Проект САТУРН: поиск когерентного упругого рассеяния нейтрино на атомах и магнитного момента нейтрино

Сессия-конференция
Секции ядерной физики ОФН РАН
«Физика фундаментальных взаимодействий»
Институт ядерной физики им. Г.И. Будкера СО РАН
Новосибирск
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При поддержке гранта РНФ № 24-12-00084

Национальный центр
ФИЗИКИ и МАТЕМАТИКИ

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

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

Саровский
тритиевый
нейтринный
эксперимент
= САТУРН

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

Национальный центр физики и математики

В направление 8 «Физика изотопов водорода» включено

«Изучение когерентного рассеяния на атомах и ядрах и электромагнитных свойств ν с использованием интенсивного тритиевого источника (анти)нейтрино»

- 1) проверка справедливости Стандартной модели
- 2) измерение магнитного момента ν с рекордной точностью

! (на два порядка лучше, чем из существующих измерений потоков реакторных нейтрино …) !

Исследования электромагнитных свойств V

- … предыстория
- … результаты
- … перспективы

!

- … вклад российских ученых (RU)
- … проект САТУРН в Национальном центре физики и математики

(RU)

630 цитирований

2009

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

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

Neutrino electromagnetic interactions: A window to new physics

+ upgrade:

Studenikin, *Electromagnetic properties of neutrino 2023*, Physics of Particles and Nuclei 55 (2024) 1444

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

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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

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NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS

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Neutrino magnetic moment: a window to new physics

A. Studenikin[a] *

[a]Department of Theoretical Physics, Moscow State University, 119991 Moscow, Russia

A short review on a neutrino magnetic moment is presented.

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 evaluation that exactly accounts for $a_l = \frac{m_l^2}{M_W^2}$ ($l = e, \mu, \tau$), leads the following result [4],

$$\mu_{ij}^D = \frac{eG_F m_i}{8\sqrt{2}\pi^2}\Big(1 + \frac{m_j}{m_i}\Big)\sum_{l=e,\mu,\tau} f(a_l)U_{lj}U_{li}^*, \quad (2)$$

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

where U_{li} 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 $a_l \ll 1$ the result [1] can be obtained

$$\mu_{ii}^D = \frac{3eG_F m_i}{8\sqrt{2}\pi^2}\Big(1 - \frac{1}{2}\sum_{l=e,\mu,\tau} a_l \mid U_{li}\mid^2\Big). \quad (3)$$

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

$$\mu_\nu = \frac{eG_F m_\nu}{8\sqrt{2}\pi^2}\begin{cases} 3 + \frac{5}{6}b, & m_l \ll m_\nu \ll M_W, \\ 1, & m_l \ll M_W \ll m_\nu. \end{cases} \quad (4)$$

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

(5)

maller than account for asses.

International Journal of Modern Physics E
(2024) 2441033 (13 pages)

DOI: 10.1142/S0218301324410337

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(RU)

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

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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.

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

Neutrino Electromagnetic Properties

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

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.

- Предыстория

современных исследований магнитного момента ν

ν exhibits unexpected properties (puzzles)

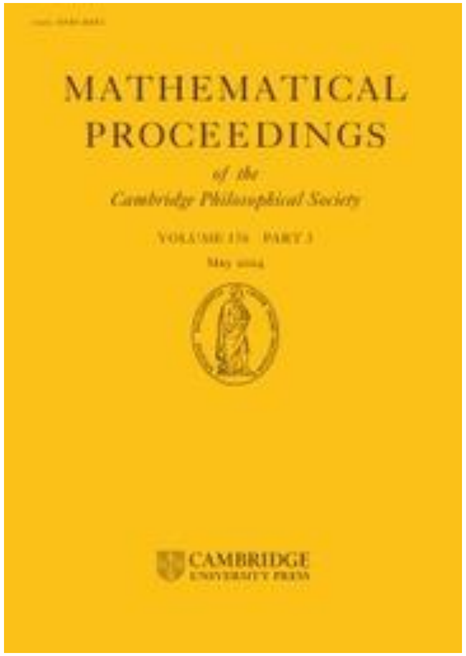
W. Pauli, 1930

neutral "neutron" $\Rightarrow$ ν E.Fermi 1933

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

Pauli himself wrote to Baade:

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



M.E. Nahmias,

An attempt to detect the neutrino,

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

... earlier years of ν ...

AN ATTEMPT TO DETECT THE NEUTRINO

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

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

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

... 90 years ago...

I. Experiments with a source of radium D and E

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

An attempt to detect the neutrino 101

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

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

> 70 years ago ...

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

ν electromagnetic properties

and possibility of measuring μ_ν

raised before experimental discovery of ν

1995

«за доказательство существования нейтрино»
(Ф.Райнес, К.Коуэн, 1956)

... problem and puzzle ...

ν electromagnetic properties

up to now nothing has been seen

... in spite of reasonable efforts ...

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

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

... Почему важны электромагнитные свойства ν ?

... Почему эм свойства ν

в новую физику ?

... Как все это связано с осцилляциями ν ?

Артур Макдональд
(Arthur McDonald)
1943 г.р.

работает
в Королевском
Университете,
Кингстон,
Канада

Нобелевская премия
2015 года по физике

объявлено
Шведской королевской
академией наук
6 октября 2015 года

« за открытие
осцилляций нейтрино,
что доказывает
наличие у нейтрино
ненулевой массы » !

Такааки Каджита
(Takaaki Kajita)
1959 г.р.

работает
в Университете
Токио, Япония

$\Rightarrow$ $m_\nu \neq 0$ ●

магнитный момент $\mu_\nu \neq 0$ ●

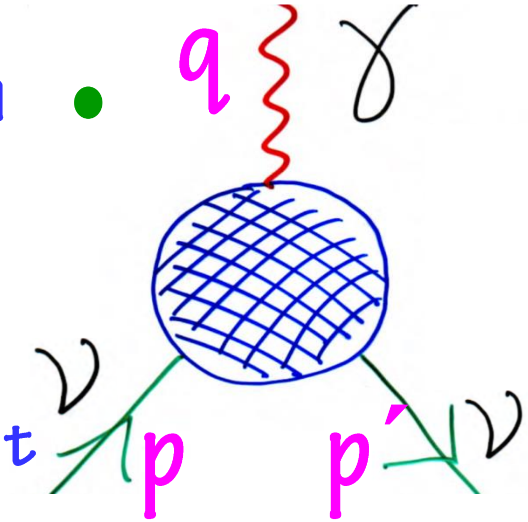
в Стандартной модели
элементарных частиц
$m_\nu = 0$!!! ●

Электромагнитные свойства ν

открывают окно в новую физику

… a bit of ν electromagnetic properties theory …

electromagnetic vertex function



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

Matrix element of electromagnetic current is a Lorentz vector

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

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

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

vectors q_μ and l_μ

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

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

Matrix element of electromagnetic current between neutrino states

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

where vertex function generally contains 4 form factors

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

1. electric
2. magnetic dipole
3. electric dipole
4. anapole

- Hermiticity and discrete symmetries of EM current $J_\mu^{\rm EM}$ put constraints on form factors

Dirac ν

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

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

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

!

Majorana ν

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

$$f_Q = f_M = f_E = 0$$

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

EM properties ⟹ a way to distinguish Dirac and Majorana ν

- форм-факторы при $q = 0$: $f_M(0) = \mu_\nu$ магнитный момент

In the easiest generalization of SM

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

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

if $m_\nu \leq 0.45\ eV$ ⟸ new KATRIN limit arXiv: 2406.13516, 19 Jun 2024

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

many orders of magnitude smaller than present experimental limits:

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

Экспериментальные (лабораторные) ограничения на магнитный момент нейтрино

по упругому рассеянию нейтрино на частицах мишени

- на электронах

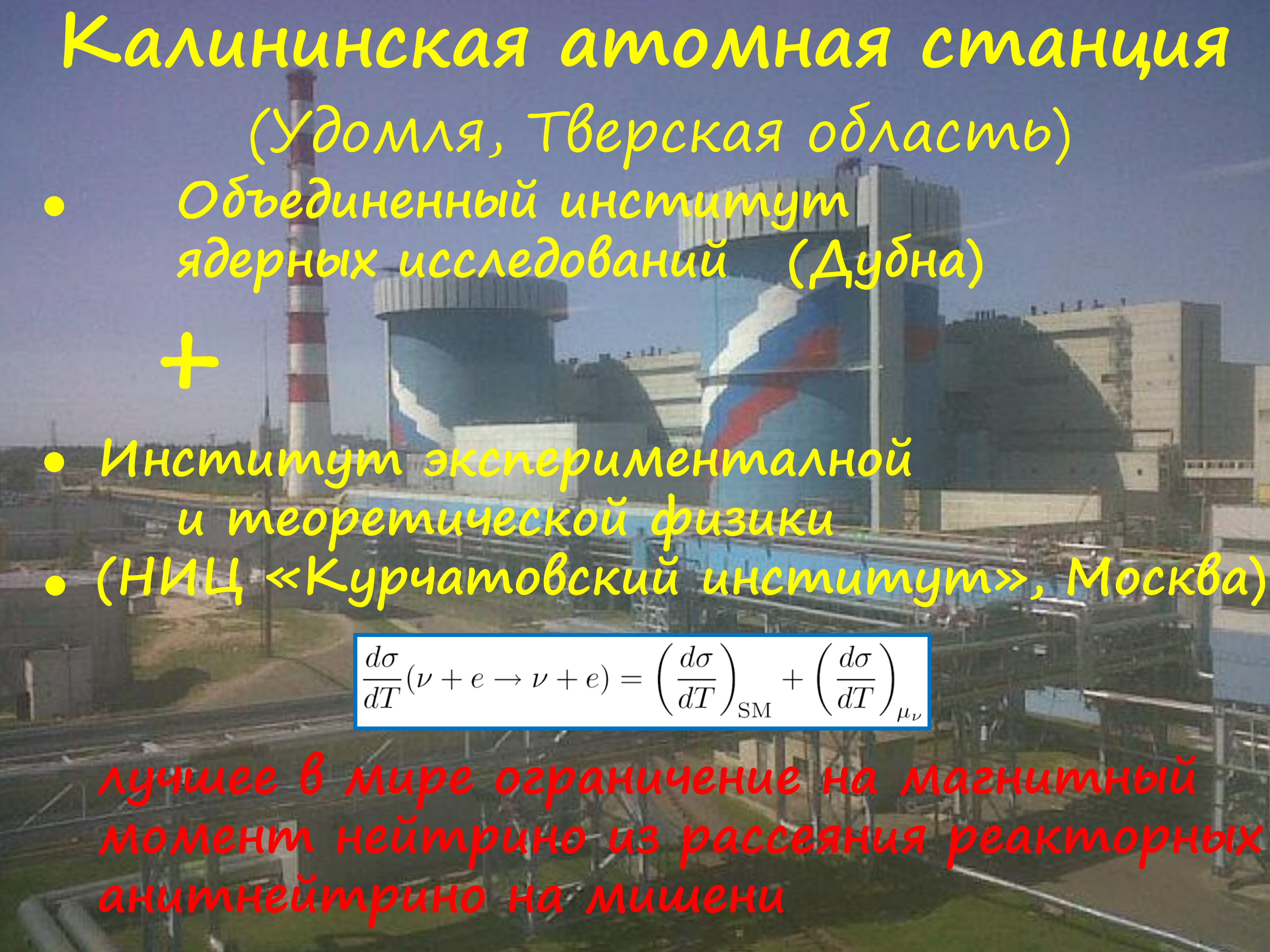
Elastic Neutrino-Electron Scattering **EνES**

- на атомных ядрах

Coherent Elastic Neutrino-Nucleus Scattering **CEνNS**

- на атомах Coherent Elastic Neutrino-Atom Scattering **CEνAS**

Проект САТУРН!



