# REVEALING NEW PROCESSES WITH SUPERFLUID LIQUID HELIUM DETECTORS: THE COHERENT ELASTIC NEUTRINO-ATOM SCATTERING


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## ABSTRACT

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. This technique allows, in principle, to measure the weak mixing angle at energy scales never reached before. In addition, such a low-energy experiment could provide a sensitive test of the neutrino magnetic moment, setting, potentially, a stronger limit than the current ones.


## COHERENT ELASTIC NEUTRINO ATOM SCATTERING

The coherent scattering of a neutrino on a target arises when the neutrino wavelength is comparable to the target size.
For nuclei (CEvNS) the typical energy of ν is MeV.
For atoms (CEvAS) the typical energy of ν is keV.
The scattering cross section against a spin zero target with mass $m_T$ is

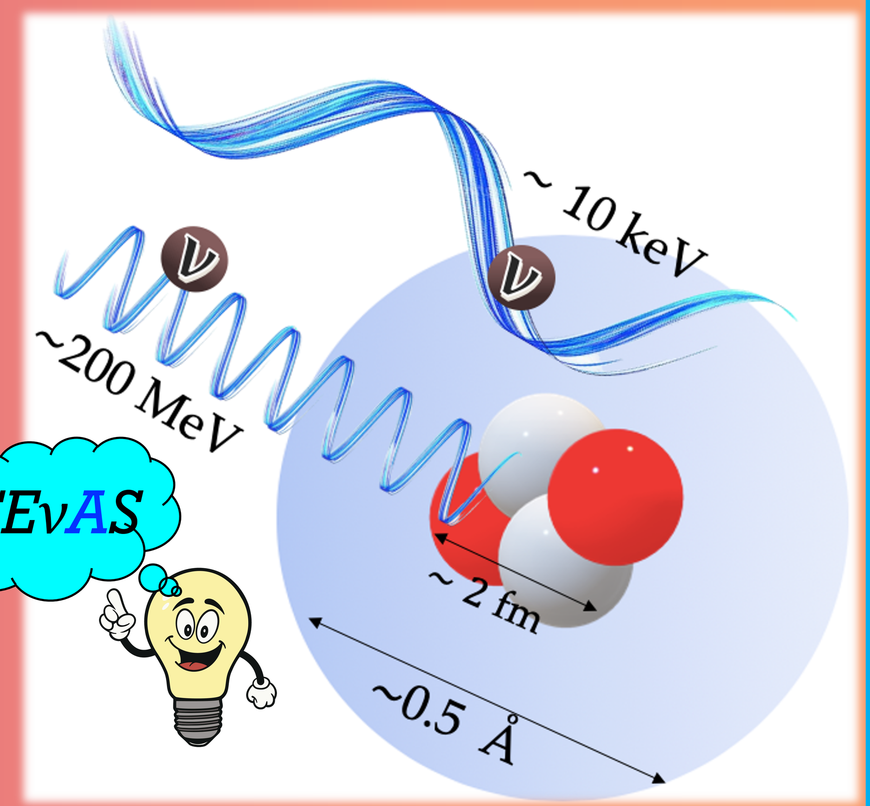
$$\frac{d\sigma}{dT_R} = \frac{G_F^2}{\pi} m_T C_V^2 \left(1 - \frac{m_T T_R}{2E_\nu^2}\right)$$

$G_F$ = Fermi costant
$m_T$ = target mass
$T_R$ = recoil energy
$E_\nu$ = neutrino energy
$C_\nu$ = coupling

Coherence condition:

$$|\vec{q}| \cdot R_{\rm atom} \sim 1$$

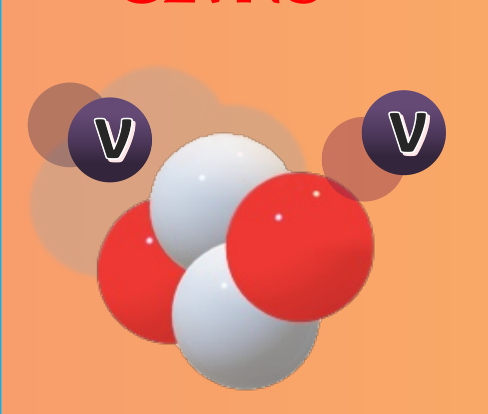
$$T_R \sim 2\ \text{meV}/(A R_{\rm atom}^2[\text{Å}])$$




