE ν NS unprecedently low threshold $T \sim 200$ eV

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

~ few years in future ?

... courtesy of Alexey Lobashevsky, first results of ν GeN were reported at TAUP 2021...

Bounds on millicharge q_ν from μ_ν (GEMMA Coll. data) two not seen contributions:

2

ν - e cross-section

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

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

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

Bounds on q_ν from ... unobserved effects of New Physics

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

Studenikin, Europhys. Lett.
107 (2014) 210011

New bounds on neutrino electric millicharge from limits on neutrino magnetic moment

Particle Data Group, 2016-2025

Expected new constraints from GEMMA:

Constraints on q_ν

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

● $|q_\nu| < 1.5 \times 10^{-12} e_0$

in ν Table of Particle Data Group since 2016

202?+ few years data taking

ν GeN experiment

... low threshold ...

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

$T \sim 200 \text{ eV}$

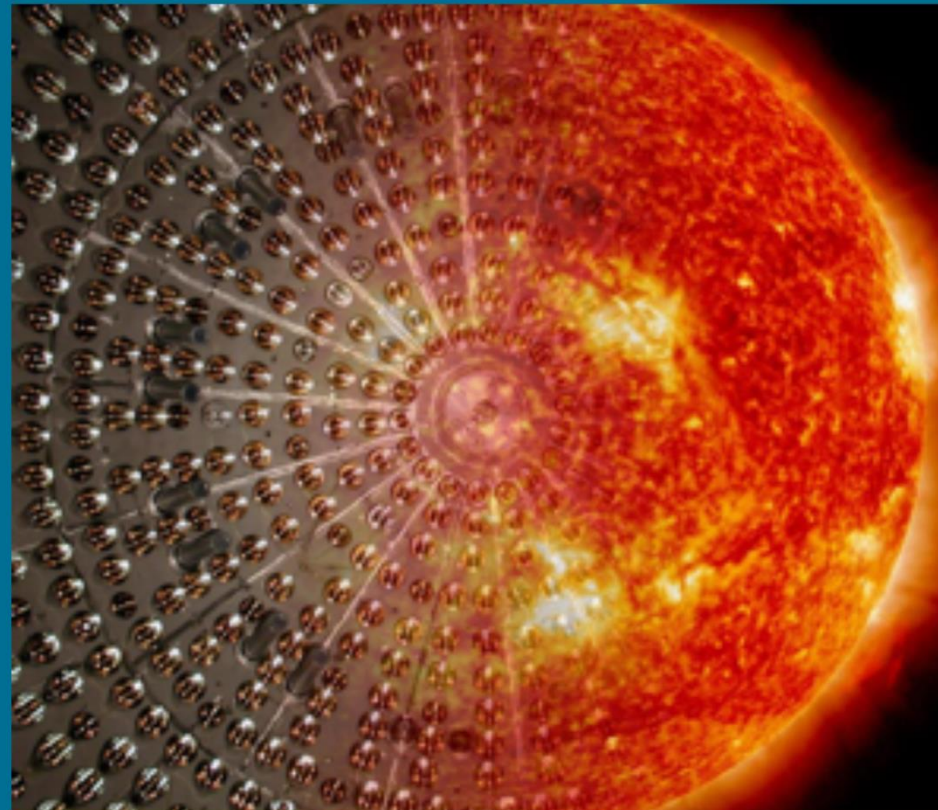
● $|q_\nu| < 1.1 \times 10^{-13} e_0$



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

BOREXINO Collaboration (2017)

NMM results from Phase 2

NEW

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, ^7Be) and backgrounds (^{85}Kr , ^{210}Po , ^{210}Bi , ^{11}C , external bgr.), **response parameters** (light yield, ^{210}Po position and width, ^{11}C edge (2×511 keV), 2 energy resolution parameters)

Constrained parameters: ^{14}C , pile up

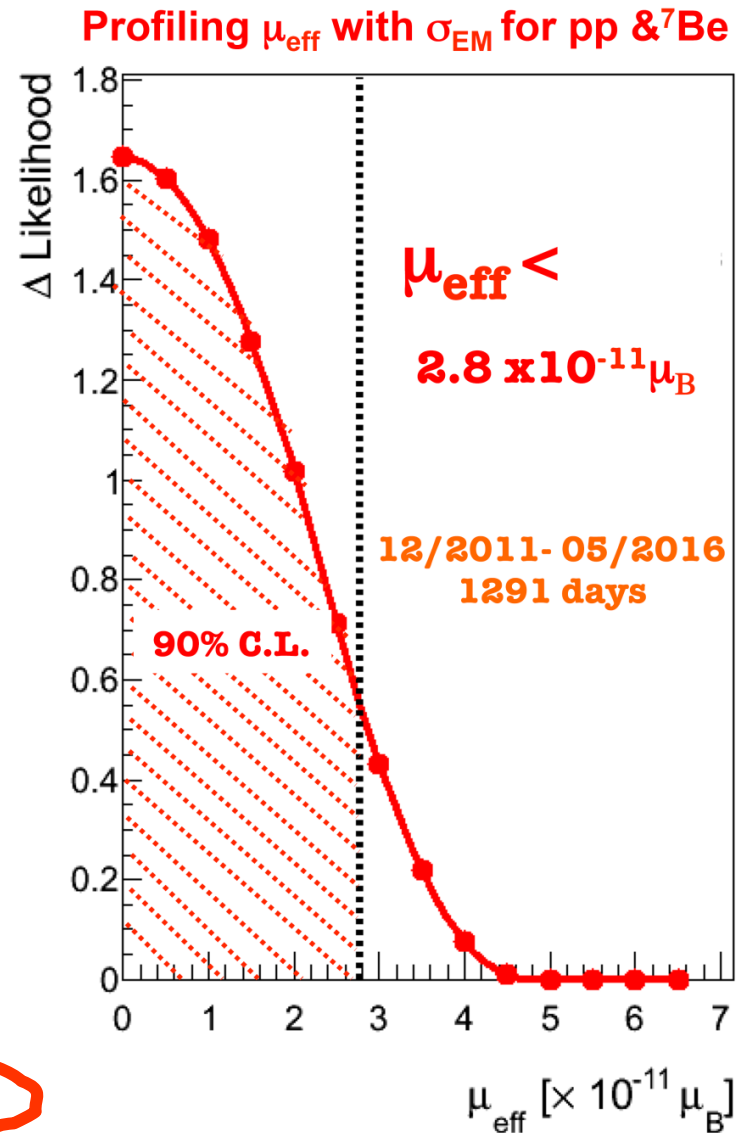
Fixed parameters: pep-, CNO-, ^8B - ν rates

Systematics: treatment of pile-up, energy estimators, pep and CNO constraints with LZ and HZ SSM

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

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

$\mu_{\text{eff}} < 2.8 \times 10^{-11} \mu_{\text{B}}$ (90% C.L.)



Effective ν magnetic moment in experiments

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

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

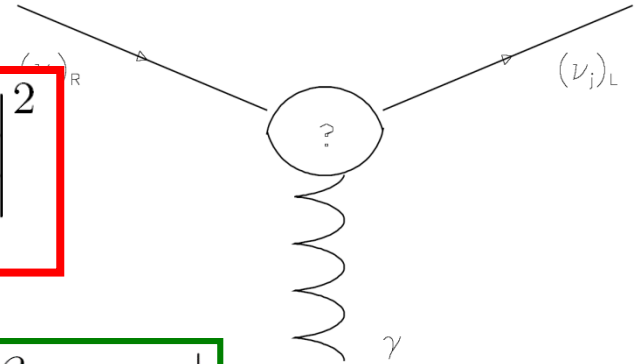
where U is the neutrino mixing matrix

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

β is the magnetic moment and ϵ is the electric moment

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 ^8B and ^7Be) 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

Konstantin A. Kouzakov^{*}

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

Alexander I. Studenikin[†]

*Department of Theoretical Physics, Faculty of Physics, Lomonosov Moscow State University,
Moscow 119991, Russia*

and Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia

(Received 11 February 2017; published 14 March 2017)

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

DOI: [10.1103/PhysRevD.95.055013](https://doi.org/10.1103/PhysRevD.95.055013)

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

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

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

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

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

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

• **Effective magnetic moment**

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

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

• Long-baselin case $L \gg L_{kj} = 2E_\nu / |\delta m_{kk'}^2|$

$$\exp(-i\delta m_{kk'}^2/2E_\nu) = \delta_{kk'}$$

effect of decoherence

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

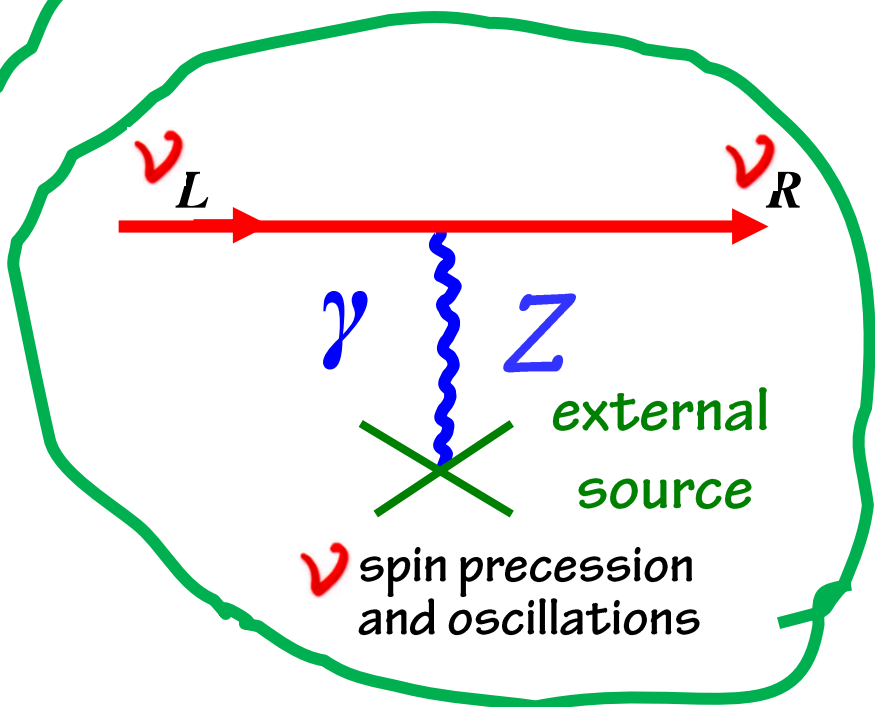
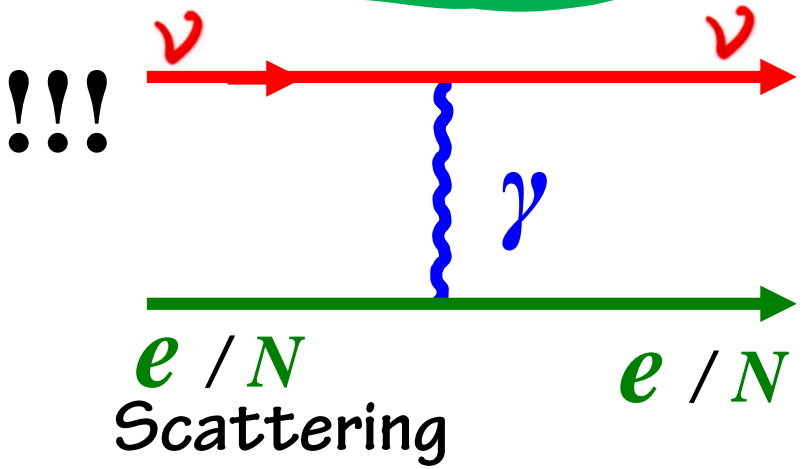
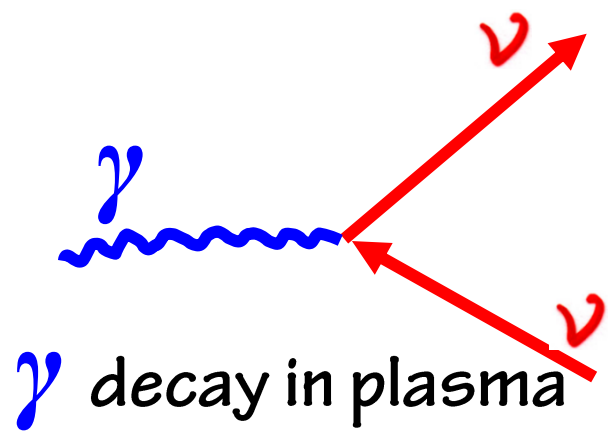
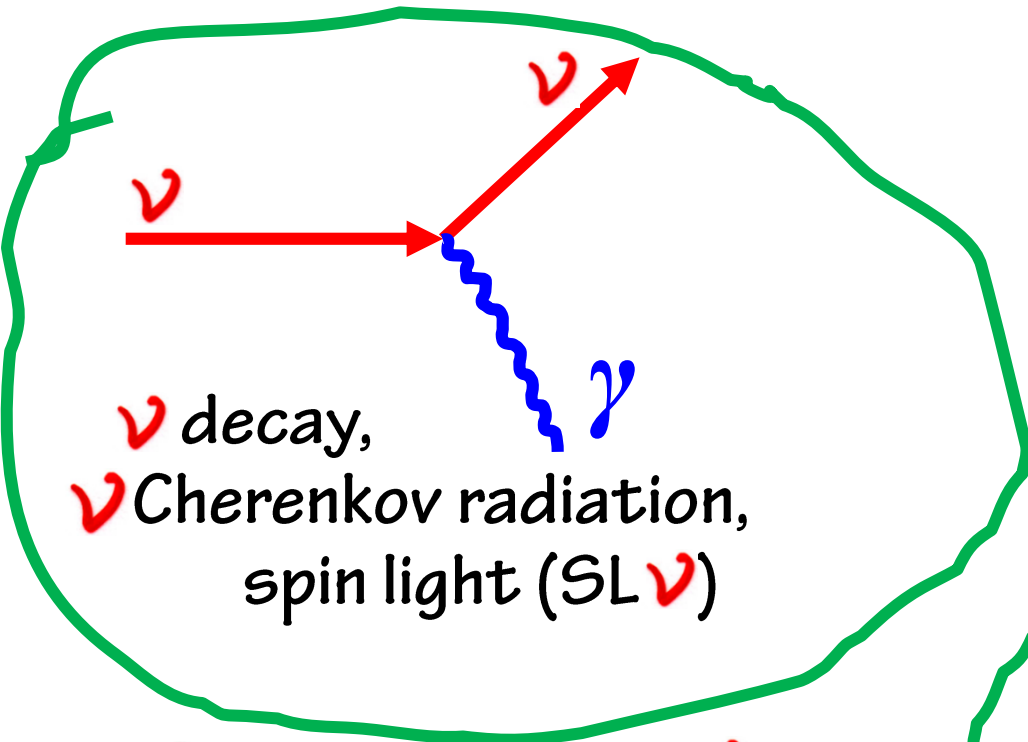
$$C_2 = g_A^2 + 2g_A P_{\nu_\ell \rightarrow \nu_e} + P_{\nu_\ell \rightarrow \nu_e}$$