Калининская атомная станция

(Удомля, Тверская область)

- Объединенный институт ядерных исследований (Дубна)

\+

- Институт эксперименталной и теоретической физики
- (НИЦ «Курчатовский институт», Москва)

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

лучшее в мире ограничение на магнитный момент нейтрино из рассеяния реакторных анитнейтрино на мишени

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

Cross-section:

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

where the Standard Model contribution

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

T is the electron recoil energy and

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

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

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

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

for anti-neutrinos $g_A \to -g_A$

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

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 $T \sim 200 \quad eV$

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

~ few years in future ?

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

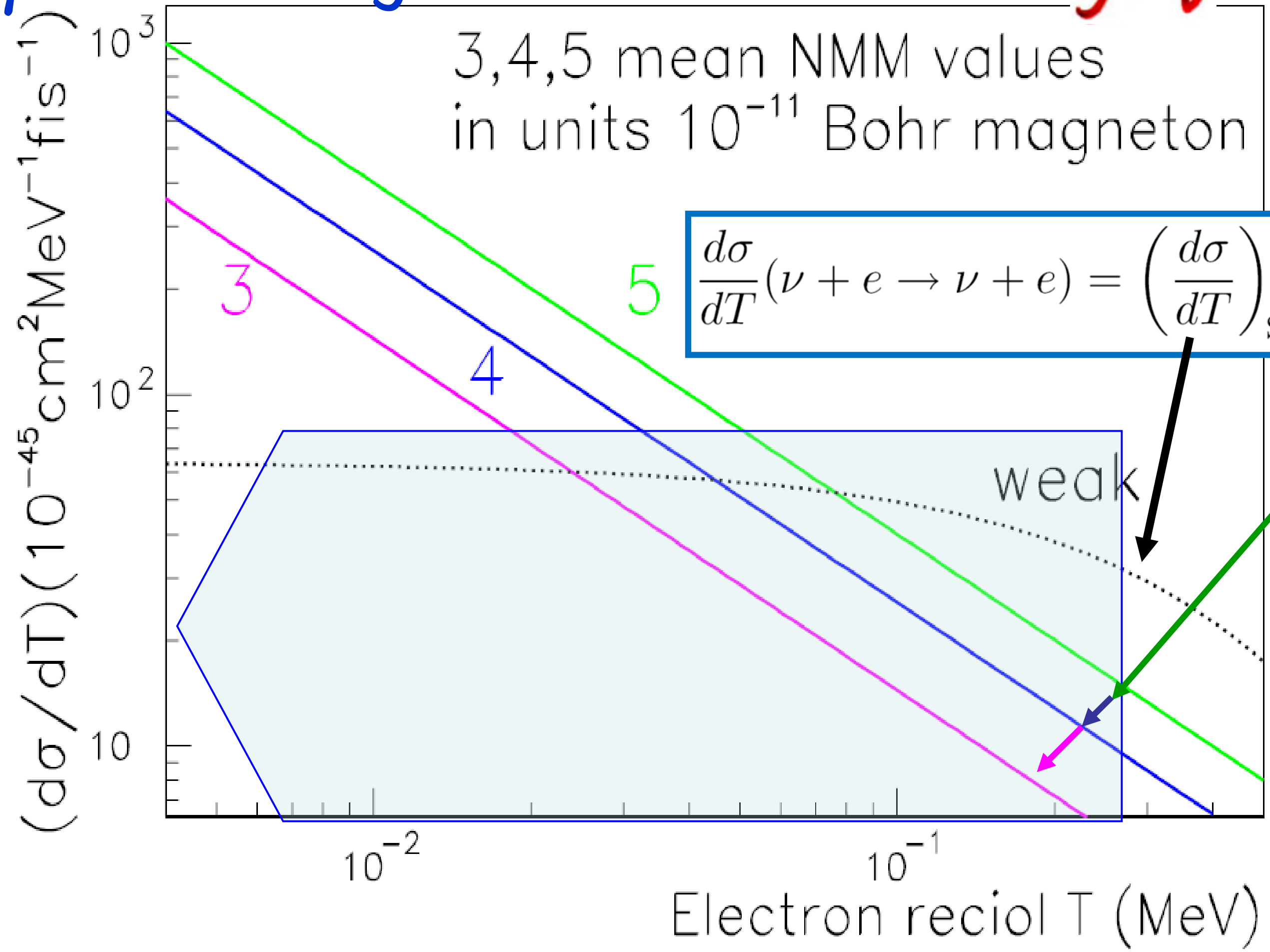
Вклад от μ_ν доминирует при малых энергиях отдачи e

$$\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} > \left(\frac{d\sigma}{dT}\right)_{SM}$$

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

… с уменьшением измеряемой энергии отдачи e возрастает чувствительность к μ_ν …

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



Ограничение на миллизаряд q_ν нейтрино

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

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

Studenikin, “New bounds on neutrino electric millicharge from limits on neutrino magnetic moment”, Europhys. Lett. 107 (2014) 21001

Ограничение на q_ν из условия

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

Particle Data Group, 2016-2018-2020-2022-2024 !

Ограничение на μ_ν

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

202? (ожидается)

$\mu_\nu^a \sim 0.7 \times 10^{-12}\ \mu_B$

$T \sim 200\ \ eV$ … беспрецедентно низкий порог …

Ограничение на q_ν

$| q_\nu | < 1.5 \times 10^{-12} e_0$ 2014

$|q_\nu| < 1.1 \times 10^{-13} e_0$ Studenikin, 2016

Mitglied der Helmholtz-Gemeinschaft

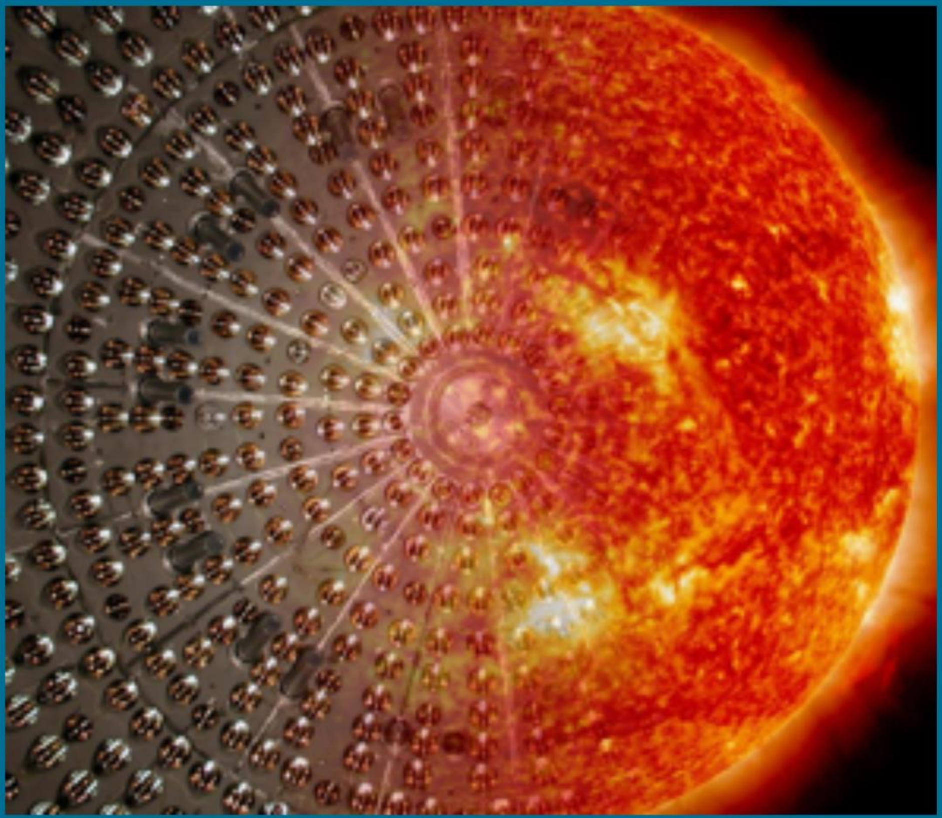
TAUP 2017
Topics in Astroparticle and Underground Physics

JÜLICH
FORSCHUNGSZENTRUM

Limiting the effective magnetic moment of solar neutrinos with the Borexino detector