Atomic Effects in Coherent Neutrino Scattering *Sehgal, L.M. and Wanninger M.* **Phys.Lett. B171 (1986)**

## DIFFERENCES BETWEEN CEvNS AND CEvAS

### CEvNS



Kinematic condition:

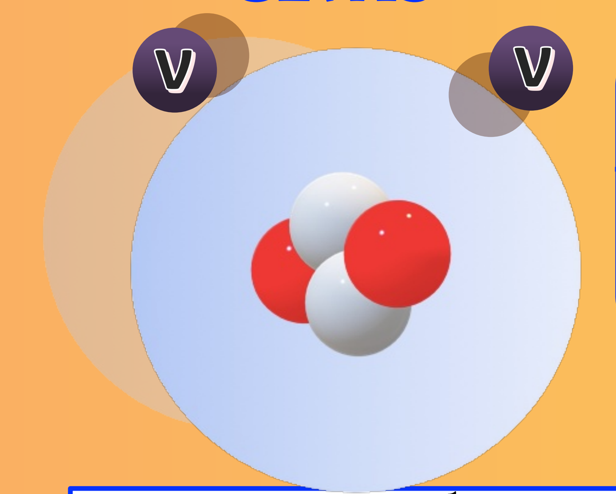
$$|\vec{q}| \cdot R_N \ll 1$$

$|\vec{q}|$ : 3-momentum transfer
$R_N$ : nucleus radius

$$C_V^{\rm CE\nu NS} = \frac{1}{2}[(1 - 4\sin^2\theta_w) Z F_Z(q^2) - N F_N(q^2)]$$

CEvNS is sensitive to the proton and neutron distribution, since nuclear form factors $F_Z$ and $F_N$ play an important role in the interaction

### CEvAS



Kinematic condition:

$$|\vec{q}| \cdot R_{\rm atom} \ll 1$$

$|\vec{q}|$ : 3-momentum transfer
$R_{\rm atom}$ : atomic radius

$$C_V^{\rm CE\nu AS} = C_V^{\rm CE\nu NS} + \frac{1}{2}(\pm 1 + 4\sin^2\theta_w) Z F_e(q^2)$$

In CEvAS, the electron component arises, modifying the coupling by adding a new term dependent on the weak mixing angle. The +(-) sign is applied for electron (muon,tau) neutrinos