$$C_3 = g_V g_A + (g_V + g_A + 1) P_{\nu_\ell \rightarrow \nu_e} + g_A \sum_{j=1}^3 |U_{\ell j}|^2 \tilde{Q}_{jj} + 2 \sum_{j,k=1}^3 |U_{\ell k}|^2 U_{ej} U_{ek}^* \tilde{Q}_{jk}$$

where the flavour transition probability $P_{\nu_\ell \rightarrow \nu_e} = \sum_{k=1}^3 |U_{\ell k}|^2 |U_{ek}|^2$ 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

ν electromagnetic interactions



Main steps in ν oscillations

69 years!
early history of
 ν oscillations

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

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

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

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

• resonances in ν flavour oscillations \Rightarrow
MSW-effect, solution for ν_\odot -problem

⑤ $\nu_{eL} \xleftrightarrow{B_\perp} \nu_{eR}$, A. Cisneros, 1971
M. Voloshin, M. Vysotsky, L. Okun, 1986, ν_\odot

⑥ $\nu_{eL} \xleftrightarrow{B_\perp} \nu_{eR}, \nu_{\mu R}$, E. Akhmedov, 1988
C.-S. Lim & W. Marciano, 1988

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



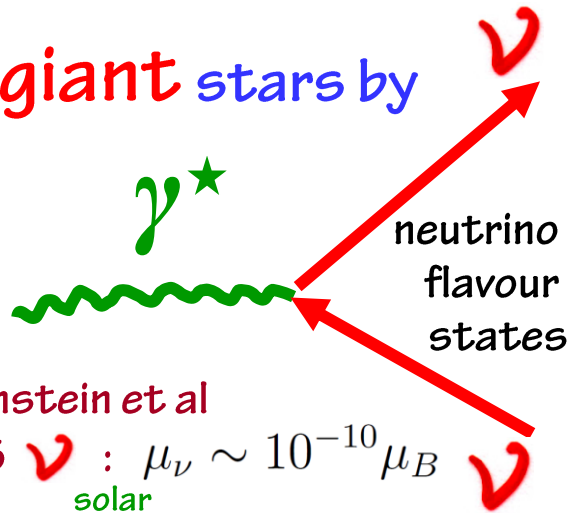
Bruno Pontecorvo
1913-1993

only in **B_\perp**
and
matter at rest

Astrophysical bounds on μ_ν

2 Astrophysical bound on μ_ν G.Raffelt, PRL 1990

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



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

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

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

$$\Gamma_{\gamma \rightarrow \nu\bar{\nu}} = \frac{\mu^2 (\omega^2 - k^2)^2}{24\pi \omega} = 0 \text{ in vacuum } \omega = k$$

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

Energy-loss rate per unit volume

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

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

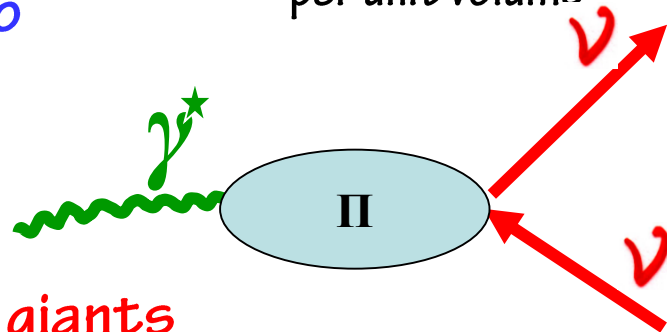
distribution function of plasmons

= Astrophysical bound on μ_ν

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

Magnetic moment **plasmon** decay enhances the Standard Model photo-neutrino cooling by photon polarization tensor

Energy-loss rate per unit volume



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...

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

G.Raffelt, PRL 1990
D+M

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



Experimental (laboratory) constraints on the magnetic moment of neutrinos

from elastic neutrino scattering on target particles

- on electrons

Elastic Neutrino-Electron Scattering

EVES

- on atomic nuclei

Coherent Elastic Neutrino-Nucleus Scattering

CEvNS

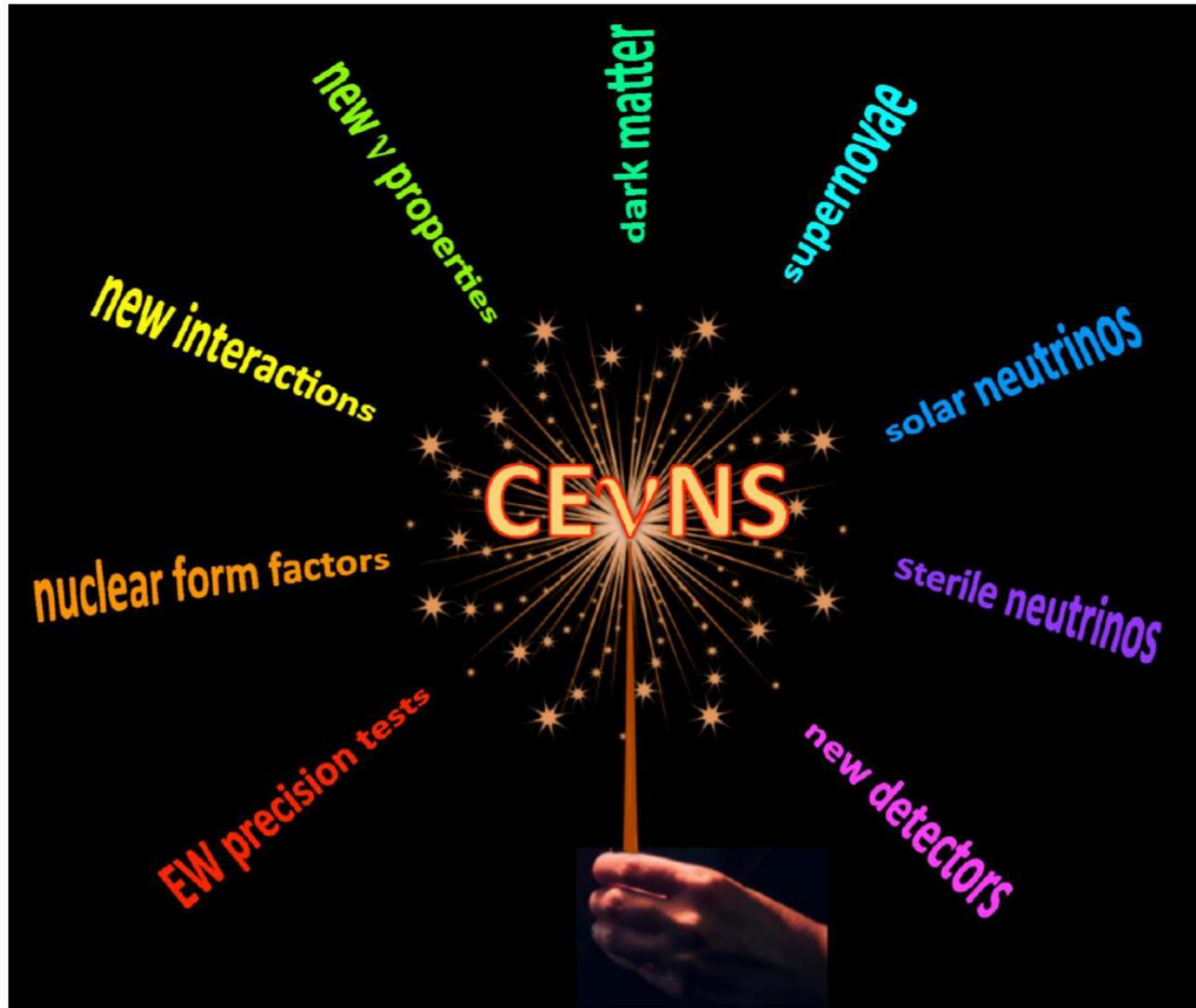
- on atoms

Coherent Elastic Neutrino-Atom Scattering

CEvAS

SATURNE project !

CE ν NS potential in studies **new physics**



[E. Lisi, Neutrino 2018]

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

O.G. Miranda,^a D.K. Papoulias,^b M. Tórtola^b and J.W.F. Valle^b

^aDepartamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, Apartado Postal 14-740 07000 Mexico, Distrito Federal, Mexico

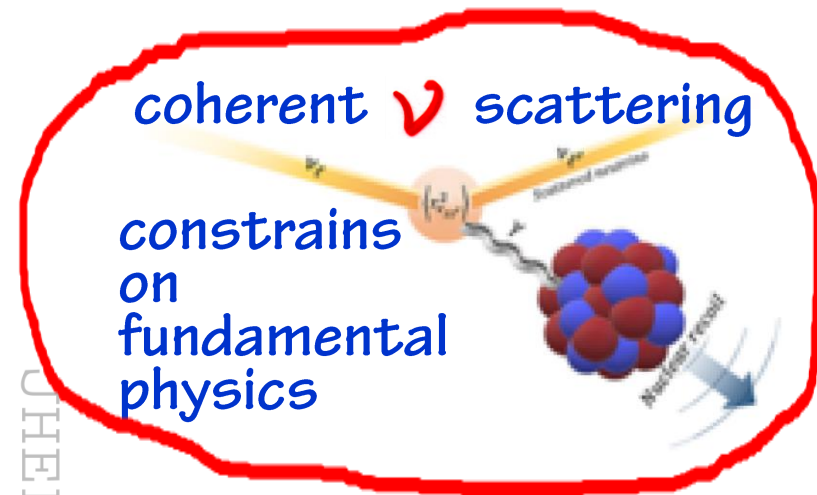
^bAHEP Group, Institut de Física Corpuscular — CSIC/Universitat de València, Parc Científic de Paterna, C/Catedrático José Beltrán 2, E-46980 Paterna, Valencia, Spain

E-mail: omr@fis.cinvestav.mx, dipapou@ific.uv.es, mariam@ific.uv.es, valle@ific.uv.es

ABSTRACT: We explore the potential of current and next generation of coherent elastic neutrino-nucleus scattering (CE ν NS) 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 CE ν NS 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 CE ν NS 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**

JHEP07(2019)103



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**
- **electromagnetic properties**
Papoulias & Kosmas **PRD 2018**
- **non-standard interactions**
Coloma, Gonzalez-Garcia, Maltoni, Schwetz **PRD 2017**
Liao & Marfatia **PLB 2017**