Livia Ludhova
on behalf of
the Borexino collaboration

IKP-2 FZ Jülich,
RWTH Aachen,
and JARA Institute, Germany



Phys. Rev. D 96 (2017) 091103

Limiting μ_ν with Borexino Phase-II solar neutrino data

NEW

BOREXINO Collaboration (2017)
NMM results from Phase 2

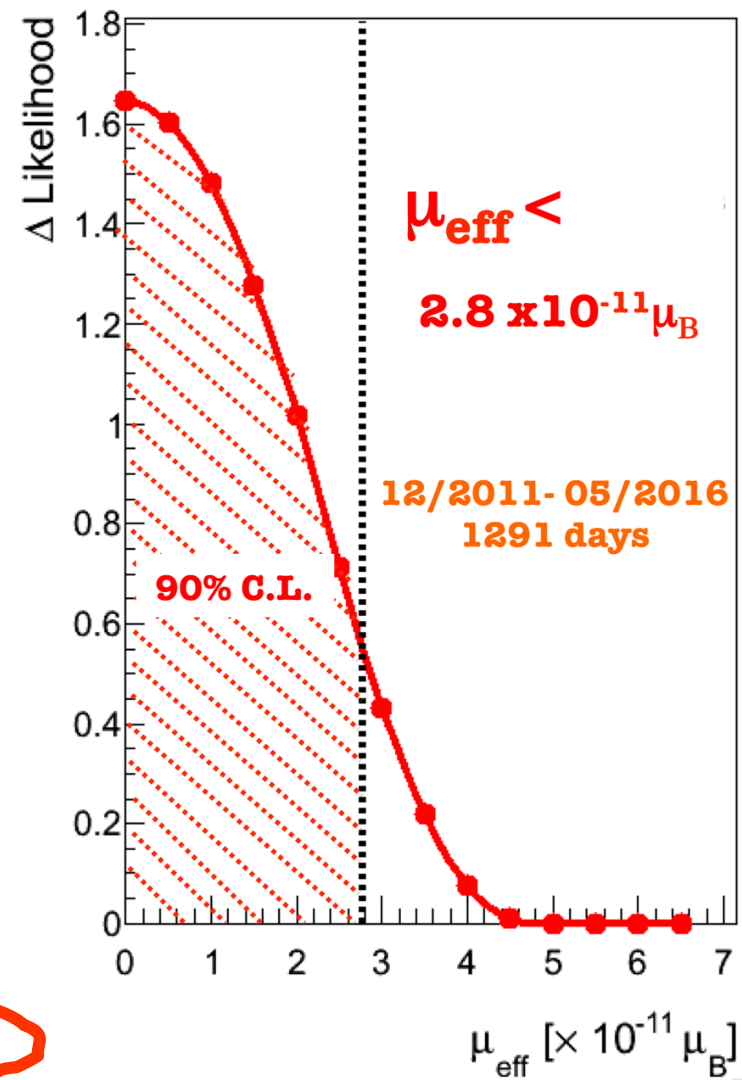
JÜLICH FORSCHUNGSZENTRUM

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

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

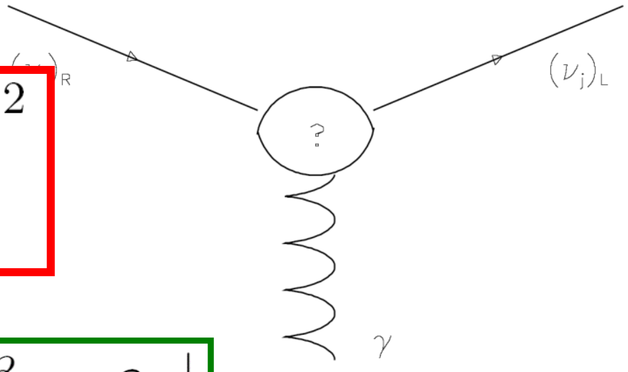
With radiochemical constraint
$\mu_{eff} < 2.6 \times 10^{-11} \mu_B$ (90% C.L.)
adding systematics
$\mu_{eff} < 2.8 \times 10^{-11} \mu_B$ **(90% C.L.)**

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



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 U_{li} – neutrino mixing matrix

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

(β_{ij}, ε_{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.

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

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

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

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

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

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

effect of decoherence

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

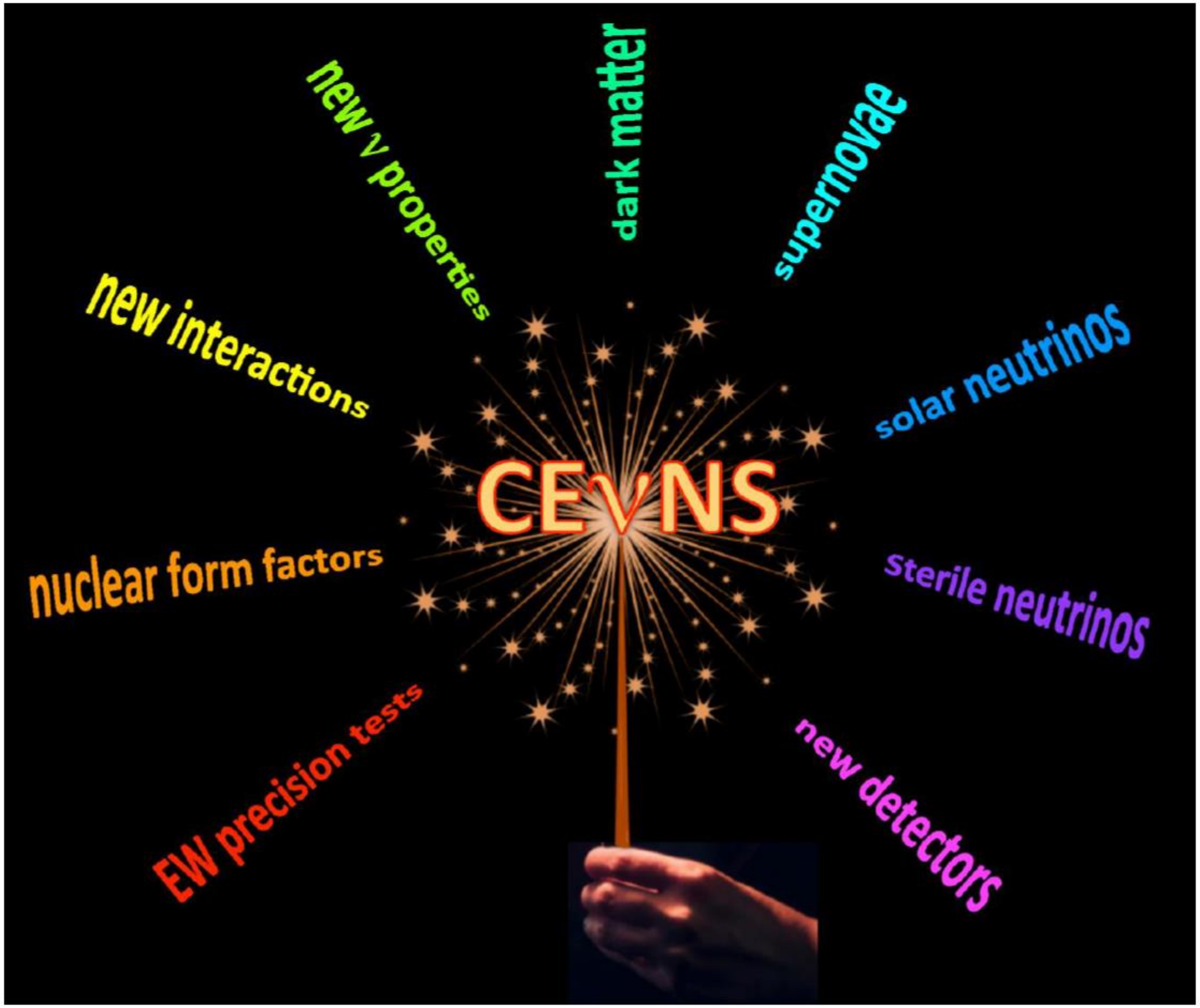
$$C_2 = g_A^2 + 2g_A P_{\nu_\ell \to \nu_e} + P_{\nu_\ell \to \nu_e}$$

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

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

CEνNS potential in studies new physics



[E. Lisi, Neutrino 2018]

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

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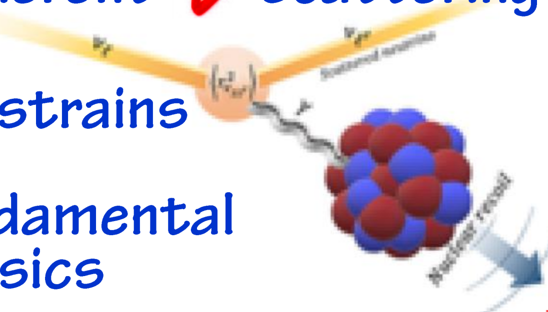
Abstract: We explore the potential of current and next generation of coherent elastic neutrino-nucleus scattering (CEνNS) experiments in probing neutrino electromagnetic interactions. On the basis of a thorough statistical analysis, we determine the sensitivities on each component of the Majorana neutrino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

- 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

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

Method	Experiment	Limit (μ_B)	CL	Year
Reactor $\bar{\nu}_e$ EνES	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 EνES	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $\nu_\mu, \bar{\nu}_\mu$ EνES	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 $\nu_\tau, \bar{\nu}_\tau$ EνES	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)	$\mu_{\nu_e} < 4.2 \times 10^{-9}$ $\mu_{\nu_\mu} < 1.8 \times 10^{-9}$	90%	2022
Reactor $\bar{\nu}_e$ CEνNS + EνES	Dresden-II (65)[a]	$\mu_{\nu_e} < 2.1 \times 10^{-10}$	90%	2022
$e^+e^- \to \nu\bar{\nu}\gamma$ (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,