## THE ROLE OF THE ATOMIC FORM FACTOR

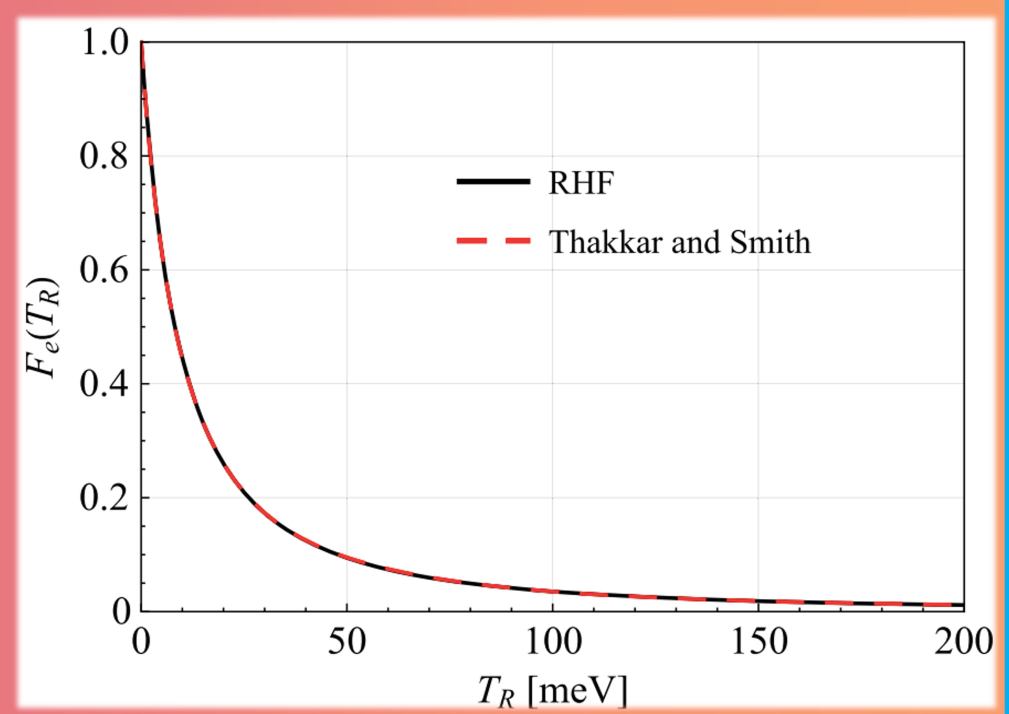
**ATOMIC FORM FACTOR**

$$F_e(q^2) = A \cdot \left(\sum_{i=1}^{4} a_i \cdot e^{-b_i (q/4\pi)^2} + c\right)$$

This is the parametrization that we used for reproducing the atomic form factor of **$^4$He**

To prove the robustness of the result we compared two form factors obtained with the **Rothraan Hartree Fock** method (avoiding electron-electron correlations) and the **variational method** (including explicitly electron-electron correlations)

The result does not change, making the theoretical uncertainty of the atomic form factor negligible




P. A. Doyle and P. S. Turner, Acta Crystallographica Section A 24, 390 (1968).
P. J. Brown et al., International Tables for Crystallogra- phyC ch. 6.1, 554 (2006).
A. J. Thakkar and V. H. Smith, Jnr, Acta Crystallographica Section A 48, 70 (1992).

## DESTRUCTIVE INTERFERENCE IN CEvAS

The main difference between the CEvNS and CEvAS cross sections is encased in the interference condition

$$F_e(T_R) = \frac{\frac{N}{Z} - (1 - 4\sin^2\theta_w)}{1 + 4\sin^2\theta_w}$$

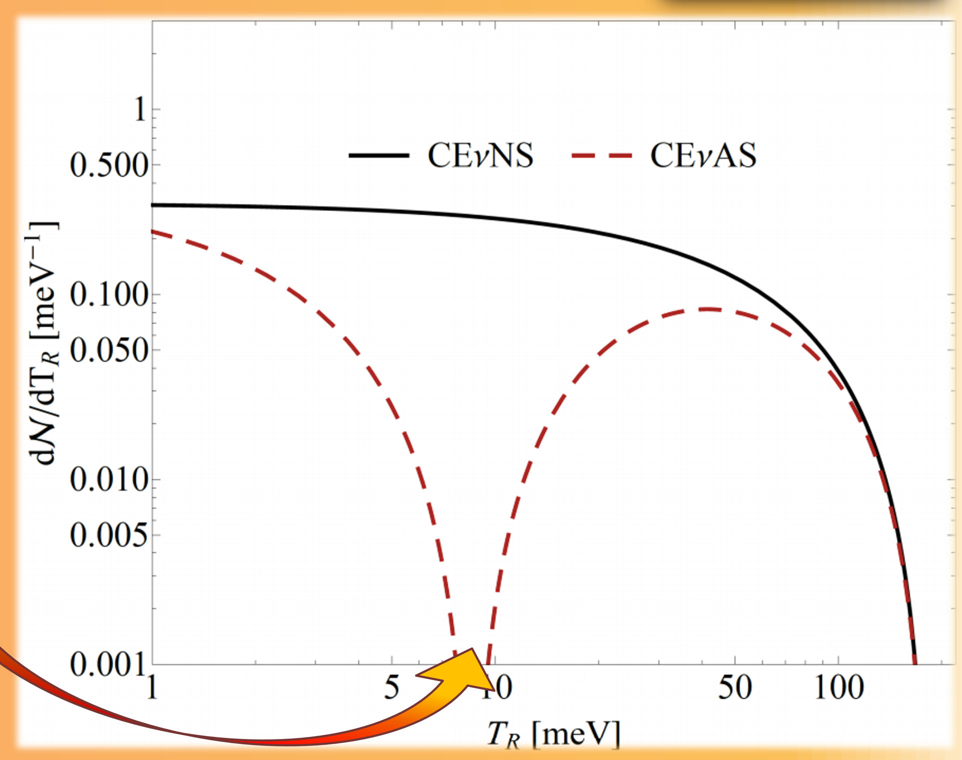
When this condition is accomplished the electron part of the coupling compensates the nuclear contribution, making the cross section vanishing