Limits for the neutrino magnetic moments obtained in laboratory short-baseline experiments

Method	Experiment	Limit (μ_B)	CL	Year
Reactor $\bar{\nu}_e$ E ν ES	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}$	90%	2012
	CONUS	$\mu_{\nu_e} < 7.5 \times 10^{-11}$	90%	2022
Accelerator ν_e E ν ES	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $\nu_\mu, \bar{\nu}_\mu$ E ν ES	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}$	90%	1992
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}$	90%	2001
Accelerator $\nu_\tau, \bar{\nu}_\tau$ E ν ES	BEBC (58)	$\mu_{\nu_\tau} < 5.4 \times 10^{-7}$	90%	1991
	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}$	90%	2001
Accelerator $\nu_e, \nu_\mu, \bar{\nu}_\mu$ CEνNS + EνES	COHERENT (61, 62)	$\mu_{\nu_e} < 4.2 \times 10^{-9}$	90%	2022
	CEνNS + EνES	$\mu_{\nu_\mu} < 1.8 \times 10^{-9}$		
Reactor $\bar{\nu}_e$ CE ν NS + E ν ES	Dresden-II (65) ^a	$\mu_{\nu_e} < 2.1 \times 10^{-10}$	90%	2022
$e^+e^- \rightarrow \nu\bar{\nu}\gamma$ (Dirac ν)	ASP, MAC, CELLO, MARK J	$\mu_\nu < 4 \times 10^{-6}$	90%	1988
	TRISTAN	$\mu_\nu < 8.0 \times 10^{-6}$	90%	2000

Giunti, Kouzakov, Li, Studenikin, Neutrino Electromagnetic Properties,

Method	Experiment	Limit (μ_B)	CL	Year
Solar elastic neutrino-electron scattering	Super-Kamiokande	$\mu_S^{\text{HE}} < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_S^{\text{LE}} < 2.8 \times 10^{-11}$	90%	2017
		$\mu_{\nu_e} < 3.9 \times 10^{-11}$		
		$\mu_{\nu_\mu}, \mu_{\nu_\tau} < 5.8 \times 10^{-11}$		
	XMASS-I	$\mu_S^{\text{LE}} < 1.8 \times 10^{-10}$	90%	2020
	XENONnT	$\mu_S^{\text{LE}} < 6.4 \times 10^{-12}$	90%	2022
	LUX-ZEPLIN	$\mu_S^{\text{LE}} < 1.36 \times 10^{-11}$	90%	2023
	PandaX-4T	$\mu_S^{\text{LE}} < 2.2 \times 10^{-11}$	90%	2024
	LUX-ZEPLIN (74)	$\mu_S^{\text{LE}} < 1.1 \times 10^{-11}$	90%	2022
		$\mu_{\nu_e} < 1.5 \times 10^{-11}$ $\mu_{\nu_\mu} < 2.3 \times 10^{-11}$ $\mu_{\nu_\tau} < 2.1 \times 10^{-11}$		
XENONnT (71)	$\mu_S^{\text{LE}} < 6.3 \times 10^{-12}$	90%	2022	
	$\mu_{\nu_e} < 8.5 \times 10^{-12}$ $\mu_{\nu_\mu} < 1.4 \times 10^{-11}$ $\mu_{\nu_\tau} < 1.2 \times 10^{-11}$			
XENONnT (71)	$\mu_{\nu_e} < 9.0 \times 10^{-12}$	90%	2022	
	$\mu_{\nu_\mu} < 1.5 \times 10^{-11}$ $\mu_{\nu_\tau} < 1.3 \times 10^{-11}$			
LUX-ZEPLIN (74) + PandaX-4T (78) + XENONnT (71)	$\mu_S^{\text{LE}} < 7.5 \times 10^{-12}$	90%	2023	
	$\mu_{\nu_e} < 1.0 \times 10^{-11}$ $\mu_{\nu_\mu}, \mu_{\nu_\tau} < 1.6 \times 10^{-11}$			
Core-collapse supernovae		$\mu_\nu \lesssim (2-8) \times 10^{-12}$		1988
		$\mu_\nu \lesssim (1-4) \times 10^{-12}$		1998
		$\mu_\nu \lesssim (1.1-2.7) \times 10^{-12}$		2009
Tip of the red giant branch		$\mu_\nu \lesssim 3 \times 10^{-12}$		1989
		$\mu_\nu \lesssim 1 \times 10^{-12}$		1993
		$\mu_\nu < 4.5 \times 10^{-12}$	95%	2013
		$\mu_\nu \lesssim 2.6 \times 10^{-12}$		2015
		$\mu_\nu < 1.2 \times 10^{-12}$	95%	2020
		$\mu_\nu \lesssim (1-5) \times 10^{-12}$		2020
		$\mu_\nu \lesssim 6 \times 10^{-12}$		2023
Solar cooling		$\mu_\nu \lesssim 4 \times 10^{-10}$		1999
Cepheid stars		$\mu_\nu \lesssim 2 \times 10^{-10}$		2020
White dwarfs		$\mu_\nu \lesssim (7-9) \times 10^{-12}$		2014
		$\mu_\nu < 5 \times 10^{-12}$	95%	2014
Big bang nucleosynthesis		$\mu_\nu \lesssim (1-2) \times 10^{-11}$		1981
		$\mu_\nu \lesssim 6.2 \times 10^{-11}$		1997
		$\mu_\nu \lesssim 4 \times 10^{-12}$		2023
Cosmological N_{eff}		$\mu_\nu < 2.7 \times 10^{-12}$	95%	2022
		$\mu_\nu < 2.6 \times 10^{-12}$	95%	2022
		$\mu_\nu < 5 \times 10^{-12}$	68%	2023

Astrophysical limits on neutrino magnetic moments μ_ν

Giunti, Kouzakov, Li, Studenikin, Neutrino Electromagnetic Properties,



Experimental (laboratory) constraints on the magnetic moment of neutrinos

from elastic neutrino scattering on target particles

- on electrons

Elastic Neutrino-Electron Scattering

EVES

- on atomic nuclei

Coherent Elastic Neutrino-Nucleus Scattering

CEvNS

- on atoms

Coherent Elastic Neutrino-Atom Scattering

CEvAS

SATURNE project !

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

M. Cadeddu¹, F. Dordel², C. Giunti³, V. Kouzakov⁴, E. Picciau⁵, and A.I. Studenikin^{5,6,4}

¹Università degli studi di Cagliari and Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Cagliari, Complesso Universitario di Monserrato—S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy

²Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Cagliari, Complesso Universitario di Monserrato—S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy

³Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy

⁴Department of Nuclear Physics and Quantum Theory of Collisions, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia

⁵Department of Theoretical Physics, Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia

⁶Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia

(Received 14 July 2019; published 29 October 2019)

We propose an experimental setup to observe coherent elastic neutrino-atom scattering (CEvAS) using electron antineutrinos from tritium decay and a liquid helium target. In this scattering process with the whole atom, that has not been observed so far, the electrons tend to screen the weak charge of the nucleus as seen by the electron antineutrino probe. The interference between the nucleus and the electron cloud produces a sharp dip in the recoil spectrum at atomic recoil energies of about 9 meV, reducing sizably the number of expected events with respect to the coherent elastic neutrino-nucleus scattering case. We estimate that with a 60 g tritium source surrounded by 500 kg of liquid helium in a cylindrical tank, one could observe the existence of CEvAS processes at 3σ in 5 yr of data taking. Keeping the same amount of helium and the same data-taking period, we test the sensitivity to the Weinberg angle and a possible neutrino magnetic moment for three different scenarios: 60, 160, and 500 g of tritium. In the latter scenario, the Standard Model (SM) value of the Weinberg angle can be measured with a statistical uncertainty of $\sin^2 \theta_W^{SM} - 0.015$. This would represent the lowest-energy measurement of $\sin^2 \theta_W$, with the advantage of being not affected by the uncertainties on the neutron form factor of the nucleus as the current lowest-energy determination. Finally, we study the sensitivity of this apparatus to a possible electron neutrino magnetic moment and we find that using 60 g of tritium it is possible to set an upper limit of about $7 \times 10^{-13} \mu_B$ at 90% C.L., that is more than one order of magnitude smaller than the current experimental limit.

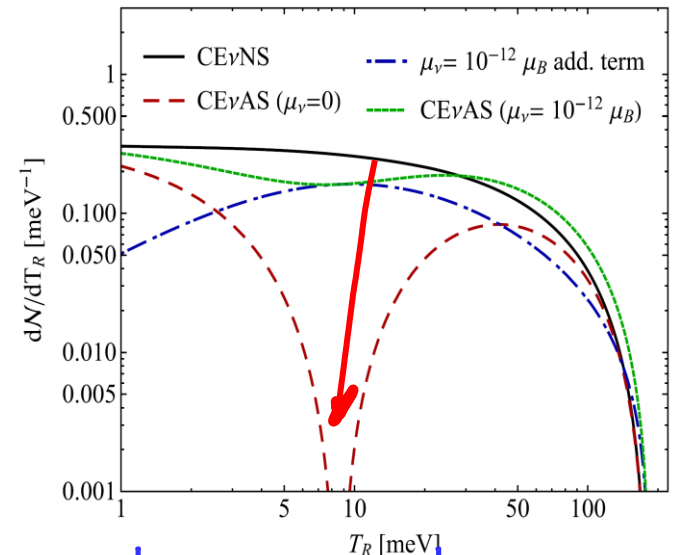
DOI: 10.1103/PhysRevD.100.073014

I. INTRODUCTION

Coherent elastic neutrino-nucleus scattering (CEvNS) has been recently observed by the COHERENT experiment [1,2], after many decades from its prediction [3–5].

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

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



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

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

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

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

¹matteo.cadeddu@ca.infn.it
²francesca.dordel@cern.ch
³carlo.giunti@to.infn.it
⁴kouzakov@gmail.com
⁵emmanuele.picciau@ca.infn.it
⁶studenik@srdsinp.msu.ru

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

CE ν NS: Coherent Elastic Neutrino-Nucleus Scattering

predicted by D. Freedman, PRD 9 (1974) 1389; V. Kopeliovich & L.Frankfurt, ZhETF Pis. Red. 19, No. 4 (1974) 236; observed by D. Akimov et al. (COHERENT Collab.), Science 357 (2017) 1123

CE ν NS

$$\triangleright |\vec{q}| R_{\text{nuc}} \ll 1$$

\vec{q} is the momentum transfer

R_{nuc} is the nuclear radius

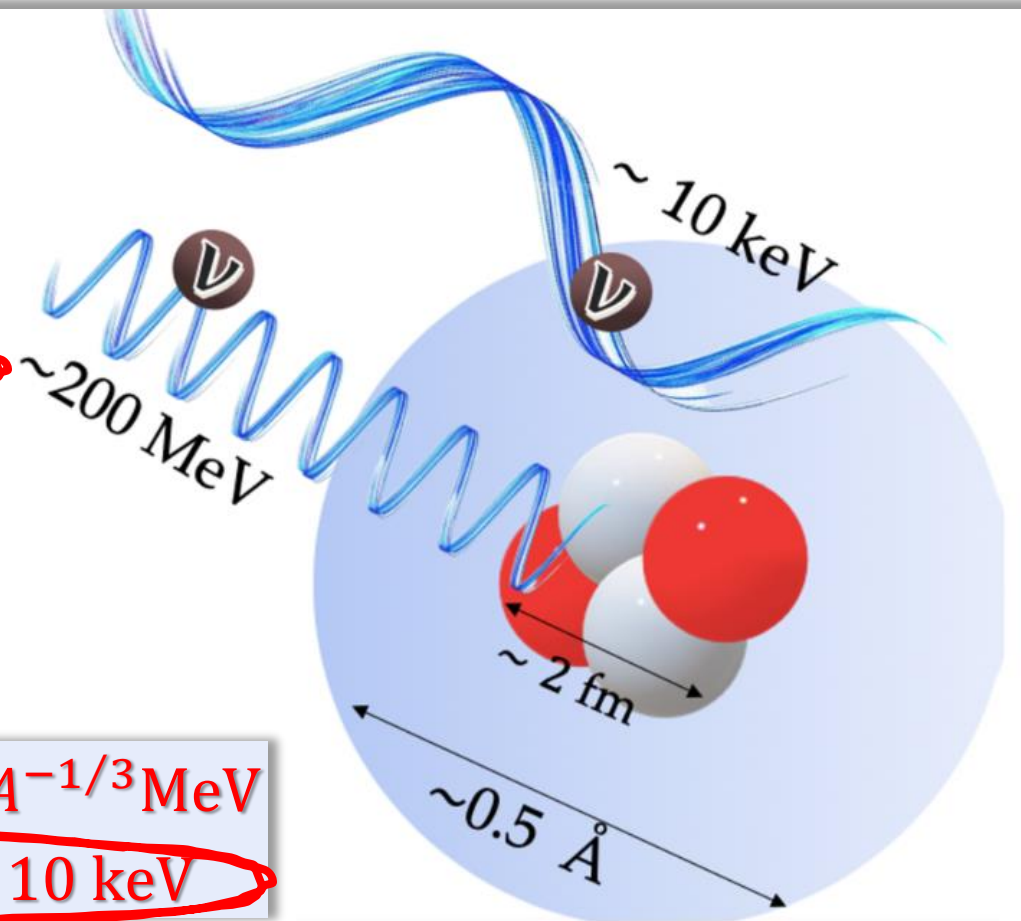
CE ν AS

$$\triangleright |\vec{q}| R_{\text{atom}} \ll 1$$

R_{atom} is the atomic radius

$$\text{CE}\nu\text{NS: } E_{\nu} \lesssim 1/R_{\text{nuc}} \sim 200A^{-1/3}\text{MeV}$$

$$\text{CE}\nu\text{AS: } E_{\nu} \lesssim 1/R_{\text{atom}} \sim 1 - 10 \text{ keV}$$



If conditions for CE ν AS are met, then so are the conditions for CE ν NS, but there is screening effect \Rightarrow reduction of numbers of events ...