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

Method	Experiment	Limit (μ_B)	CL	Year
Solar elastic neutrino–electron scattering	Super-Kamiokande	$\mu_S^{HE} < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_S^{LE} < 2.8 \times 10^{-11}$ $\mu_{\nu_e} < 3.9 \times 10^{-11}$ $\mu_{\nu_\mu}, \mu_{\nu_\tau} < 5.8 \times 10^{-11}$	90%	2017
	XMASS-I	$\mu_S^{LE} < 1.8 \times 10^{-10}$	90%	2020
	XENONnT	$\mu_S^{LE} < 6.4 \times 10^{-12}$	90%	2022
	LUX-ZEPLIN	$\mu_S^{LE} < 1.36 \times 10^{-11}$	90%	2023
	PandaX-4T	$\mu_S^{LE} < 2.2 \times 10^{-11}$	90%	2024
	LUX-ZEPLIN (74)	$\mu_S^{LE} < 1.1 \times 10^{-11}$ $\mu_{\nu_e} < 1.5 \times 10^{-11}$ $\mu_{\nu_\mu} < 2.3 \times 10^{-11}$ $\mu_{\nu_\tau} < 2.1 \times 10^{-11}$	90%	2022
	XENONnT (71)	$\mu_S^{LE} < 6.3 \times 10^{-12}$ $\mu_{\nu_e} < 8.5 \times 10^{-12}$ $\mu_{\nu_\mu} < 1.4 \times 10^{-11}$ $\mu_{\nu_\tau} < 1.2 \times 10^{-11}$	90%	2022
	XENONnT (71)	$\mu_{\nu_e} < 9.0 \times 10^{-12}$ $\mu_{\nu_\mu} < 1.5 \times 10^{-11}$ $\mu_{\nu_\tau} < 1.3 \times 10^{-11}$	90%	2022
	LUX-ZEPLIN (74) + PandaX-4T (78) + XENONnT (71)	$\mu_S^{LE} < 7.5 \times 10^{-12}$ $\mu_{\nu_e} < 1.0 \times 10^{-11}$ $\mu_{\nu_\mu}, \mu_{\nu_\tau} < 1.6 \times 10^{-11}$	90%	2023
Core-collapse supernovae		$\mu_\nu \lesssim (2\text{–}8) \times 10^{-12}$		1988
		$\mu_\nu \lesssim (1\text{–}4) \times 10^{-12}$		1998
		$\mu_\nu \lesssim (1.1\text{–}2.7) \times 10^{-12}$		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
		$\mu_\nu \lesssim (1\text{–}5) \times 10^{-12}$		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		$\mu_\nu \lesssim (7\text{–}9) \times 10^{-12}$		2014
		$\mu_\nu < 5 \times 10^{-12}$	95%	2014
Big bang nucleosynthesis		$\mu_\nu \lesssim (1\text{–}2) \times 10^{-11}$		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,

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

CEνNS vs CEνAS Y.Gaponov, V.Tikhonov, Yad.Fiz. 26 (1977) 594

CEνNS: 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

CEνNS

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

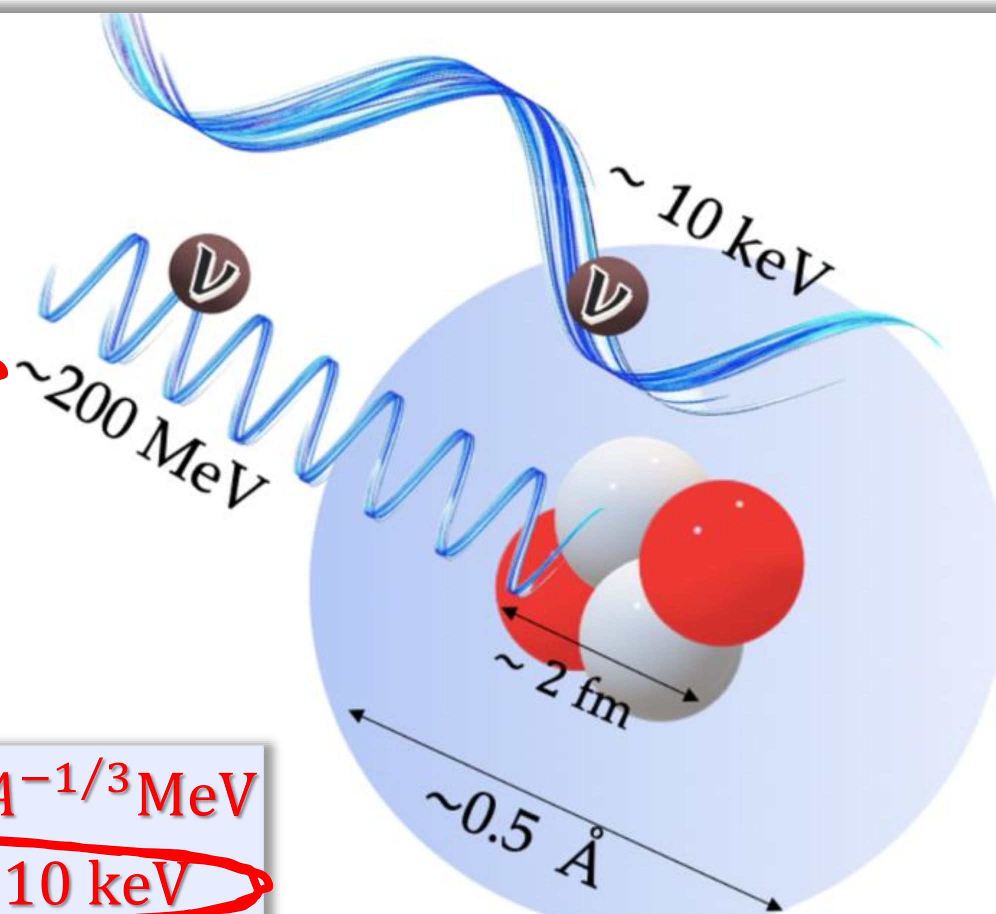
$\vec{q}$ is the momentum transfer

R_{nuc} is the nuclear radius

CEνAS

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

R_{atom} is the atomic radius



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

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

Если реализуется режим CEνAS, то реализуется и CEνNS

Измерения процесса CEνAS в эксперименте САТУРН

Упругое рассеяние ν на атоме He-4:

$$\overline{\nu_e} + \mathrm{He} \to \mathrm{He} + \overline{\nu_\ell} \qquad Q = 18.6\ \mathrm{keV}$$

Сечение (T – энергия отдачи атома)

$$\frac{d\sigma^{CE\nu AS}}{dT} = \frac{d\sigma^{CE\nu AS}_{SM}}{dT} + \frac{d\sigma^{CE\nu AS}_{\mu_\nu}}{dT} \qquad t_{1/2} = 12.3\ \mathrm{yrs}$$

$\langle E_{\overline{\nu}_e} \rangle = 12.9\ \mathrm{keV}$

тритиевые ν
+
гелиевая мишень
=
CEνAS

Вклад слабого взаимодействия (СМ)

$$\frac{d\sigma^{CE\nu AS}_{SM}}{dT} = \frac{G_F^2 M_{He}}{\pi} C_V^2 \left(1 - \frac{M_{He} T}{2E_\nu^2}\right),$$

$$C_V = Z\left(\frac{1}{2} - 2\sin^2\theta_W\right) - \frac{1}{2}N + Z\left(\frac{1}{2} + 2\sin^2\theta_W\right) F_{el}(|\vec{q}|),$$

Z=N=2 число p и n в ядре He-4, $M_{He} = 3.728$ ГэВ масса атома He-4

$F_{el}(|\vec{q}|)$ атомный электронный формфактор (фурье-образ нормированной на ед. электронной плотности в атоме He-4)

Вклад магнитного момента μ_ν

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

Atomic recoil energy scale in CEνAS

From conservation of energy and momentum:

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

T_R is atomic recoil energy

$m \approx A$ GeV is atomic mass

In the reactor CEνNS experiment CONNIE: Threshold is 15 eV$_{ee}$ (with CCD sensors)

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

If E_ν~10 keV: $T_R \lesssim \frac{200}{A}$ meV

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

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

(RU)

- проект измерения (впервые) когерентного упругого рассеяния ν на атоме

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

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

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

DOI: 10.1103/PhysRevD.100.073014

I. INTRODUCTION

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

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

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

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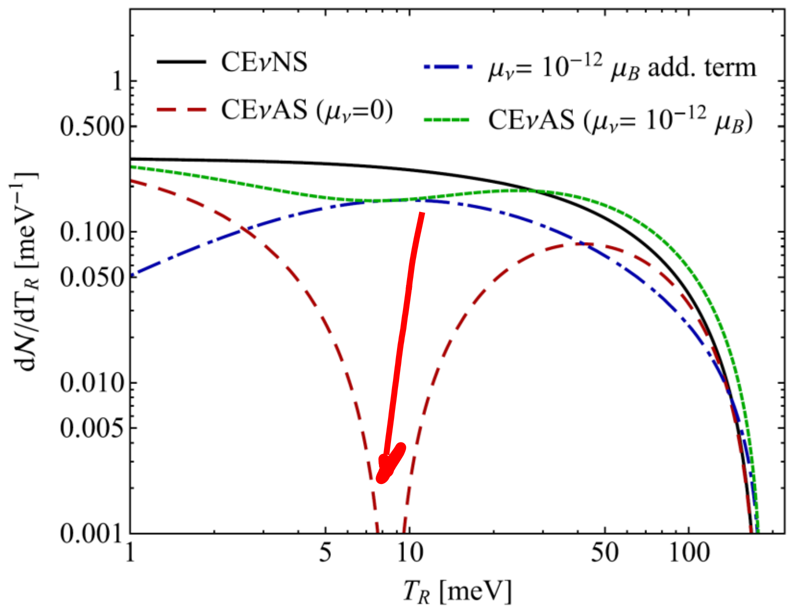
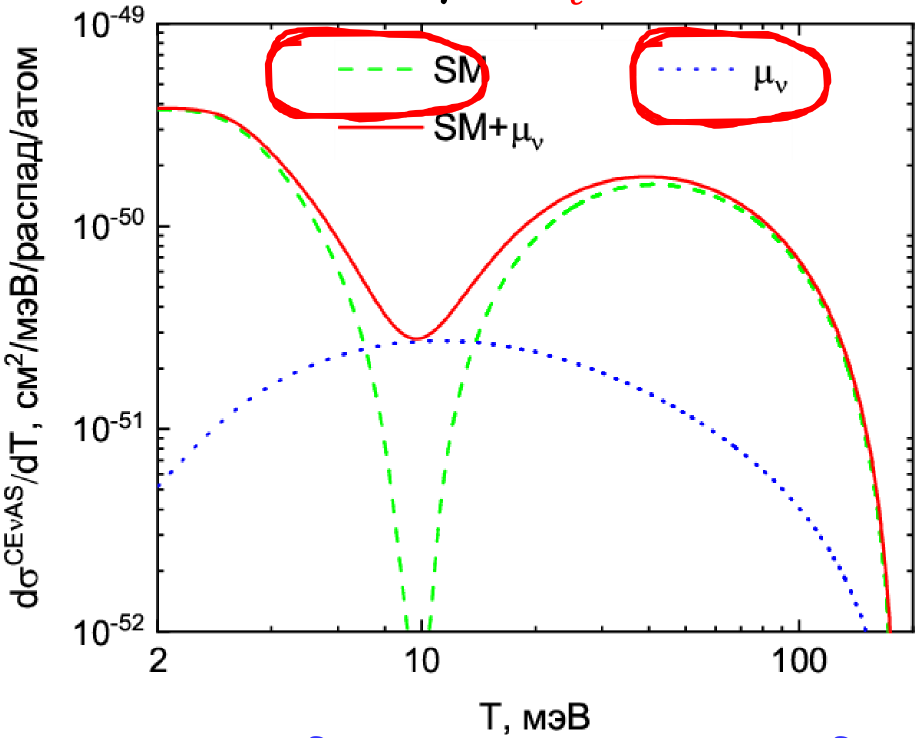