**The cancellation condition depends on the value of $\sin^2\theta_w$**

Considering $^4$He as a target, $\sin^2\theta_W$ = 0.2 3857 [PDG] and the atomic form factor on the left we reach the condition of

**COMPLETE SCREENING AT**

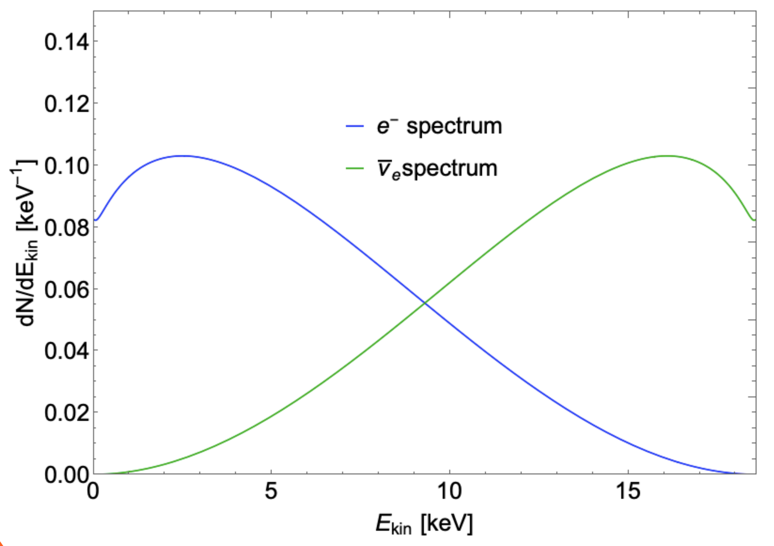
$$T_R \simeq 9\ \text{meV}$$




## PROPOSING AN EXPERIMENTAL SETUP TO OBSERVE CEvAS

### SOURCE: Tritium Beta Decay

$$^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$$

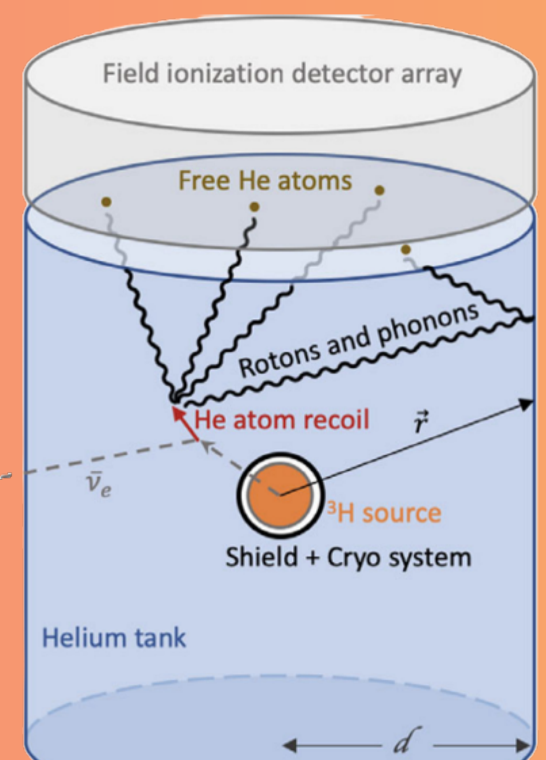



To investigate CEvAS scattering it's necessary to use a **low-energy scale neutrino** probe, in order to get the kinematic condition for reaching the coherence with the whole atom

The **Q-value** of the process is **18.58 keV** and the neutrino spectrum is peaked at ~16 keV

$$N_\nu(t) = N_{^3\text{H}} \cdot (1 - e^{-t/\tau})$$

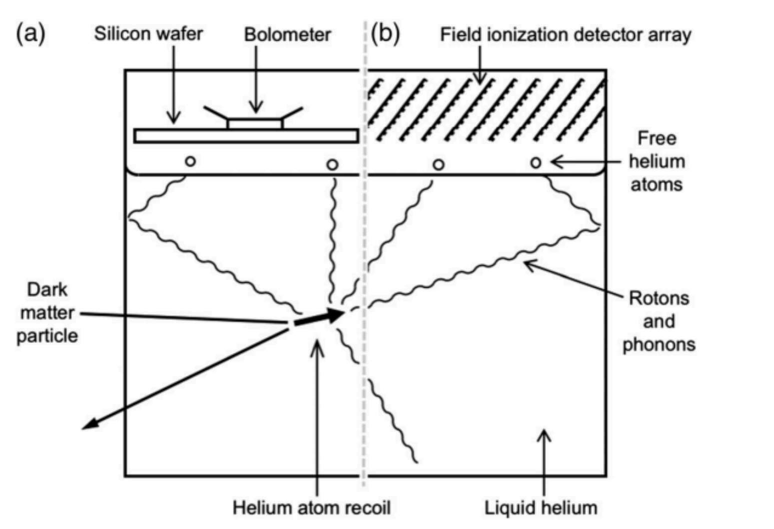
Number of neutrinos depending on **τ = 17.74 yr** and on the amount of $^3$H used as a source