Measurements of $CE\nu AS$ process in SATURNE

\checkmark elastic scattering on $He-4$ atom:



Cross-section (T – recoil energy of the atom)

$$\frac{d\sigma^{CE\nu AS}}{dT} = \frac{d\sigma_{SM}^{CE\nu AS}}{dT} + \frac{d\sigma_{\mu\nu}^{CE\nu AS}}{dT} \quad t_{1/2} = 12.3 \text{ yrs}$$

Contribution of the weak interaction (SM)

$$\frac{d\sigma_{SM}^{CE\nu AS}}{dT} = \frac{G_F^2 M_{He}}{\pi} C_V^2 \left(1 - \frac{M_{He} T}{2E_\nu^2} \right), \quad C_V = Z \left(\frac{1}{2} - 2 \sin^2 \theta_w \right) - \frac{1}{2} N + Z \left(\frac{1}{2} + 2 \sin^2 \theta_w \right) F_{el}(|\vec{q}|),$$

$Z=N=2$ number of p and n in $He-4$ nuclei, $M_{He} = 3.728 \text{ GeV}$ for $He-4$ atom

$F_{el}(|\vec{q}|)$ atomic electronic form factor (Fourier transform of the normalized electron density in a $He-4$ atom)

Contribution of the magnetic moment μ_ν

$$\frac{d\sigma_{\mu\nu}^{CE\nu AS}}{dT} = \frac{\pi \alpha^2 Z^2}{m_e^2} \left(\frac{\mu_{\bar{\nu}_e}}{\mu_B} \right)^2 \left(\frac{1}{T} - \frac{1}{E_\nu} + \frac{T}{4E_\nu^2} \right) [1 - F_{el}(|\vec{q}|)]^2$$

$$\langle E_{\bar{\nu}_e} \rangle = 12.9 \text{ keV}$$

tritium \checkmark

+

helium target

||

CEνAS

Atomic recoil energy scale in CE ν AS

- From conservation of energy and momentum:

$$T_R \leq \frac{2E_\nu^2}{m}$$

T_R is atomic recoil energy
 $m \approx A \text{ GeV}$ is atomic mass

*In the reactor CE ν NS experiment CONNIE:
Threshold is 15 eV_{ee}
(with CCD sensors)*

*Aguilar-Arevalo et al.,
arXiv:2403.15976v1 [hep-ex]*

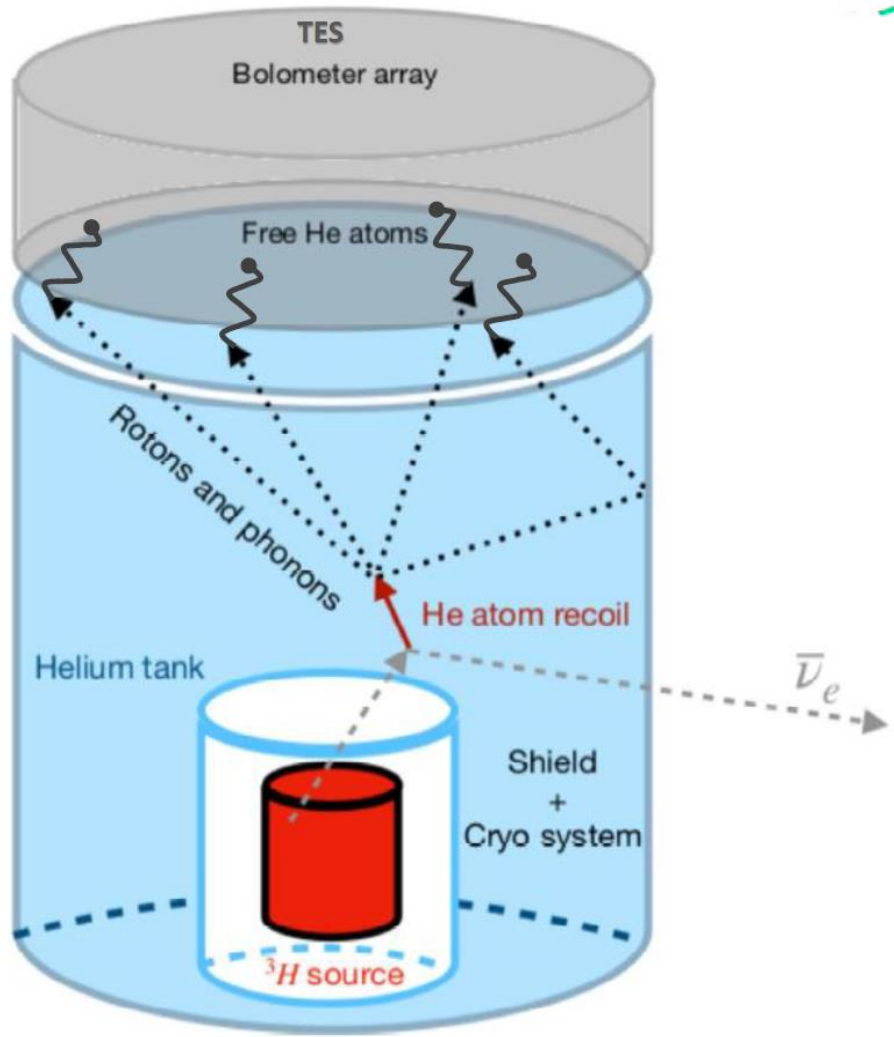
- If $E_\nu \sim 10 \text{ keV}$: $T_R \lesssim \frac{200}{A} \text{ meV}$

For the lightest atom ($A=1$): $T_R \lesssim 200 \text{ meV}$

Light atomic targets, such as H or He, and new detector technologies are needed to observe CE ν AS

Detection method to study CE ν AS

Titanium Tritid TiT_2



```
graph TD; A[Tritium neutrino] --> B[Elastic neutrino-atom scattering]; B --> C[He atom recoil (1-185 meV)]; C --> D[Phonons and rotons (0.7-1.2 meV per q. p.)]; D --> E[Quantum evaporation (0.6 meV per atom)]; E --> F[Adsorption onto TES (6-50 meV per adatom)]; F --> G[Signal];
```

The basic idea of SATURNE :

1) recoil energy of the atom ${}^4\text{He}$
(from ν ${}^3\text{He}$ approximately 100 meV)

2) the main channel of energy loss

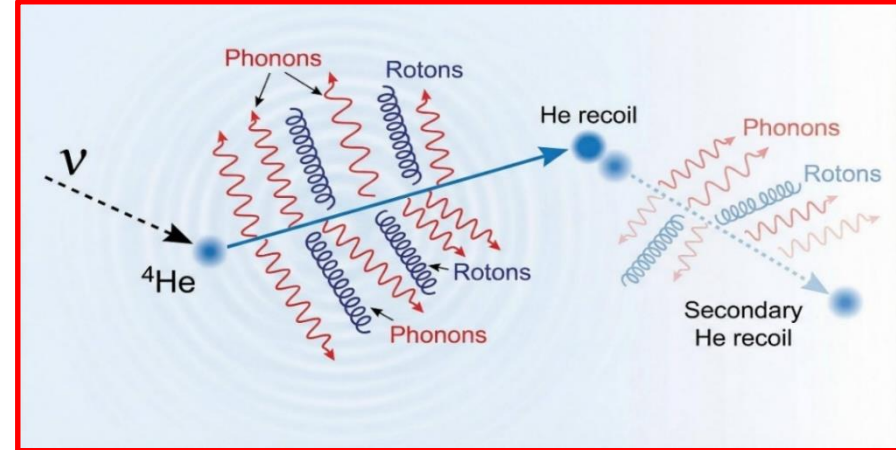
${}^4\text{He}$ – is collective excitations (phonons+rotons)

3) collective excitations (phonons + rotons) ballistically
to the surface – quantum evaporation of ${}^4\text{He}$

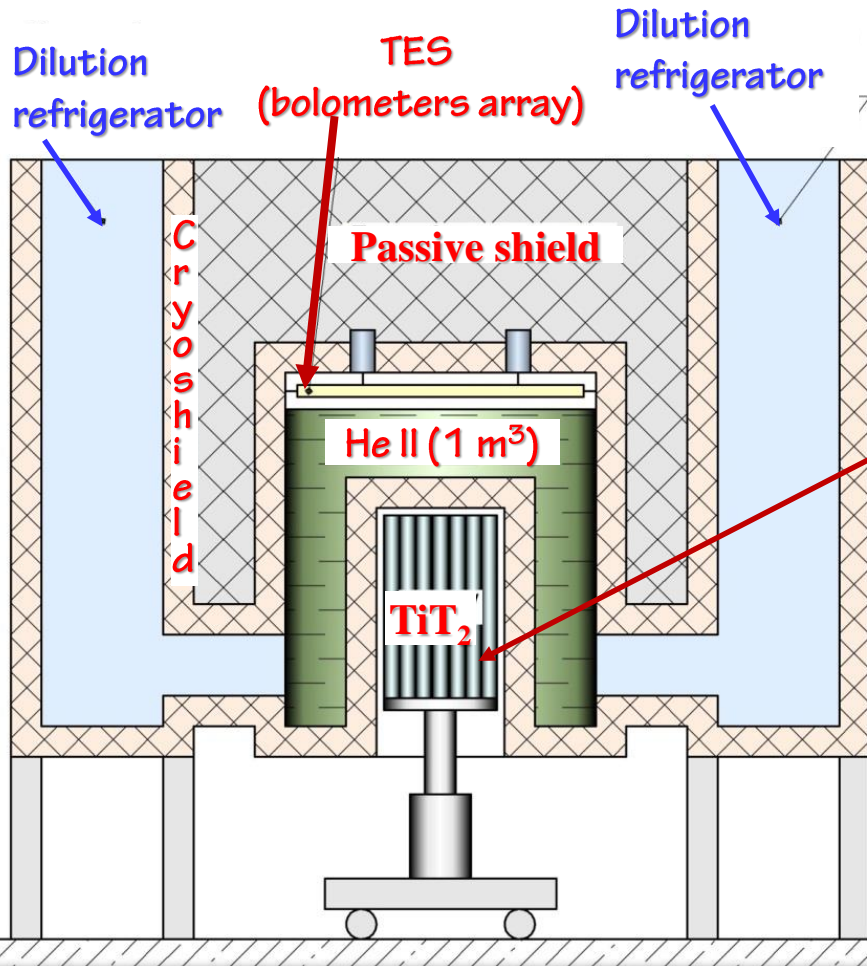
4) adsorbed on the bolometer (detector) substrate

5) due to adsorption – Van der Waals enhancement

6) a signal of tens of meV is measured by microcalorimeters
based on TES (transition edge sensors)



He II detector concept to study $CE\nu AS$



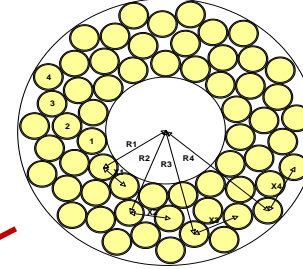
Tritium neutrino source (TNS)