получение рекордного ограничения (60 г ^{3}H)

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

(или обнаружение μ_ν)

Дифференциальное сечение CEvAS (сплошная линия), усредненное по спектру тритиевых нейтрино, в случае атомной He-4 мишени при $\mu_{\overline{\nu_e}} = 3 \times 10^{-13}\,\mu_B$

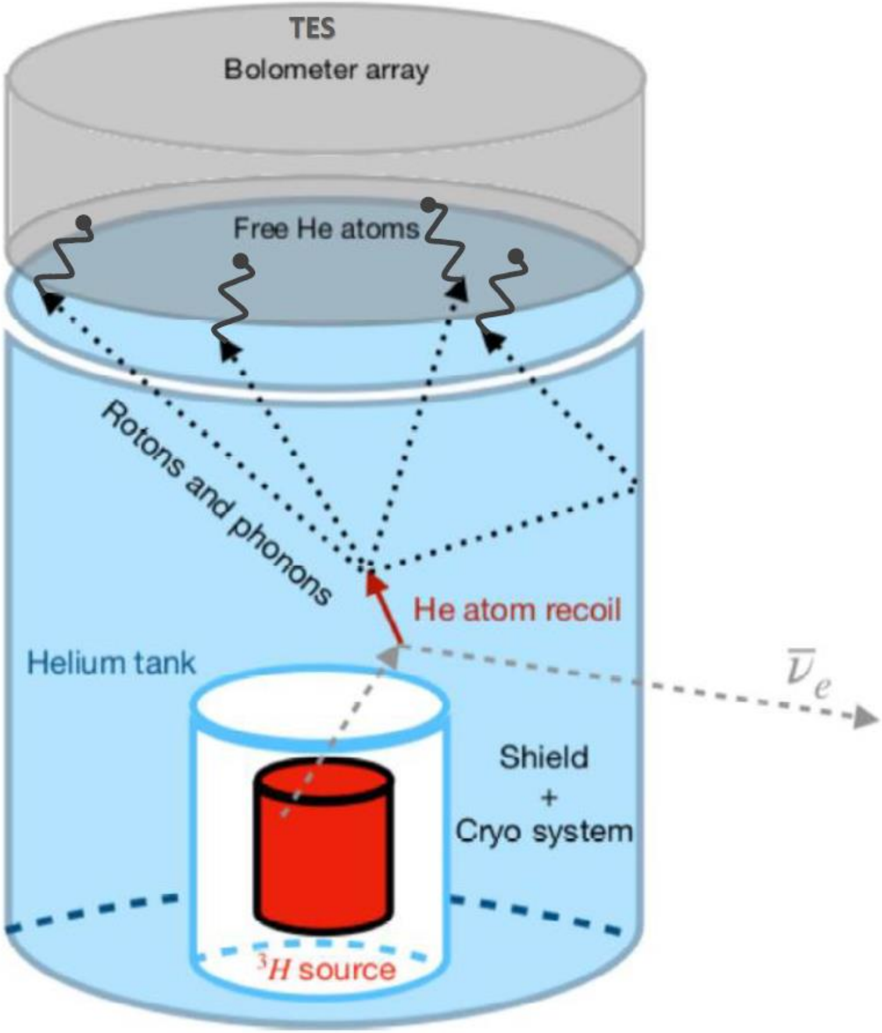


- Усредненное сечение задает (с точностью до размерного коэффициента) спектр атомов отдачи при CEvAS.

- Полное зануление спектра в СМ при T~ 9 мэВ – экранировке слабого заряда ядра полем слабого взаимодействия атомных электронов .

- Вклад μ_ν приводит к сильному отклонению от предсказания СМ .

Detection method to study CEνAS



Tritium neutrino

↓

Elastic neutrino-atom scattering

↓

He atom recoil (1-185 meV)

↓

Phonons and rotons (0.7-1.2 meV per q. p.)

↓

Quantum evaporation (0.6 meV per atom)

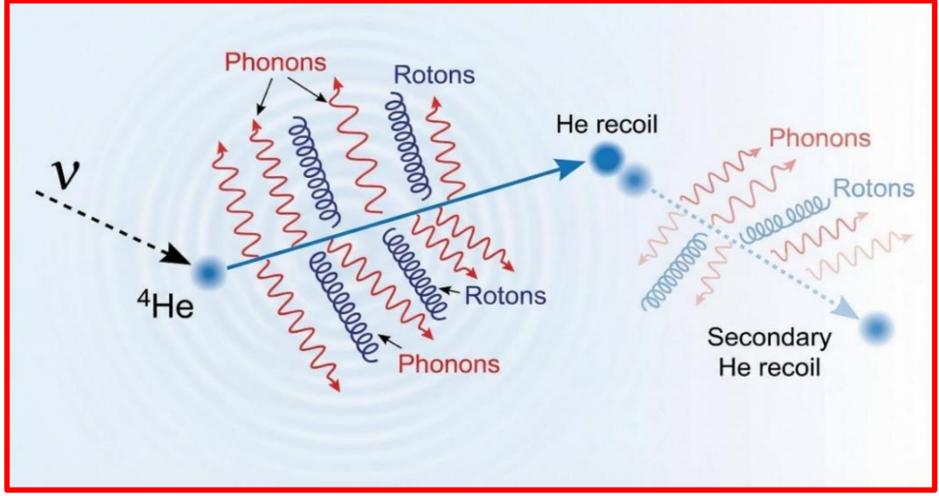
↓

Adsorption onto TES (6-50 meV per adatom)

↓

Signal

Исходная идея САТУРН :



1) энергия отдачи атома ^{4}He от $\nu_{^3He}$ примерно 100 мэВ

2) основной канал потери энергии ^{4}He – коллективные возбуждения (фононы+ротоны)

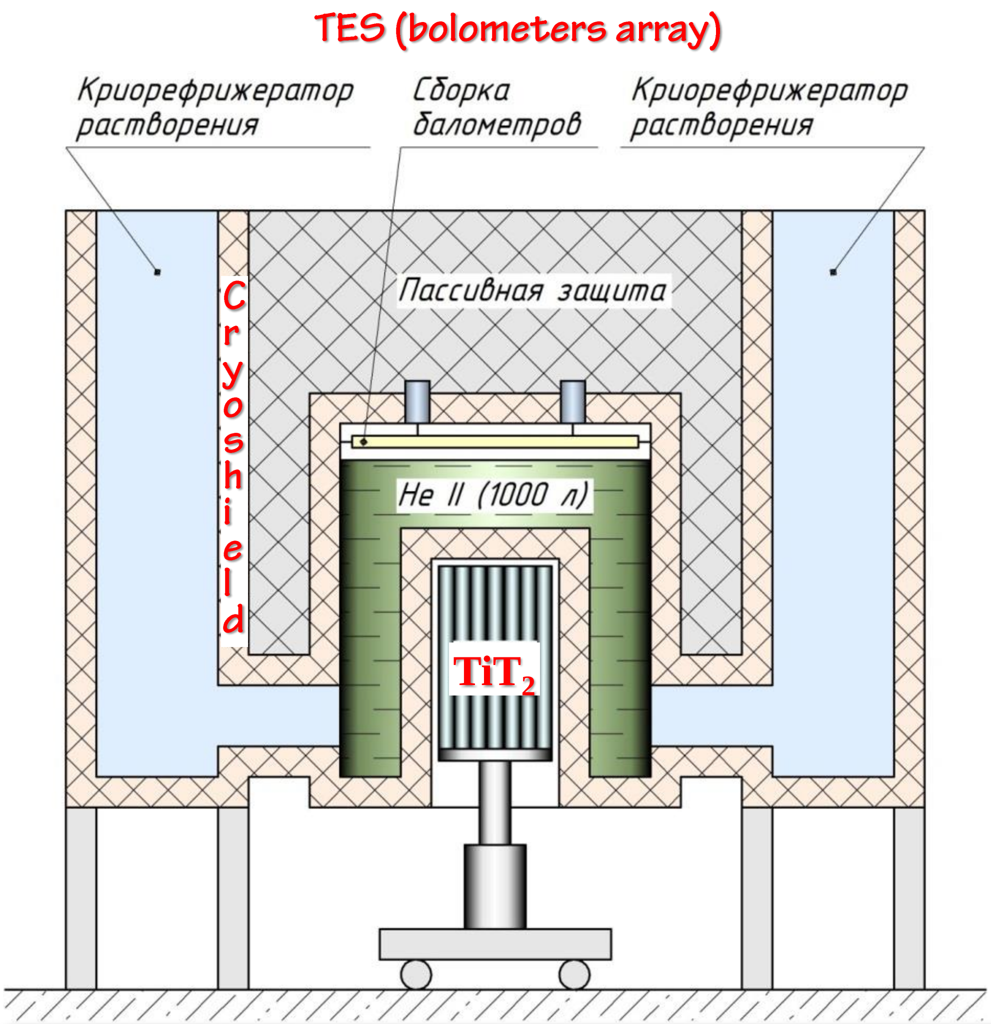
3) баллистически до поверхности–квантовое испарение ^{4}He

4) адсорбируются на подложке болометра (детектора)

5) за счет адсорбции – Ван-дер-Вальсово усиление

6) сигнал в десятки мэВ измеряется микрокалориметрами на основе TES (transition edge sensors)

He II detector concept to study CEνAS

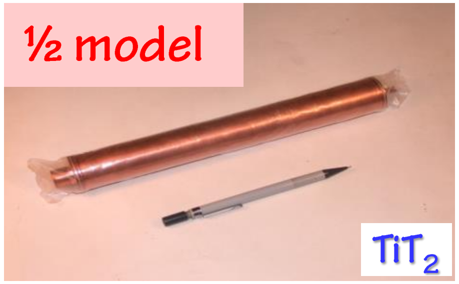


Tritium neutrino source (TNS)