### DETECTION: Superfluid Helium Detector

To detect a recoil of the order of meV, the only technology that probably will be available in the near future is based on **helium evaporation**, a method thought for low-mass dark matter

As soon as the interacting particle scatters on the target, the release of energy is **propagated through phonons and rotons** towards the surface, making evaporate helium atoms




Dark Matter Detection Using Helium Evaporation and Field Ionization H. J. Maris,G. M. Seidel, D. Stein **Phys.Rev.Lett. 119 (2017) 18, 181303**
Direct detection of sub-GeV dark matter using a superfluid 4He target S.A. Hertel, A. Biekert, J. Lin, V. Velan ,D.N. McKinsey. **Phys.Rev. D100 (2019) no.9, 092007**

## SENSITIVITY TO PHYSICS PARAMETERS

To assess the potentiality of this process, hopefully detectable in the future, we studied the sensitivity under the optimistic case of zero-background, 500 kg of He for the detector, 5 years of data taking and 3 different scenarios of tritium amount: 60 g, 160g and 500 g. Even though building such a setup in the near future seems difficult, the possibility to measure parameters at scales never reached before makes the idea worthy to be explored. The first two scenarios allow for the possibility to distinguish CEvAS from CEvNS at 3σ and 5σ C.L., respectively

### Weak Mixing Angle

Some weak mixing angle measurements, especially at low scale, are able to constrain the presence of new bosons beyond the Standard Model

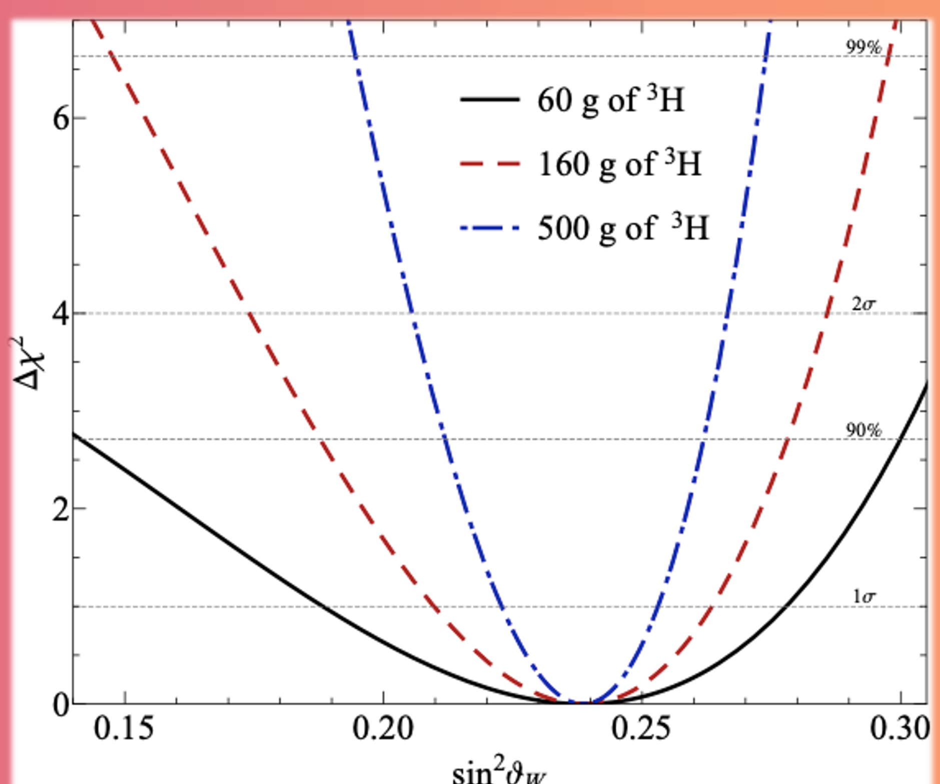
$$\sin^2\theta_W = \sin^2\theta_W^{SM}{}^{+0.04}_{-0.05}$$