1-4 kg, 10-40 MCi

A.Yukhimchuk et al. Fusion Science & Technology 48, No.1 (2005) 731-736

- Tubular elements with TiT_2

titanium tritid



1/2 model



● The tritium source design includes copper tubular elements

✓ flux: $F_{max} \sim 1 \times 10^{14} \text{ cm}^2 \text{ s}^{-1}$ (1 kg)

✓ flux: $F_{max} \sim 2 \times 10^{14} \text{ cm}^2 \text{ s}^{-1}$ (4 kg)

Helium II detector (1000 L)

- Liquid He-4 at 40-60 mK

- Array of 1000 TESs (transition edge sensors)

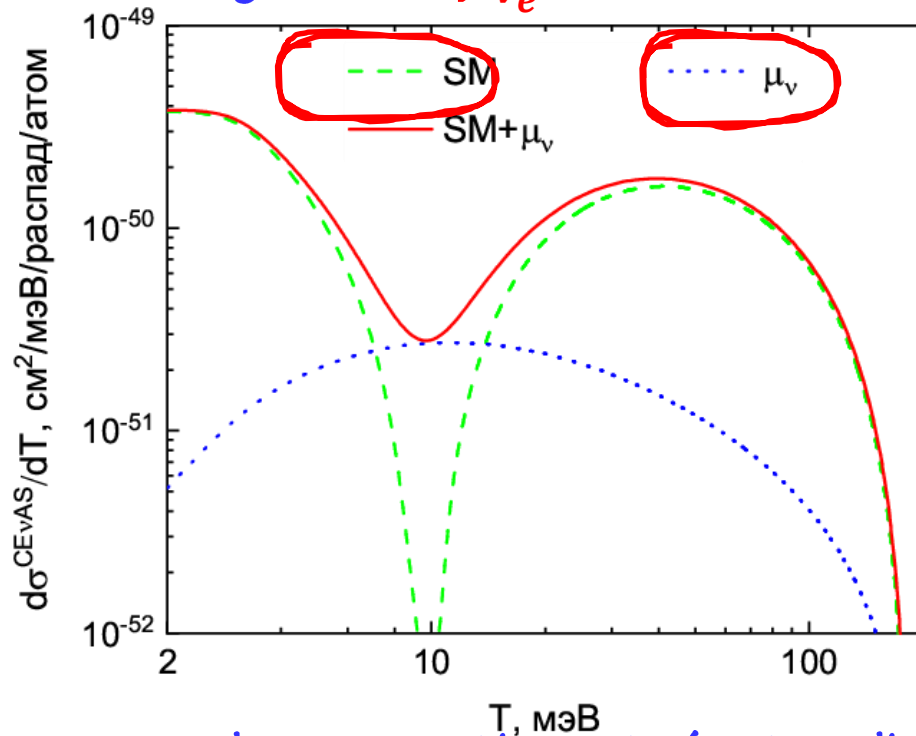
- 1000-channel SQUID readout

Expected results after 5 years of data collection:

- number of $CE\nu AS$ events within SM: 60 for 1 kg of T_2 and 200 for 4 kg of T_2

- sensitivity to neutrino magnetic moment: $\mu_\nu \sim (2-4) \times 10^{-13} \mu_B$ at 90% C.L.

Differential cross section **CEvAS** (solid line), averaged over the spectrum of tritium neutrinos, in the case of an atomic He-4 target for $\mu_{\bar{\nu}_e} = 3 \times 10^{-13} \mu_B$



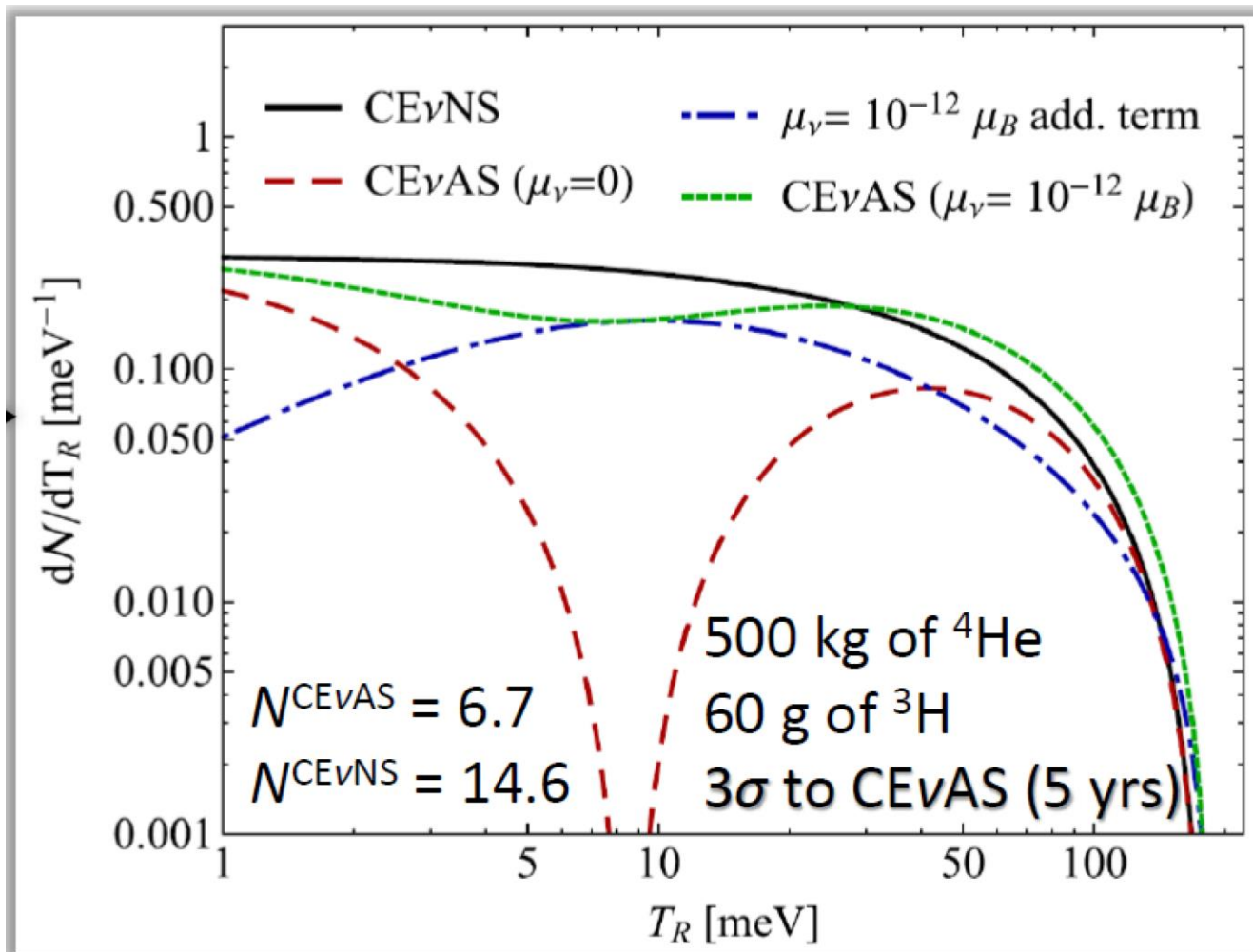
● The averaged cross-section sets (up to a dimensional factor) the spectrum of recoil atoms at **CEvAS**

● Complete screening of spectrum in SM at $T \sim 9 \text{ meV}$ - when atomic effects are considered, electrons screen the weak charge of nucleus

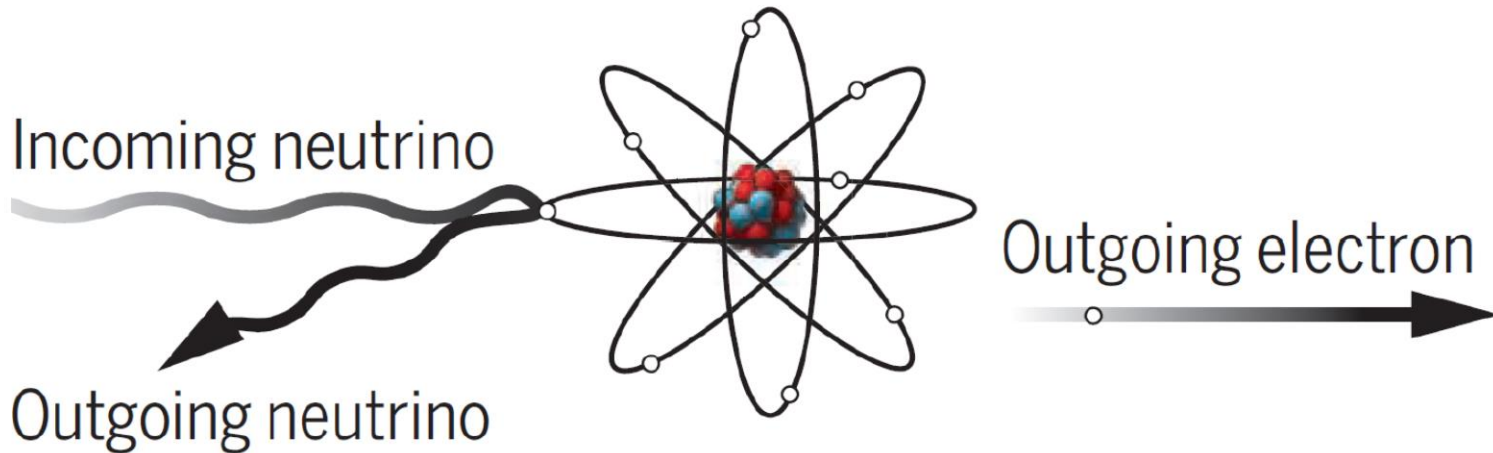
● The μ_ν contribution leads to a strong deviation from the SM prediction

Opportunity to observe **CEVAS**

(~ 2 times fewer events than with only the mode at CEvNS, without atomic electrons)



Atomic ionization channel



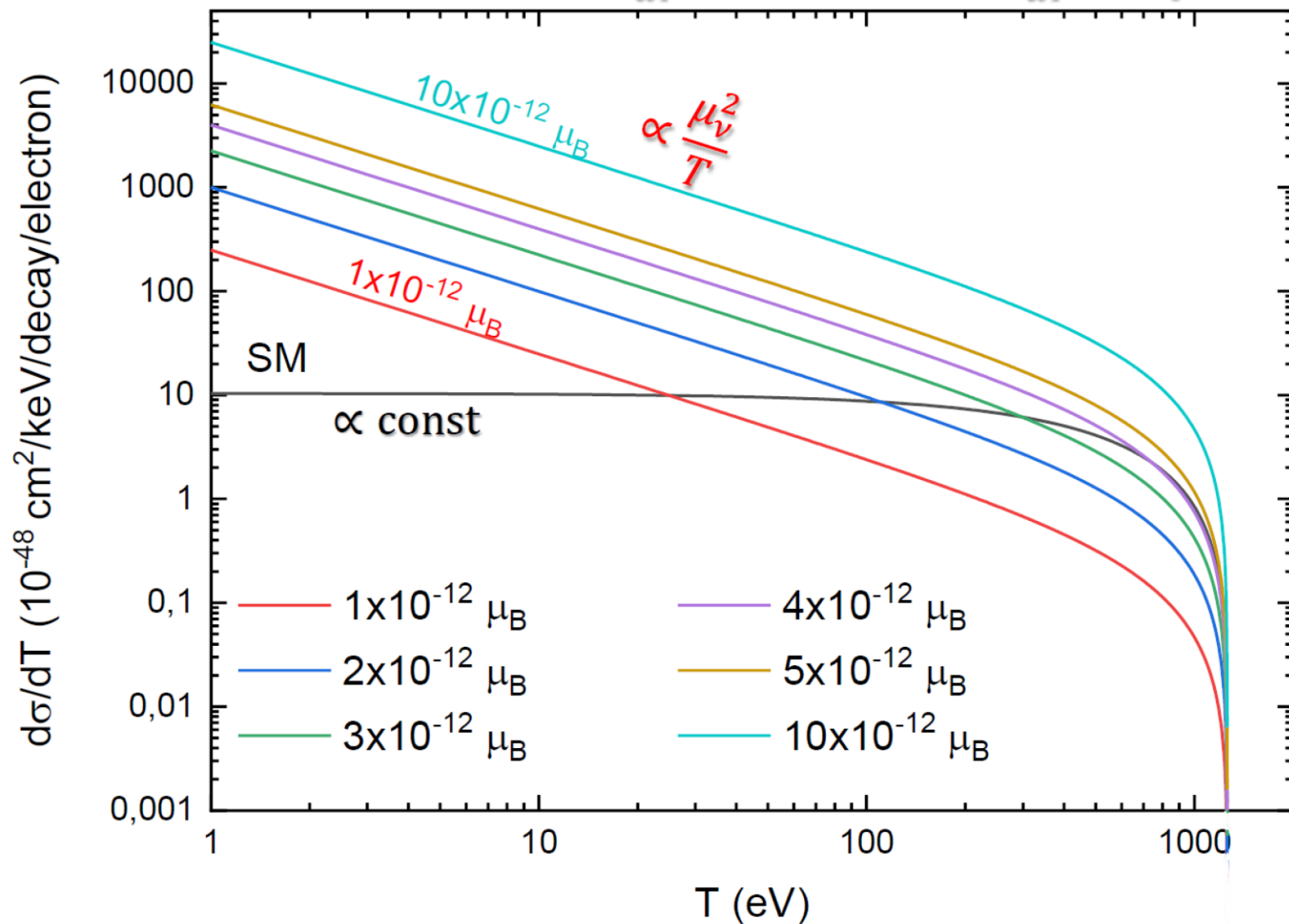
World leading laboratory constraints on μ_{ν} , like those from XENONnT and GEMMA, are obtained by studying the atomic ionization channel (elastic $\nu - e^-$ scattering)