1-4 kg, 10-40 MCi

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

- Tubular elements with TiT_2



тритидтитана

Helium II detector (1000 L)

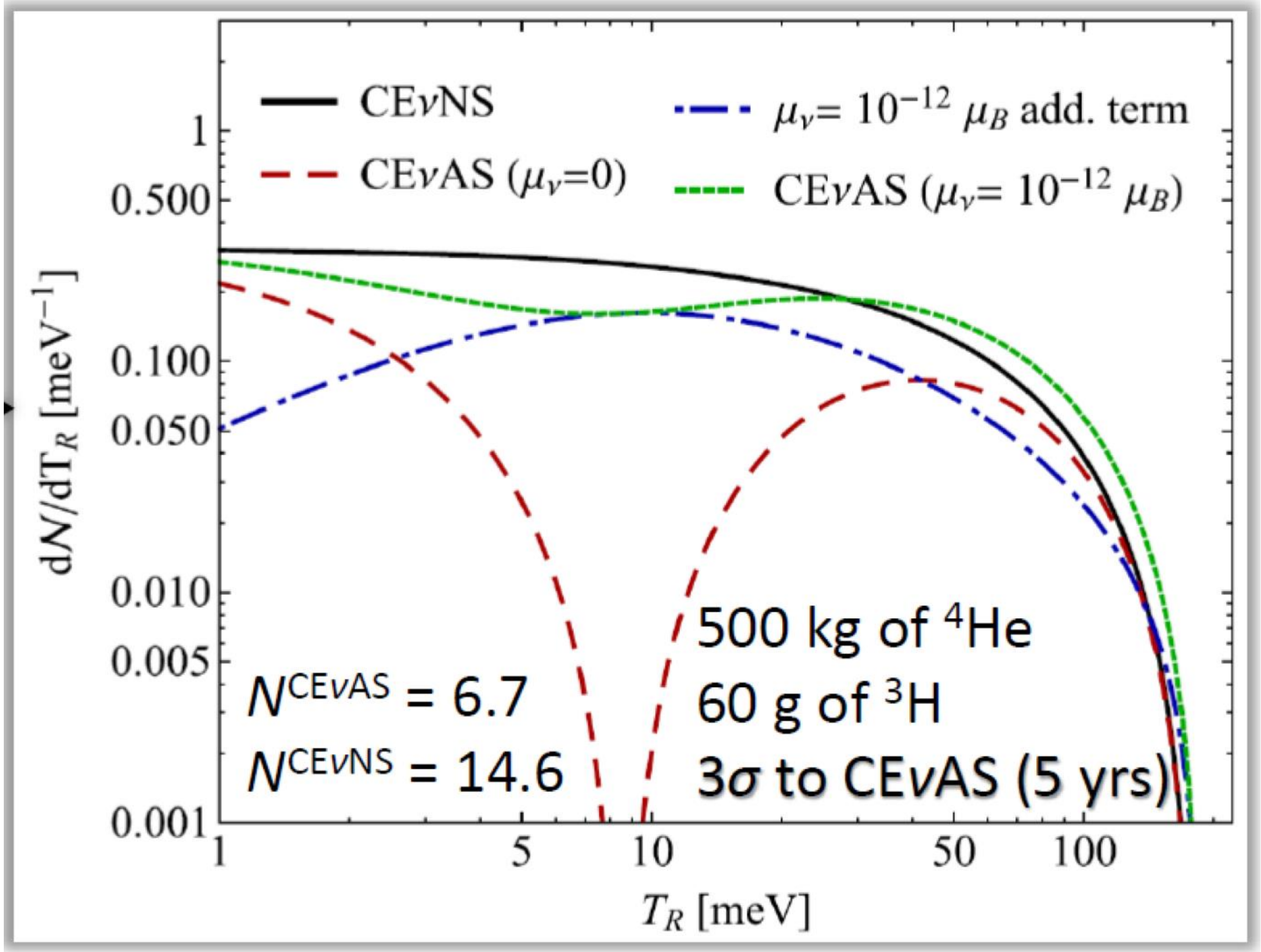
- Liquid He-4 at 40-60 mK
- Array of 1000 TESs (transition edge sensors)
- 1000-channel SQUID readout

Expected results after 5 years of data collection:

- number of CEνAS events within SM: 60 for 1 kg of T_2 and 200 for 4 kg of T_2
- sensitivity to neutrino magnetic moment: $\mu_\nu \sim (2\text{-}4)\times 10^{-13}\ \mu_B$ at 90% C.L.

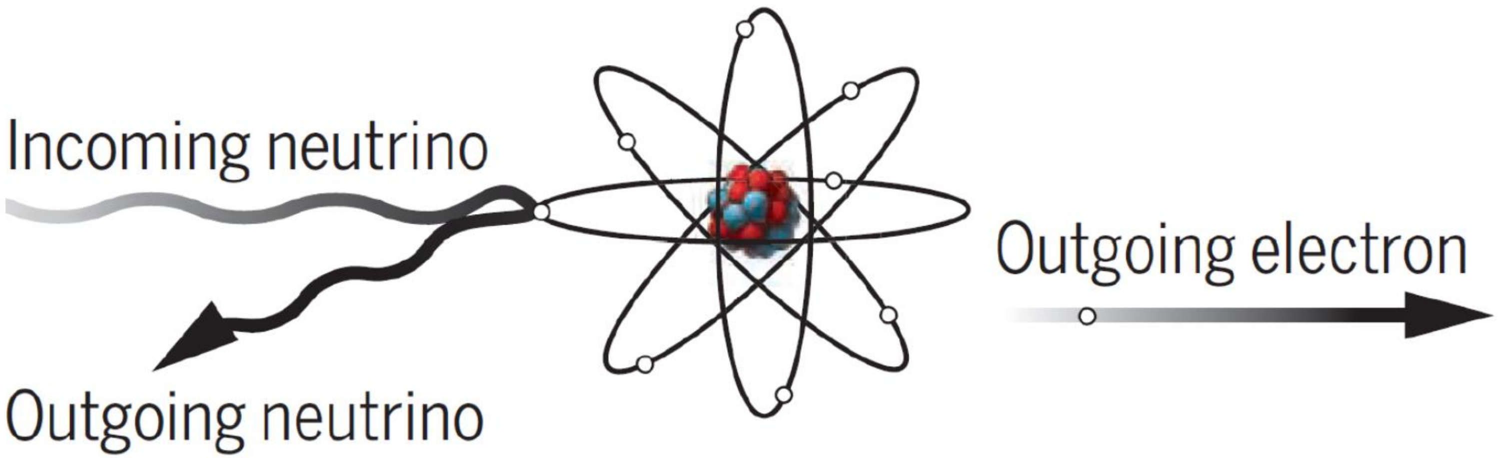
Возможность наблюдать CEνAS

(~ в 2 раза меньше событий, чем только с учетом режима при CEνNS, без учета атомных электронов)