$$\sin^2\theta_W = \sin^2\theta_W^{SM}{}^{+0.025}_{-0.029}$$

$$\sin^2\theta_W = \sin^2\theta_W^{SM}{}^{+0.015}_{-0.016}$$

Momentum transfer scale:

$$\langle q \rangle \simeq 2 \times 10^{-5}\ \text{GeV}$$




### Neutrino Magnetic Moment

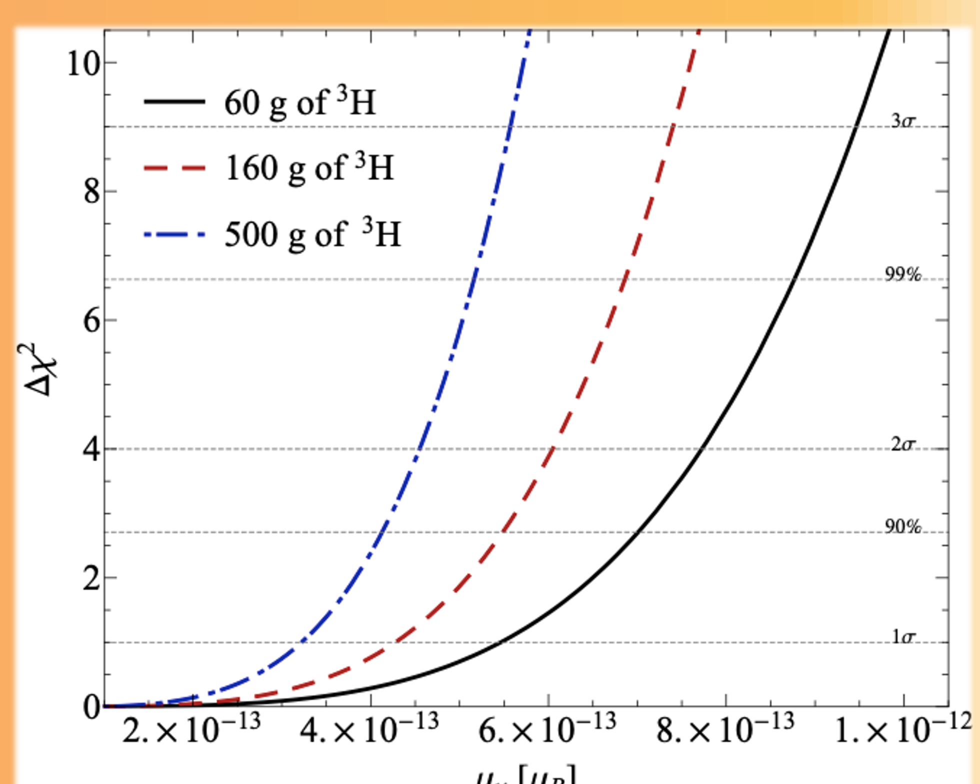
CEvAS is highly sensitive to the neutrino magnetic moment because of the $1/T_R$ dependence, which enhances the cross section at low energies

$$\left.\frac{d\sigma^{\rm CE\nu AS}}{dT_R}\right|_{\mu_\nu \neq 0} \simeq \frac{d\sigma^{\rm CE\nu AS}}{dT_R} + \frac{\pi\alpha^2 Z^2}{m_e^2}\left(\frac{\mu_\nu}{\mu_B}\right)^2 \left(\frac{1}{T_R} - \frac{1}{E_\nu}\right)(1 - F_e(T_R))^2$$

In the most optimistic scenario the limit wuold be

$$\mu_\nu < 4.1 \times 10^{-13} \mu_B\ (90\%\ \text{C.L.})$$

It is two order of magnitude better than the current limit





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Potentialities of a low-energy detector based on $^4$He evaporation to observe atomic effects in coherent neutrino scattering and physics perspectives
*M. Cadeddu, F. Dordei, C. Giunti, K. A. Kouzakov, E. Picciau, and A. I. Studenikin*
**Phys. Rev. D 100, 073014**


K. Kouzakov and A. Studenikin acknowledge the support from the RFBR grant No. 20-52-53022



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