In **SATURNE** we develop

- Si crystal detector *криогенный кремний на базе ОИЯИ*
- CsI(pure) scintillation detector
*низкотемпературный
сцинтилляционный цезий-йод разрабатывает ИЯИ РАН*

Differential cross sections for ionization of Si by tritium $\bar{\nu}_e$

At small T values: $\frac{d\sigma_{SM}}{dT} \propto \text{const}$, and $\frac{d\sigma(\mu)}{dT} \propto \frac{\mu_\nu^2}{T}$

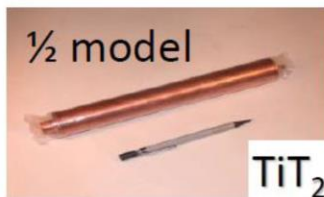
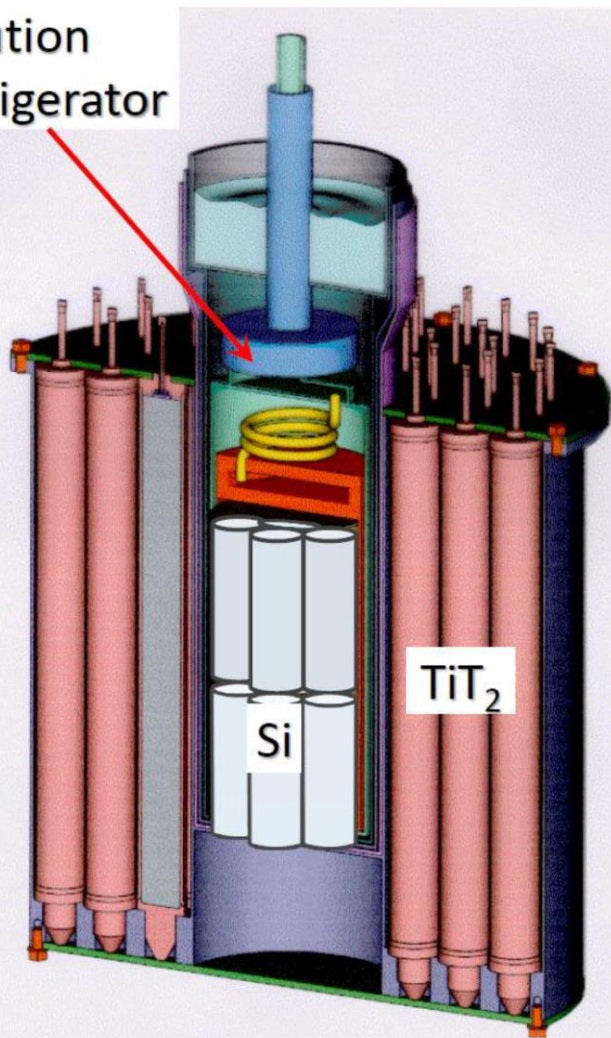


The detector's energy threshold is to be as low as possible

Si detector concept

... implemented at JINR

Dilution
refrigerator



Tritium neutrino source (1-4 kg)

- tubular elements with TiT_2



Silicon cryodetectors ($T=10-50$ mK)

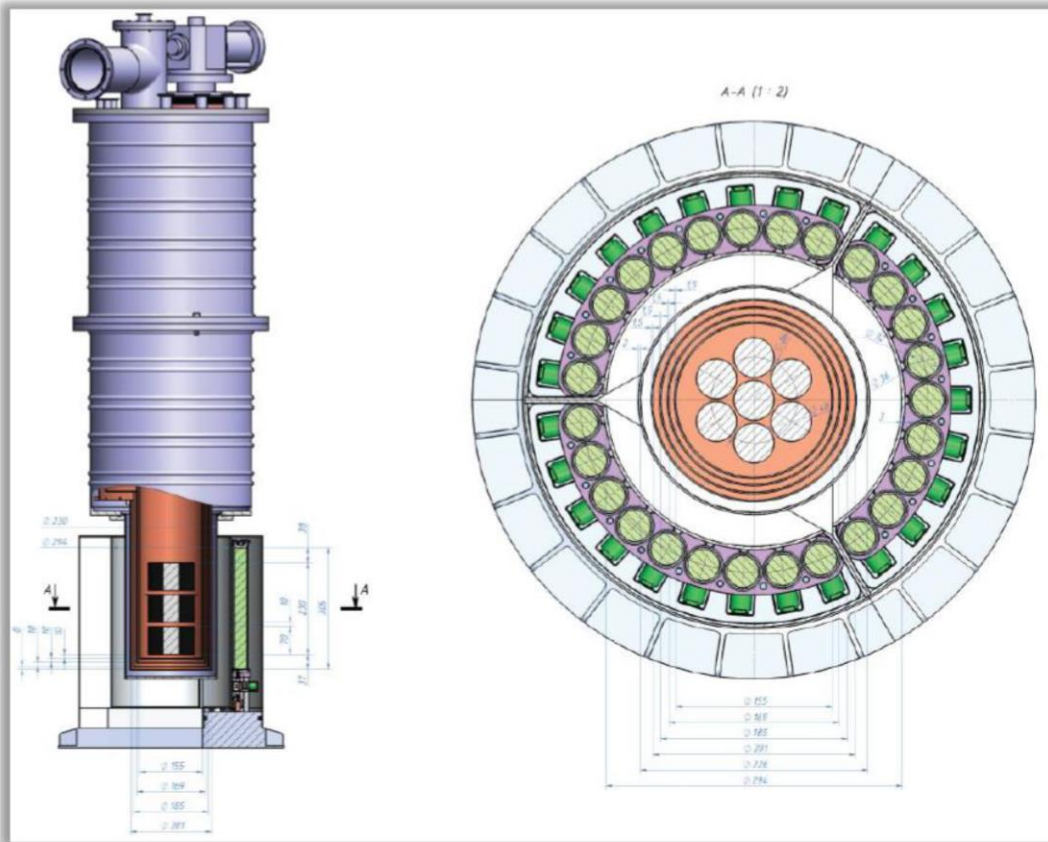
(14-28) \times 125 cm³, $M=2.9-5.7$ kg

with TES or CEB mounted on each
Si crystal

The Si detector with an ultra-low threshold $E_{th} \sim 10$ eV or even $E_{th} \sim 1$ eV owing to the **Neganov-Trofimov-Luke effect (heat amplification of ionization signal)**

*B. Neganov and V. Trofimov, USSR patent no. 1037771, Otkrytia i Izobreteniya **146** (1985) 215;
P. N. Luke, J. Appl. Phys. **64** (1988) 6858.*

Projected μ_ν -sensitivity of Si detector



Tritium mass is 1 kg (10 MCi)

$$\Delta\chi^2 = \chi^2 - \chi_{\min}^2$$

$$\chi^2 = \left(\frac{N_{SM} - N}{\sqrt{N_{SM}}} \right)^2$$

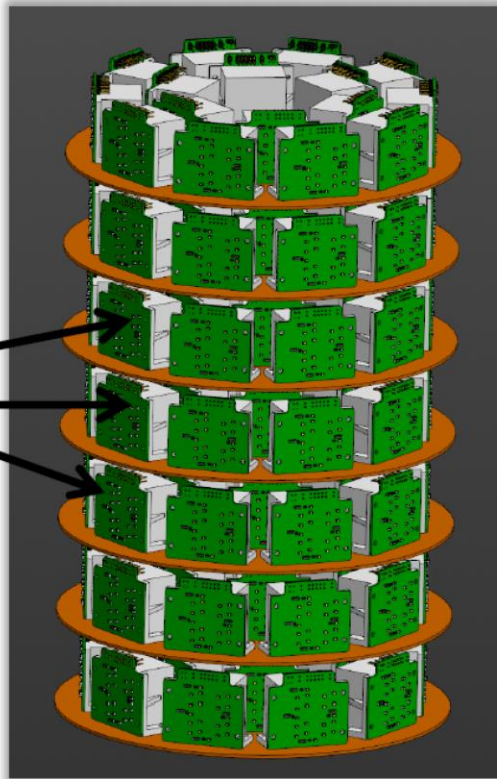
$$N = N_{SM} + N_{\mu\nu}$$

1 year of taking data	14 cylinders, 2.9 kg		21 cylinders, 4.3 kg		28 cylinders, 5.7 kg	
	1 σ B	10 σ B	1 σ B	10 σ B	1 σ B	10 σ B
N_{SM}	7.96	7.94	11.52	11.49	14.61	14.57
$\mu_\nu, 10^{-12}\mu_B$	1.76	2.03	1.61	1.85	1.51	1.74
90% CL						

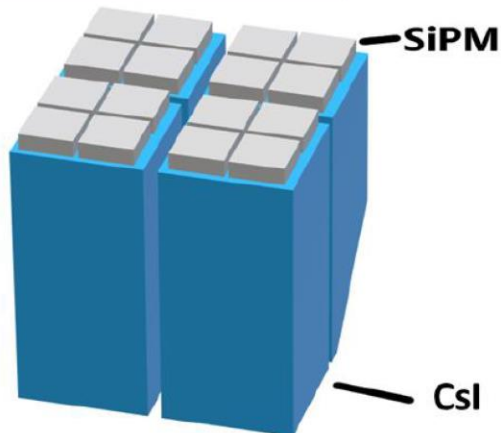
CsI(pure) detector concept ... implemented at INR RAS