M. Cadeddu, F. Dordei, C. Giunti, K. Kouzakov, E. Picciau, A. Studenikin, PRD **100** (2019) 073014

Atomic ionization channel



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

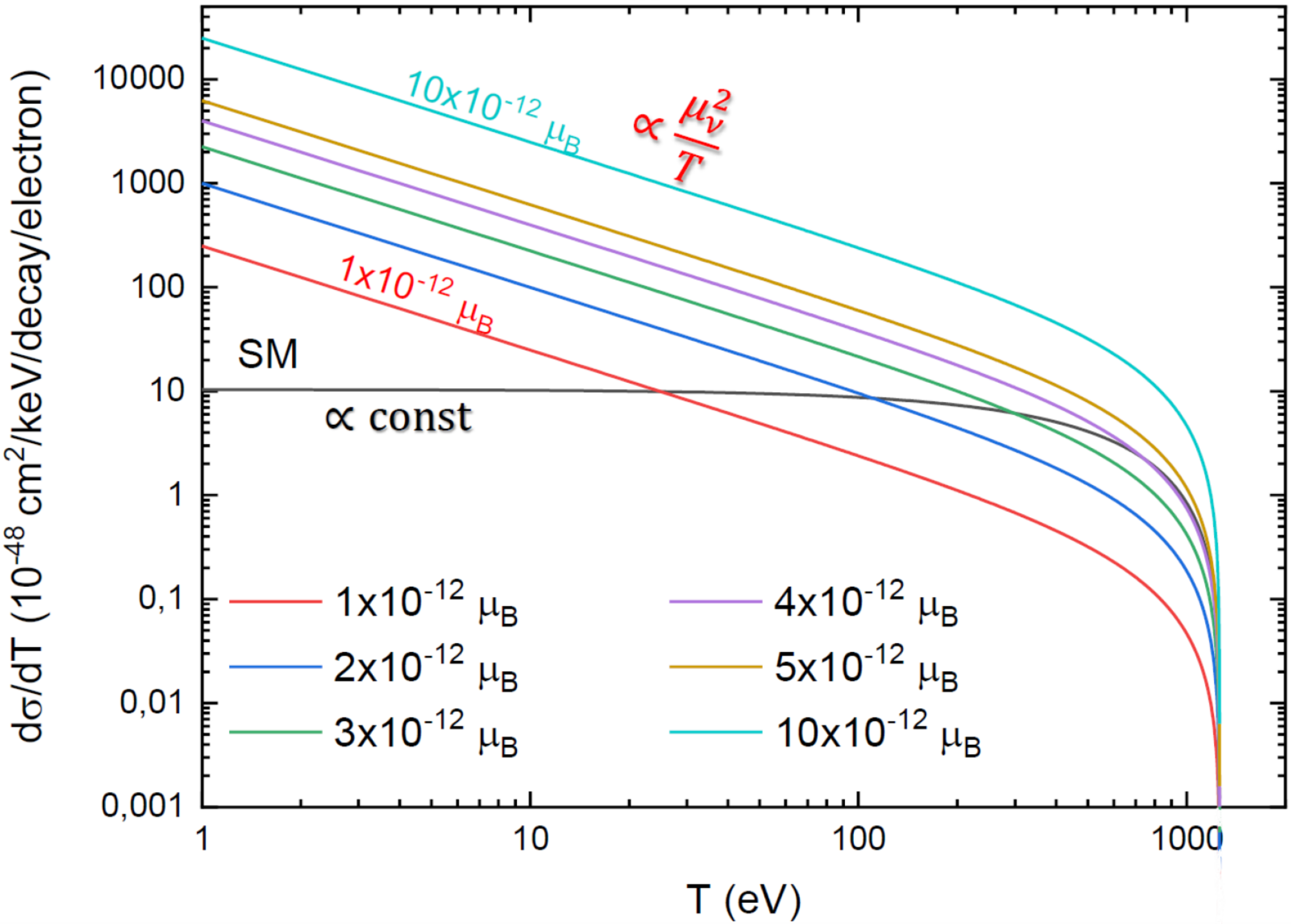
In **SATURNE** we develop

- 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 $\bar{\nu}_e$

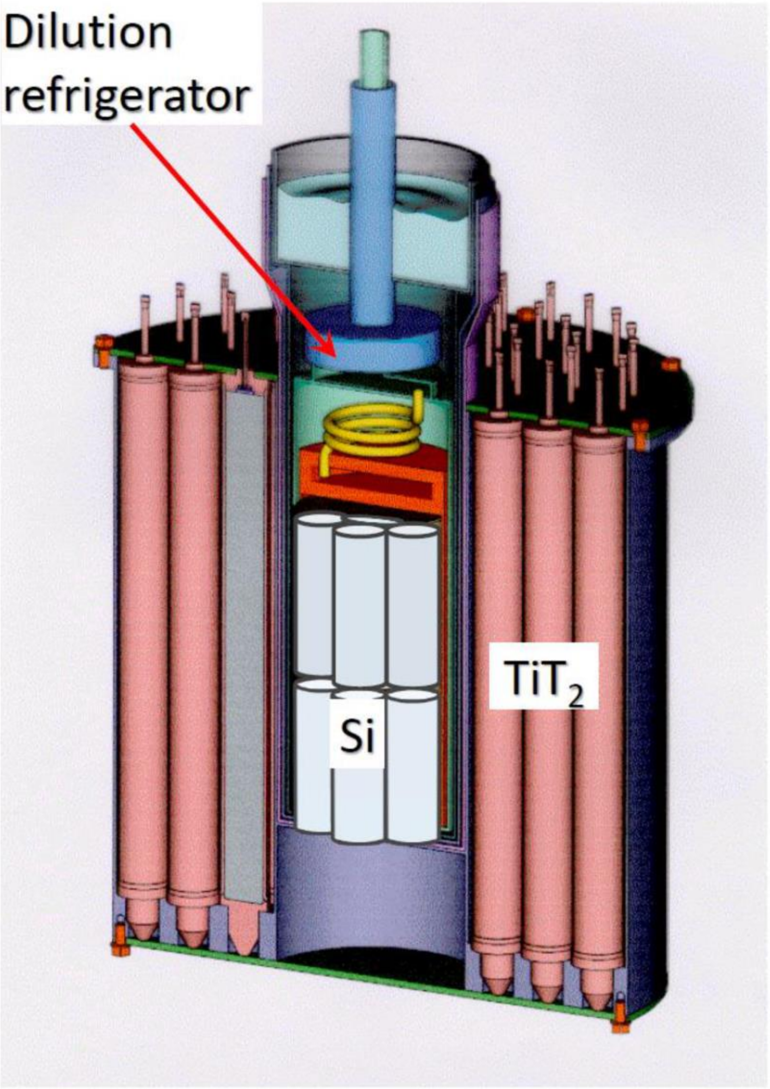
At small T values: $\frac{d\sigma_{SM}}{dT} \propto \text{const}$, and $\frac{d\sigma_{(\mu)}}{dT} \propto \frac{\mu_\nu^2}{T}$

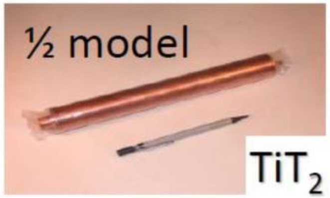


The detector's energy threshold is to be as low as possible

Si detector concept

на базе ОИЯИ





Tritium neutrino source (1-4 kg)

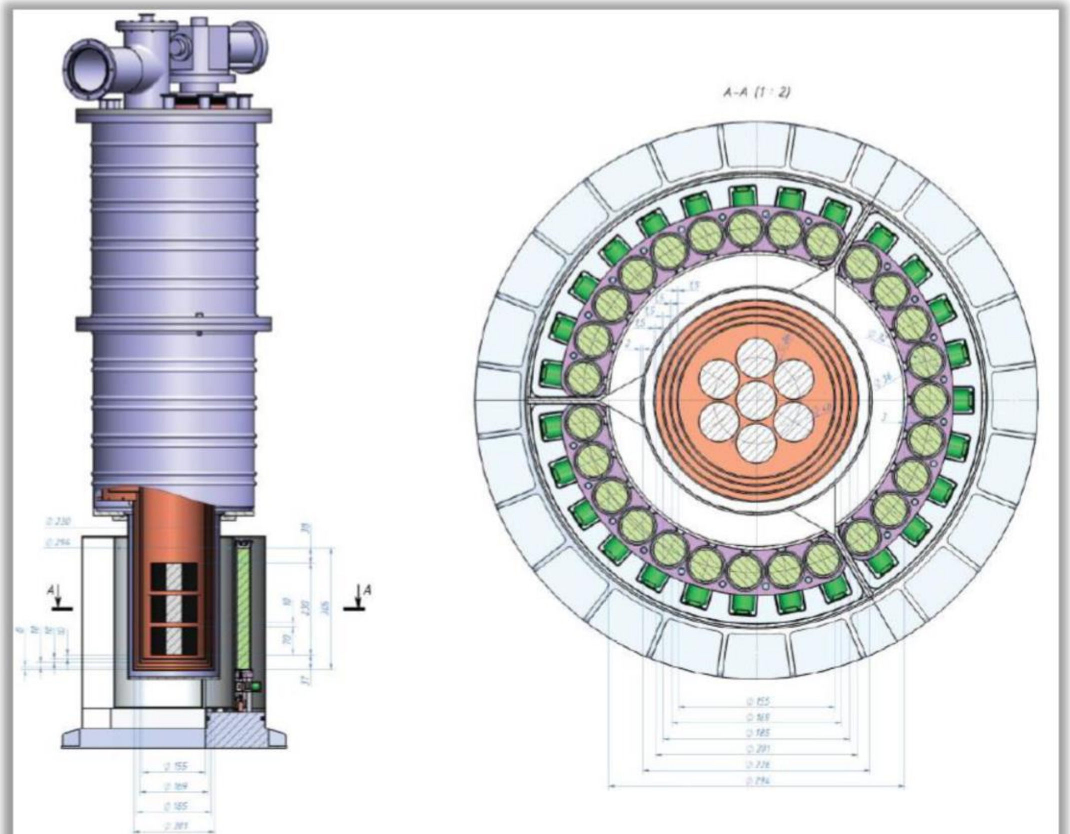
- tubular elements with TiT_2

Silicon cryodetectors (T=10-50 mK)
(14-28)×125 cm^3, 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}~10 eV or even E_{th}~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)

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

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

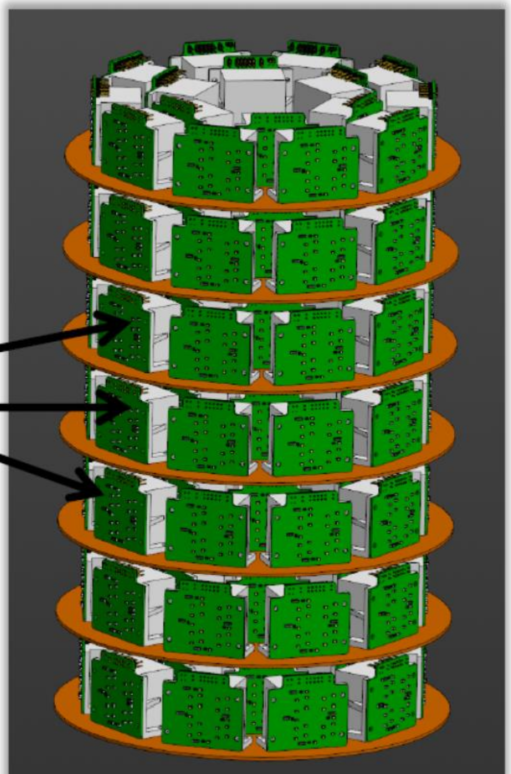
$$N = N_{SM} + N_{\mu_\nu}$$

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

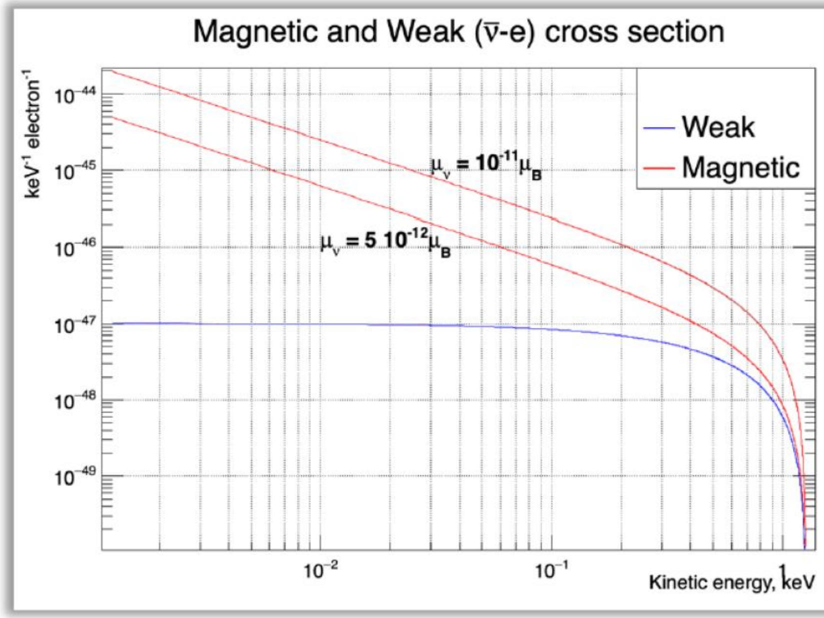
CsI(pure) detector concept *разрабатывает ИЯИ РАН*