Detector assembly

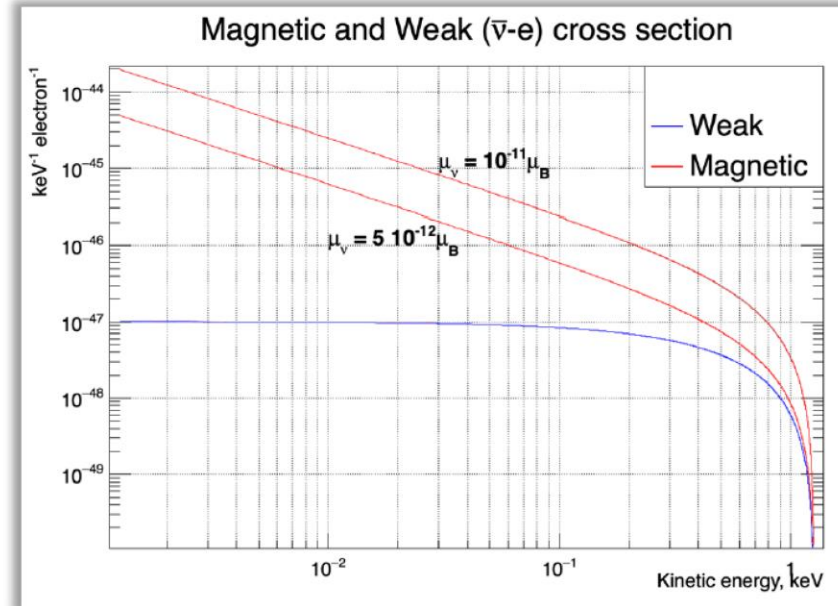
Layers of modules



Detector module



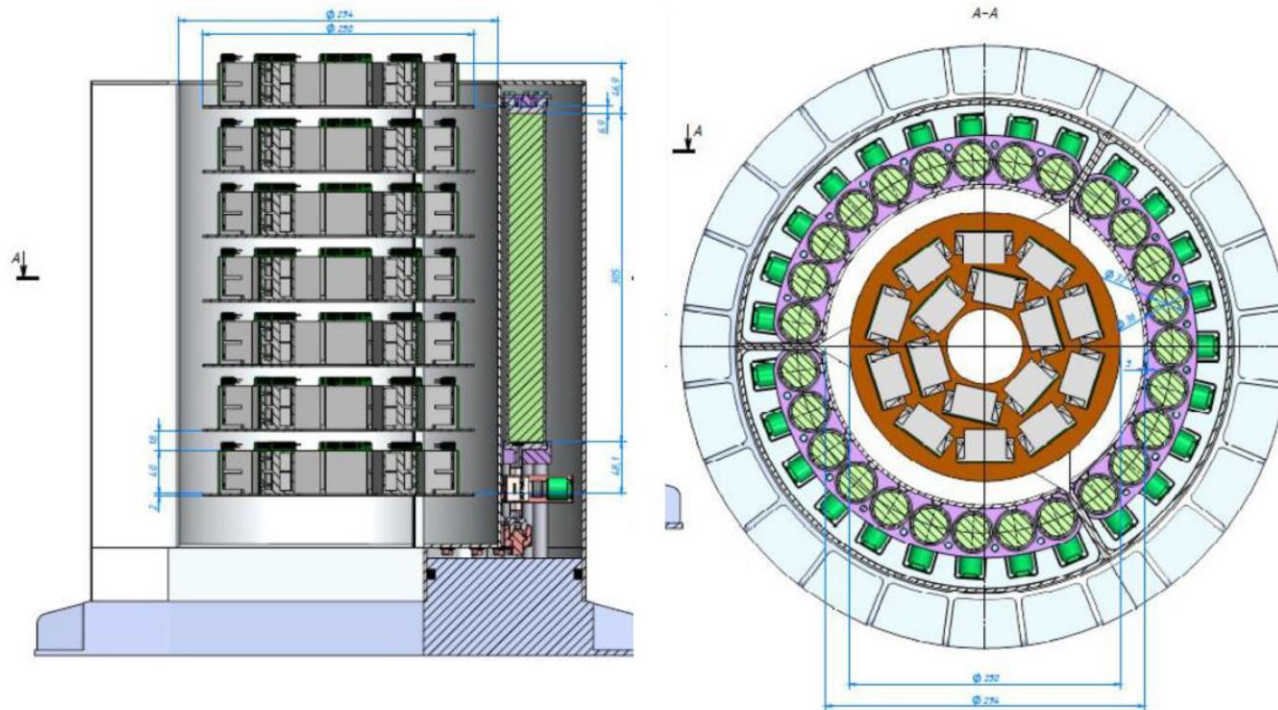
Abdurashitov, Vlasenko, Ivashkin, Silaeva, Sinev, *Phys. Atom. Nuclei* **85** (2022) 701



15x15x25 mm³ CsI(pure) crystals
at T=77 K, total mass is M=7.5-10.5 kg

- SiPM readout (two SiPMs per each crystal)
- Light collection at a level of ~ 30 photoelectrons/keV
- Energy threshold is $E_{\text{th}} \sim 100$ eV

Projected μ_ν -sensitivity of CsI detector



**Tritium mass is
1 kg (10 MCi)**

$$\Delta\chi^2 = \chi^2 - \chi_{\min}^2$$

$$\chi^2 = \left(\frac{N_{SM} - N}{\sqrt{N_{SM}}} \right)^2$$

$$N = N_{SM} + N_{\mu_\nu}$$

1 year of taking data	5 layers, 7.5 kg				7 layers, 10.5 kg			
	100 eB	200 eB	300 eB	400 eB	100 eB	200 eB	300 eB	400 eB
N_{SM}	12.48	11.53	10.52	9.50	15.71	14.51	13.24	11.96
$\mu_\nu, 10^{-12} \mu_B$	2.31	2.66	2.91	3.11	2.18	2.51	2.75	2.93
90% CL								

Conclusion

- The main goal of the SATURN project is to perform the first-ever coherent elastic scattering of neutrinos on an atom.
- Search for the electromagnetic properties of electron neutrinos in laboratory experiments with record sensitivity $\mu_\nu \sim 3 \times 10^{-13} \mu_B$ (90% CL)

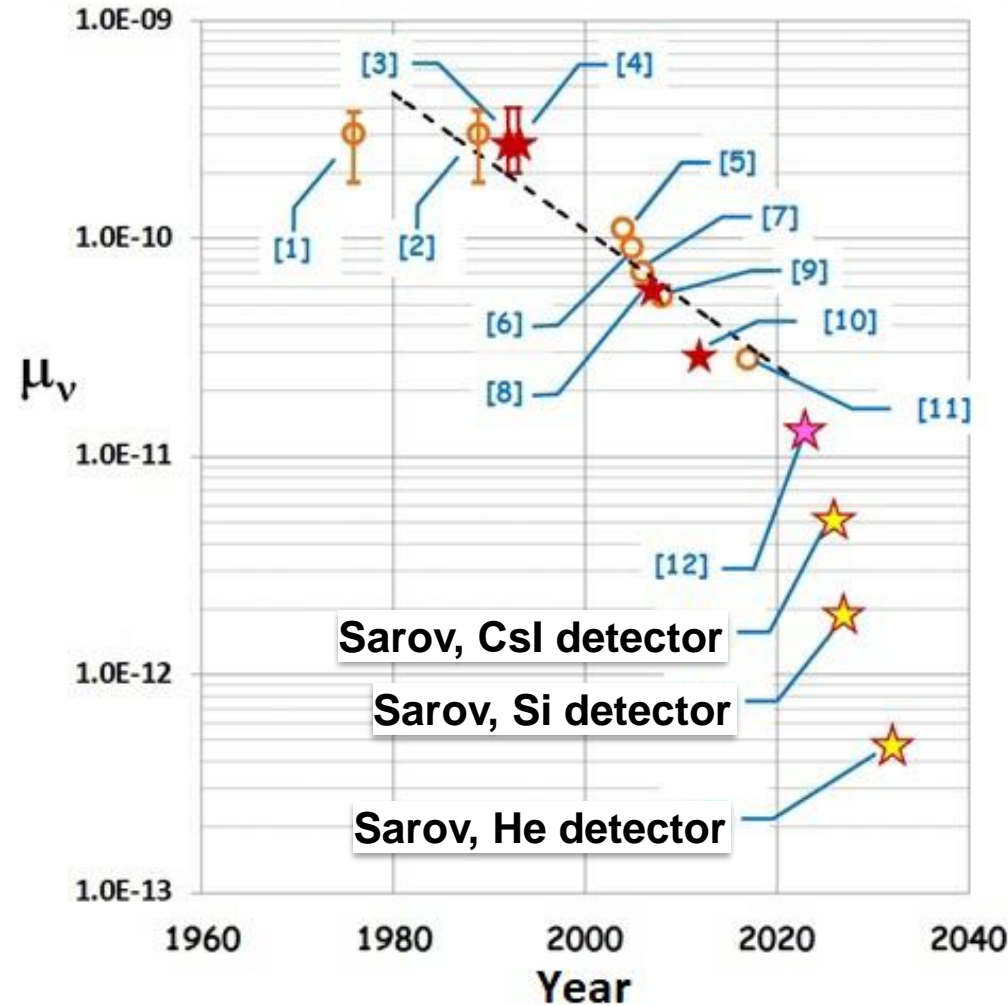


- a high-intensity tritium source of electron antineutrinos with activity 10 MCi (40 MCi)
- a detector based on superfluid helium-4 with a detection threshold 1-10 meV
- deep-level low background neutrino lab with Infrastructure for working with large numbers of \checkmark ... first measurements at Baksan in 2026 ...

Intermediate stages

- of a low-temperature CsI scintillation detector (registration threshold of 100-200 eV):
 $\mu_\nu \sim (2-3) \times 10^{-12} \mu_B$ (90% CL) INR RAS
- cryogenic Si detector with thermal amplification effect (registration threshold 1-10 eV) $\mu_\nu \sim (1.5-2) \times 10^{-12} \mu_B$ (90% CL) JINR

Progress of experimental sensitivity to μ_ν



- [1] Savannah River, first observation (1976)
- [2] Vogel & Engel (1989)
- [3] Kurchatov Institute, Krasnoyarsk (1992)
- [4] Rovno NPP (1993)
- [5] Super-Kamiokande (2004)
- [6] MUNU (2005)
- [7] TEXONO (2006)
- [8] GEMMA I (2007)
- [9] BOREXINO (2008)
- [10] GEMMA I (2012)
- [11] BOREXINO (2017)
- [12] GEMMA-2 (vGEN) (2022?)

The SATURNE Collaboration



Национальный центр
ФИЗИКИ и МАТЕМАТИКИ



RUSSIAN FEDERAL NUCLEAR CENTER

ALL-RUSSIAN RESEARCH INSTITUTE OF EXPERIMENTAL PHYSICS



**PRODUCTION
ASSOCIATION
MAYAK**



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



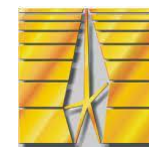
**LOMONOSOV MOSCOW
STATE UNIVERSITY**



**JOINT INSTITUTE
FOR NUCLEAR RESEARCH**



IPM RAS



**Ioffe
Physical-
Technical
Institute**

... papers ...

- M. Cadeddu, F. Dordei, C. Giunti, K. Kouzakov, E. Picciau and A. Studenikin, *Potentialities of a low-energy detector based on 4He evaporation to observe atomic effects in coherent neutrino scattering and physics perspectives*, *Phys. Rev. D* **100** (2019) 073014
- G. Donchenko, K. Kouzakov, and A. Studenikin, *Elastic neutrino-atom scattering as a probe of neutrino millicharge and magnetic moment*, *JETP Lett.* **117** (2023) 879
- A.A. Yukhimchuk et al., *Physics of hydrogen isotopes*, *FIZMAT* **1** (2023) 5 (in Russian)
- O. Moskalev et al., *On implementation of the SATURNE project*,
Moscow Univ.Phys.Bull. **79** (2024) Suppl 1, 252
- M. Cadeddu et al., *The status of SATURNE*, *Moscow Univ. Phys. Bull.* **79** (2024) Suppl 1, 243
- M. Cadeddu et al., *Search for neutrino magnetic moment with coherent elastic neutrino-atom scattering: The experimental concept*, *Moscow Univ.Phys.Bull.* **79** (2024) Suppl 1, 256
- M. Cadeddu et al., *SATURNE: Current status and physics potential*,
Int.J.Mod.Phys.E **33** (2024) 2441011
- K.Kouzakov et al., *Neutrino scattering on superfluid helium with account for neutrino electromagnetic properties and collective effects*, *Phys. Atom. Nucl.* (2025)

2025

SATURNE \Rightarrow development of theory of \checkmark oscillations, quantum decoherence, and scattering...

- K.Stankevich, A.Studenikin, M.Vyalkov, **Generalized Lindblad master equation for neutrino evolution, Phys.Rev.D 111 (2025) 3, 036014**

PHYSICAL REVIEW D 111, 036014 (2025)

Generalized Lindblad master equation for neutrino evolution

Konstantin Stankevich[✉] and Alexander Studenikin[✉]
Faculty of Physics, Lomonosov Moscow State University, 119992 Moscow, Russia
and Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia

Maksim Vyalkov[✉]
Department of Theoretical Physics, Faculty of Physics,
Lomonosov Moscow State University, 119992 Moscow, Russia;
Branch of Lomonosov Moscow State University in Sarov, 607328, Russia;
and National Centre for Physics and Mathematics, 607182 Sarov, Russia

[✉] (Received 11 October 2024; accepted 27 January 2025; published 11 February 2025)

A new theoretical framework, based on the quantum field theory of open systems applied to neutrinos, has been developed. This framework aims to describe the neutrino evolution in external environment, taking into account the effect of neutrino quantum decoherence. We have applied this approach to investigate a novel mechanism for neutrino quantum decoherence, which arises due to the neutrino decay into a lighter neutrino state and a massless particle, as well as the inverse process of absorption of a massless particle by a neutrino. We derived the new generalized Lindblad master equation for the neutrino evolution that accounts for neutrino transitions between states with different momenta. We also demonstrate that studying of neutrino quantum decoherence through this master equation provides a unique possibility to determine or limit the neutrino decay width. On this basis we obtained the constraint on neutrino lifetime $\frac{L}{\tau} > 1.83 \times 10^{-10} \frac{L}{\text{km}}$ (for the case of the Dirac neutrino scalar decay and neutrino degenerate hierarchy).

DOI: 10.1103/PhysRevD.111.036014

- A.Popov, A.Studenikin, **High-energy neutrinos flavour composition as a probe of neutrino magnetic moments, Phys.Rev.D 111 (2025) 123001**

PHYSICAL REVIEW D 111, 123001 (2025)

High-energy neutrinos flavor composition as a probe of neutrino magnetic moments

Artem Popov[✉] and Alexander Studenikin[✉]
Department of Theoretical Physics, Moscow State University, Moscow 119991, Russia

[✉] (Received 29 December 2024; accepted 5 May 2025; published 2 June 2025)

Neutrino propagation in the Galactic and extragalactic magnetic fields is considered. We extend an approach developed in [A. Popov and A. Studenikin, Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field, Eur. Phys. J. C 79, 144 (2019)] to describe neutrino flavor and spin oscillations using wave packets. The evolution equations for the neutrino wave packets in a uniform and nonuniform magnetic fields are derived. The analytical expressions for neutrino flavor and spin oscillations probabilities accounting for damping due to the wave packet separation are obtained for the case of a uniform magnetic field. It is shown that terms in the flavor oscillations probabilities that depend on the magnetic field strength are characterized by two coherence lengths. One of the coherence lengths coincides with the coherence length for neutrino oscillations in vacuum, while the second one is proportional to the cube of the average neutrino momentum p_0^3 . The probabilities of flavor and spin oscillations are calculated numerically for neutrino interacting with the nonuniform Galactic magnetic field. It is shown that oscillations on certain frequencies are suppressed on the Galactic scale due to the neutrino wave packets separation. The flavor compositions of high-energy neutrino flux coming from the Galactic center and ultra-high energy neutrinos from an extragalactic source are calculated accounting for neutrino interaction with the magnetic field and decoherence due to the wave packet separation. It is shown that for neutrino magnetic moments $\sim 10^{-11} \mu_B$ and larger these flavor compositions significantly differ from ones predicted by the vacuum neutrino oscillations scenario.

DOI: 10.1103/PhysRevD.111.123001

- K.Kouzakov, F.Lazarev, A.Studenikin, **Electromagnetic interactions in elastic neutrino-nucleon scattering, Phys.Rev.D 111 (2025) 3, 035025**

PHYSICAL REVIEW D 111, 035025 (2025)

Electromagnetic interactions in elastic neutrino-nucleon scattering

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

Fedor M. Lazarev[✉] and Alexander I. Studenikin[✉]
Department of Theoretical Physics, Faculty of Physics,
Lomonosov Moscow State University, Moscow 119991, Russia

[✉] (Received 19 September 2024; accepted 28 January 2025; published 24 February 2025)

A thorough account of electromagnetic interactions of massive Dirac neutrinos as well as their spin-flavor state in the theoretical formulation of elastic neutrino-nucleon 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 and spin change of neutrinos propagating from the source to the detector is taken into account in the form of a spin-flavor density matrix of the neutrino arriving at the detector. The potential effects of the neutrino charge radii, magnetic moments, and spin polarization in the neutrino-nucleon scattering experiments are outlined.

DOI: 10.1103/PhysRevD.111.035025

- A.Lichkunov, K.Stankevich, A.Studenikin, **Neutrino quantum decoherence in a fluctuating ALPs field. Phys. Rev. D 112 (2025) 123007**

Neutrino quantum decoherence in a fluctuating ALPs field

Alexey Lichkunov^{*}
Department of Theoretical Physics, Faculty of Physics,
Lomonosov Moscow State University, 119992 Moscow, Russia,
Pushkov Institute of Terrestrial Magnetism, Ionosphere and
Radiowave Propagation (IZMIRAN), 108840 Moscow, Troitsk, Russia

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

Alexander Studenikin[†]
Department of Theoretical Physics and Department of Physics of Particles and Extreme States of Matter,
Faculty of Physics, Lomonosov Moscow State University, 119992 Moscow, Russia

The evolution of neutrinos in a fluctuating classical axion-like particles (ALPs) field is investigated. The equation for the neutrino density matrix is obtained in the Redfield form, and the corresponding dissipative matrix is derived. Estimates on the ALP-neutrino coupling constants are obtained using the limits on the decoherence parameter determined from the analysis of reactor neutrino experiments data.

Научного совета РАН «Физика нейтрино и нейтринная астрофизика»

Дата и место проведения: 11 декабря 2025 года, ИЯИ РАН, Москва.

Присутствовали:

а) члены Научного совета

В.А.Бедняков, д.ф.-м.н., ОИЯИ; Л.Б.Безруков, д.ф.-м.н., ИЯИ РАН, М.И.Высоцкий, член-корр. РАН, ФИАН; В.Н.Гаврин, академик, ИЯИ РАН, С.П.Денисов, академик, ИФВЭ; А.В.Дербин, д.ф.-м.н., ПИЯФ, Ж.-А. М. Джилкибаев, д.ф.-м.н., ИЯИ РАН; Ю.Г.Куденко, член-корр. РАН, ИЯИ РАН; В.А.Матвеев, академик, ОИЯИ; Д.В.Наумов – Ученый секретарь Научного совета, д.ф.-м.н., ОИЯИ; А.Г.Ольшевский, д.ф.-м.н., ОИЯИ; А.А.Петрухин, д.ф.-м.н., МИФИ; Г.И.Рубцов, член-корр. РАН, ИЯИ РАН; В.А.Рябов, д.ф.-м.н., ФИАН; М.Д.Скорохватов, д.ф.-м.н., НИЦ КИ, А.И.Студеникин, д.ф.-м.н., МГУ; И.И.Ткачев, академик, ИЯИ РАН; С.В.Троицкий – Председатель Научного совета, член-корр. РАН, ИЯИ РАН;

б) М.М.Вялков, МГУ; Д.С.Горбунов, член.-кор. РАН, ИЯИ РАН; А.П.Ивашкин, к.ф.-м.н., ИЯИ РАН; К.А.Кузаков, д.ф.-м.н., МГУ; Ф.М.Лазарев, МГУ; А.Л.Панкратов, д.-ф.-м.н., НГТУ; А.Р.Попов, к.ф.-м.н., МГУ, К.Л.Станкевич, к.ф.-м.н., МГУ; А.А.Юхимчук, д.т.н., РФЯЦ-ВНИИЭФ.

Обсуждали:

Нейтринный проект SATURNE – современный статус и перспективы.

С докладами выступили:

- 1) К.А.Кузаков (МГУ), «Проект SATURNE: общий обзор»,
- 2) А.А.Юхимчук (РФЯЦ-ВНИИЭФ), «Проект SATURNE».

Scientific Council of Russian Academy of Sciences

«Physics of neutrinos and neutrino astrophysics»

● approval

● recommendation

for

SATURNE

White Paper

SATURNE White Paper

submitted (under review) for publication in

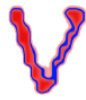
FizMath - journal of National Centre for Physics and Mathematics

ПРОЕКТ САТУРН – ПОИСК ЭЛЕКТРОМАГНИТНЫХ СВОЙСТВ НИЗКОЭНЕРГЕТИЧНЫХ ЭЛЕКТРОННЫХ АНТИНЕЙТРИНО ОТ ТРИТИЕВОГО ИСТОЧНИКА В РАМКАХ НАУЧНОЙ ПРОГРАММЫ НЦФМ

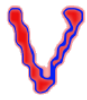
А.А.Юхимчук и др. (более 50 авторов)

Содержание

1. Цели и основные задачи проекта.....	2		
1.1 Мировые тенденции в области исследований электромагнитных свойств нейтрино	4		
1.1.1 Нейтрино и проблемы фундаментальной физики	4		
1.1.2 Электромагнитные свойства массивного нейтрино	5		
1.1.3 Электромагнитные свойства нейтрино в экспериментах по рассеянию.....	8		
1.1.4 Процессы электромагнитного взаимодействия нейтрино.....	12		
1.1.5 Новейшее развитие исследований электромагнитных свойств нейтрино	13		
1.2 Преимущества тритиевого источника (анти)нейтрино	17		
1.3 Концепция проекта.....	18		
2. Искусственный тритиевый источник (анти)нейтрино (ТИН).....	19		
2.1 Свойства трития, его получение и влияние на организм человека	19		
2.2 Тритий в фундаментальных и прикладных исследованиях	20		
2.3 Истоки тритиевого эксперимента по поиску магнитного момента нейтрино.....	22		
2.4 Эволюция взглядов на конструкцию ТИН.....	25		
2.5 Выбор носителя трития.....	30		
2.6 Конструктивное исполнение тритиевого источника	32		
2.7 Время жизни тритиевого источника.....	35		
3. Система детектирования	37		
3.1 Концепция сцинтилляционного криогенного детектора нейтрино.....	39		
3.2 Устройство сцинтилляционных модулей.....	41		
3.3 Механика и криогеника детектора нейтрино.....	47		
3.4 Схема съема и обработки сигнала с детектора.....	49		
3.5 Предварительные результаты тестирования сцинтилляционных модулей детектора нейтрино.....	52		
3.6 Оценка ожидаемой чувствительности к магнитному моменту нейтрино (для CsI)	55		
3.7 Криогенный кремниевый детектор с эффектом теплового усиления и порогом регистрации менее 10 эВ.....	56		
3.8 Состояние разработок криогенных кремниевых детекторов с NTL-усилением в мире.	59		
3.9 СИН-термометры в качестве микрокалориметров.....	68		
		3.10 Оценка ожидаемой чувствительности к магнитному моменту нейтрино (для Si)79	
		3.11 Криогенный жидкогелиевый детектор с порогом регистрации менее 0,01 эВ	79
		3.12 Оценка ожидаемой чувствительности к магнитному моменту нейтрино (для He) ..	86
		4. Фоновые условия	88
		4.1 Требования к фоновым условиям	88
		4.2 Низкофоновая нейтринная лаборатория Сарова	90
		4.3 Низкофоновые условия в БНО.....	91
		5. Ключевые НИР и НИОКР	95
		5.1. Теоретические исследования фундаментальных свойств и взаимодействий нейтрино	95
		5.2. Теоретические исследования отклика разрабатываемых систем детектирования на низкоэнергетические внешние возмущения, вызываемые нейтрино и темной материей 96	
		5.3. Теоретический анализ возможностей использования трития для поиска реликтовых и стерильных нейтрино	96
		6. Прочие вопросы.....	97
		6.1 Коллаборация САТУРН.....	97
		6.2 Подготовка кадров.....	97
		6.3 Дополнительная инновационная и технологическая ценность проекта	98
		6.4 Благодарности	98
		Список литературы.....	98



Neutrino Unbound



Future Neutrino Experiments

<https://www.nu.to.infn.it>

-  **ANNIE** Neutrino Interactions ([Home](#), [INSPIRE](#), [Wikipedia](#))  [References](#)
-  **DUNE** Accelerator LBL Oscillations, Atmospheric and Supernova Neutrinos, Proton Decay ([Home](#), [INSPIRE](#), [Wikipedia](#))  [References](#)
-  **ECHO** Electron Neutrino Mass ([Home](#), [INSPIRE](#))  [References](#)
-  **ESSnuSB** Accelerator LBL Oscillations ([Home](#), [INSPIRE](#))  [References](#)
-  **GRAND** High-Energy Astrophysical Neutrinos ([Home](#), [INSPIRE](#))  [References](#)
-  **HOLMES** Electron Neutrino Mass ([Home](#), [INSPIRE](#))  [References](#)
-  **HUNT** High-Energy Astrophysical Neutrinos ([Home](#), [INSPIRE](#))  [References](#)
-  **Hyper-Kamiokande** Accelerator LBL Oscillations, Atmospheric and Supernova Neutrinos, Proton Decay ([Home](#), [INSPIRE](#), [Wikipedia](#))  [References](#)
-  **JSNS²** Accelerator SBL Oscillations, Experiment ([Home](#), [INSPIRE](#))  [References](#)
-  **JNE** Solar, Geo and Supernova Neutrinos ([Home](#), [INSPIRE](#))  [References](#)
-  **JUNO** Reactor LBL Oscillations, Atmospheric, Solar, Geo Neutrinos ([Home](#), [INSPIRE](#), [Wikipedia](#))  [References](#)
-  **LEGEND** Neutrinoless Double Beta Decay (⁷⁶Ge) ([Home](#))  [References](#)
-  **P-ONE** High-Energy Astrophysical Neutrinos ([Home](#), [INSPIRE](#))  [References](#)
-  **SATURNE** Coherent Elastic Neutrino-Atom Scattering ([INSPIRE](#))  [References](#)
-  **SBN** Accelerator SBL Oscillations, and Experiment ([Home](#), [INSPIRE](#))  [References](#)
-  **TRIDENT** High-Energy Astrophysical Neutrinos ([Home](#), [INSPIRE](#))  [References](#)
-  **WATCHMAN** Reactor Anti-Neutrino Monitor ([Home](#), [INSPIRE](#))  [References](#)

unique experiment to search for
CEvAS
and
study electromagnetic
properties of ν

Спасибо за внимание!