Detector assembly

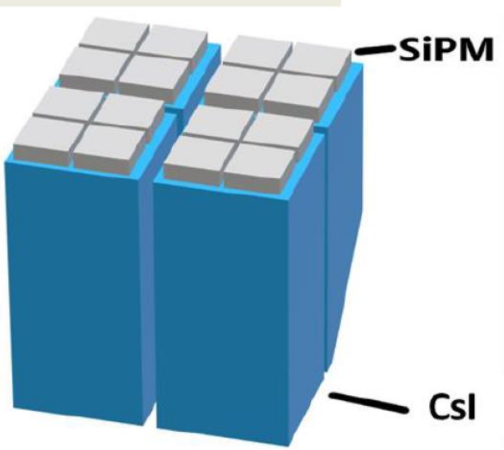
Layers of modules



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



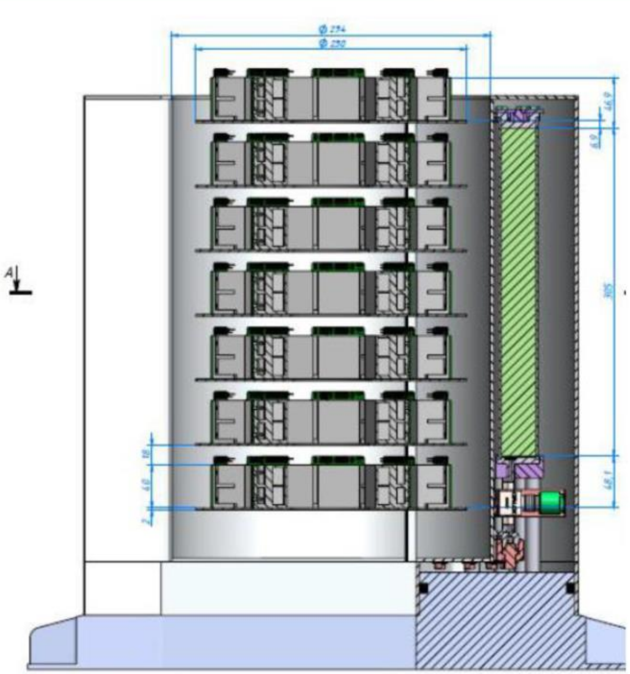
Detector module

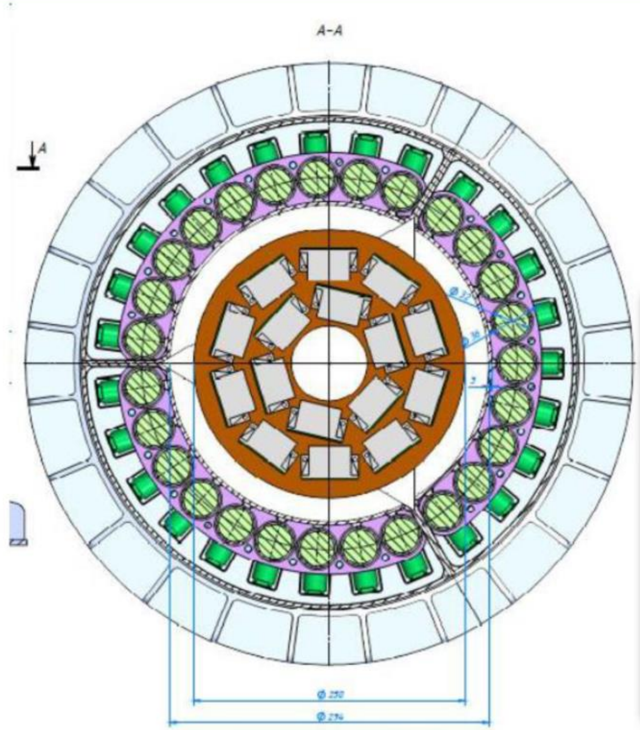


15x15x25 mm³ CsI(pure) crystals
at T=77 K, total mass is M=7.5-10.5 kg

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

Projected μ_ν-sensitivity of CsI detector





Tritium mass is 1 kg (10 MCi)

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

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

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

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

Заключение

- Основной целью проекта САТУРН является проведение впервые в мире регистрации когерентного упругого рассеяния нейтрино на атоме

- Поиск электромагнитных свойств электронного нейтрино в лабораторных экспериментах с рекордной чувствительностью $\mu_\nu \sim 3 \times 10^{-13}\ \mu_B$ (90% CL)

Задачи

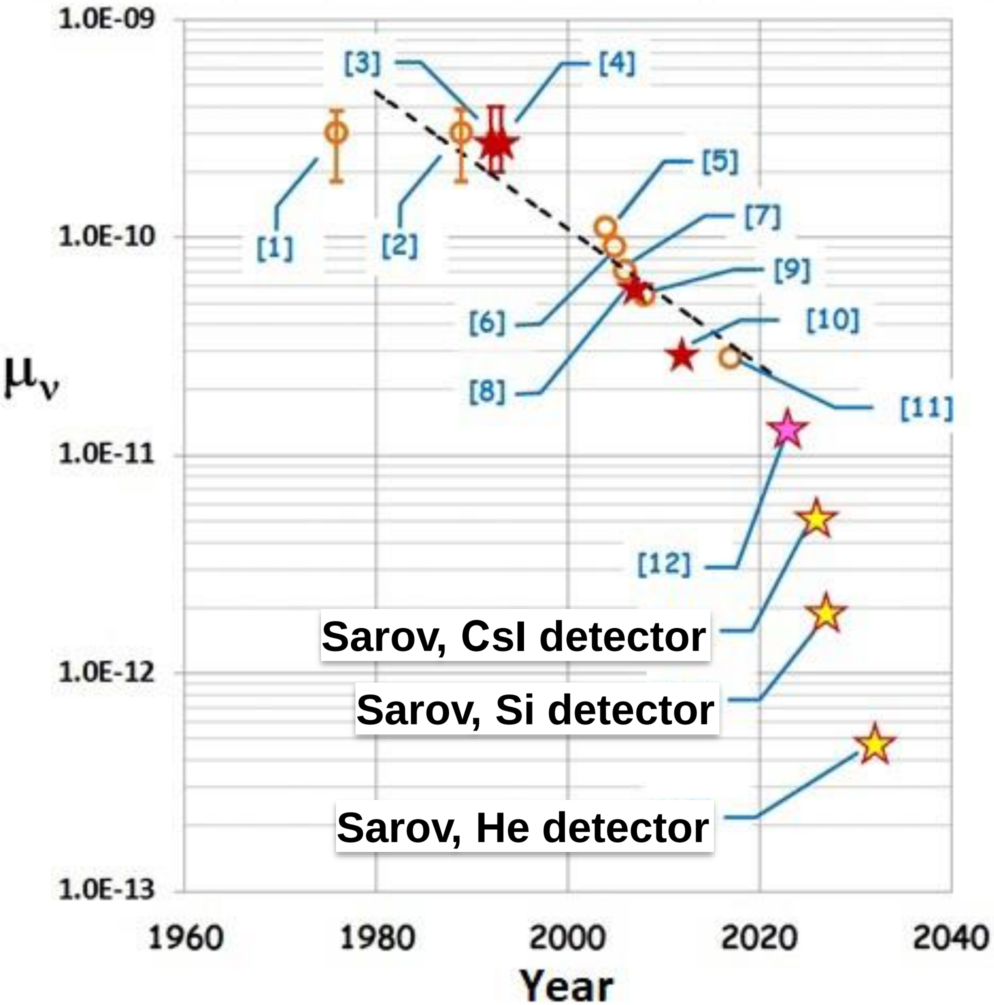
- высокоинтенсивный тритиевый источник электронных антинейтрино с активностью 10 МКи (40 Мки)
- детектор на основе сверхтекучего гелия-4 с порогом регистрации 1-10 мэВ
- низкофоновая нейтринная лаборатория глубокого заложения с инфраструктурой для работы с большими количествами

Промежуточные этапы

… первые измерения на Баксан в 2026 году…

- низкотемпературный сцинтилляционный CsI детектор ИЯИ РАН (порог регистрации 100-200 эВ): $\mu_\nu \sim (2\text{-}3) \times 10^{-12}\ \mu_B$ (90% CL)
- криогенный Si детектор с эффектом теплового усиления ОИЯИ (порогом регистрации 1-10 эВ): $\mu_\nu \sim (1.5\text{-}2) \times 10^{-12}\ \mu_B$ (90% CL)

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 (νGEN) (202?)

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The SATURNE Collaboration

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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

LOBACHEVSKY UNIVERSITY

JOINT INSTITUTE FOR NUCLEAR RESEARCH

ИЯИ

IPM RAS

Ioffe Physical-Technical Institute

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… публикации …

- 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)

Выписка из протокола заседания

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».

Научный совет РАН

«Физика нейтрино и нейтринная астрофизика»

Совещание по проекту SATURNE в Госкорпорации «РОСАТОМ» 18 февраля 2026 год

УТВЕРЖДАЮ

Первый заместитель генерального директора
ГК «Росатом»-директор Дирекции по ЯОК

О.Н. Шубин

Протокол
Совещания о состоянии дел по нейтринному проекту НЦФМ (проект SATURNE) 18.02.2026г.

Присутствовали:
Бисикало Д.В. (НЦФМ), Болоздыня А.И. (НИЯУ-МИФИ), Гребенкин К.Ф. (ВНИИТФ), Ильгисонис В.И. (ГК «Росатом»), Москалев О.А. (ГК «Росатом»), Рыкованов Г.Н. (ГК «Росатом», ВНИИТФ), Сергеев А.М. (НЦФМ), Студеникин А.И. (МГУ), Шарков Б.Ю. (ОИЯИ), Юхимчук А.А. (ВНИИЭФ), Якушев Е.А. (ОИЯИ)

Заслушали сообщения:

1. Г.Н. Рыкованов «Перспективы реализации нейтринного проекта SATURNE и анализ рекомендаций Научного совета РАН «Физика нейтрино и нейтринная астрофизика» от 11.12. 2025г.».
2. А.А. Юхимчук «О состоянии дел по проекту SATURNE».
3. А.И. Болодзыня «О состоянии дел по проекту РЭД-100 регистрации антинейтрино на 4-м блоке Калининской АЭС».

Neutrino Unbound

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

Future Neutrino Experiments

- **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
- **JSNS^2** 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 (^{76}Ge) (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

Единственный CEνAS эксперимент
+
уникальный потенциал для поиска ЭМ свойств нейтрино

Спасибо за внимание!