The theory of electromagnetic effect in low-energy processes of neutrino scattering on atoms and condensed matter

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based on poster presentations:
Neutrino magnetic moments in low-energy neutrino scattering on condensed matter systems, TAUP 2021
Collective effects in neutrino scattering on solid and liquid targets, EPS-HEP2021

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Outline

- Introduction
- Coherent neutrino scattering on an atom
- Neutrino scattering on a system of atoms
- Neutrino scattering on liquid ^{4}He
- Conclusions

Introduction

- The usage of liquid and solid-state detectors is being discussed to search for light particles of dark matter in order to achieve sensitivity to low-energy signals at a level of $\sim$1 meV. [Maris H.J., et al. Dark matter detection using helium evaporation and field ionization, Phys. Rev. Lett. **119** (2017) 181303]
- Such detectors can also be used to study low-energy neutrino scattering in order to both test the Standard Model and search for new physics [M.Cadeddu, F. Dordei, C. Giunti, K. Kouzakov, E. Picciau, A. Studenikin. Potentialities of a low-energy detector based on He 4 evaporation to observe atomic effects in coherent neutrino scattering and physics perspectives, Phys. Rev. D **100** (2019) 073014].
- We develop the theory of neutrino scattering on a condensed matter systems at low energy transfer with the account for the collective effects in the target
- In the present work we study the contribution of neutrino magnetic moment to the neutrino coherent elastic scattering on a condensed matter system

Coherent neutrino scattering on an atom

Kinematic condition CEνNS

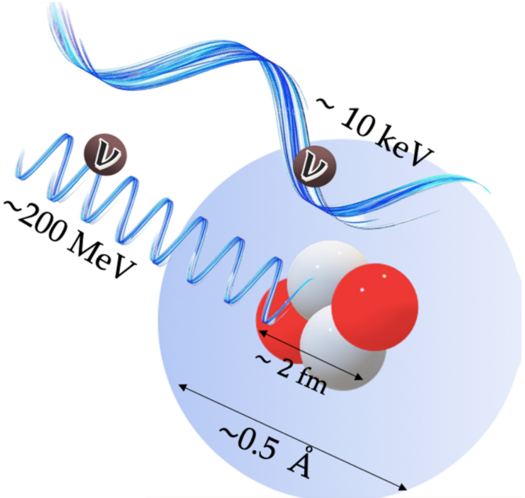
- $|\mathbf{q}|R_{\rm nuc} \ll 1$,

where $|\mathbf{q}|$ is 3-momentum transfer, $R_{\rm nuc}$ is the radius of nucleus.

Kinematic condition CEνAS

- $|\mathbf{q}|R_{\rm atom} \ll 1$,

where $R_{\rm atom}$ is radius of an atom.



The SM cross section for CEνAS

Gaponov, Y. V., Tikhonov, V. N. (1977). Elastic scattering of low energy neutrinos by atomic systems. Yadernaya Fizika, **26**(9), 594-600

$$\left(\frac{d\sigma}{dT}\right)_{\mathrm{atom}} = \frac{G_F^2 m}{\pi}\left[C_V^2\left(1-\frac{mT}{2E_\nu^2}\right)+C_A^2\left(1+\frac{mT}{2E_\nu^2}\right)\right]$$

$$\begin{aligned} C_V &= Z\left(\tfrac{1}{2}-2\sin^2\theta_W\right)-\tfrac{1}{2}N+Z\left(\mp\tfrac{1}{2}+2\sin^2\theta_W\right)F_{\mathrm{el}},\\ C_A^2 &= (C_A^{\mathrm{nuc}})^2+\tfrac{1}{4}\sum_{n,l}\left[\left(L_+^{\mathrm{nl}}-L_-^{\mathrm{nl}}\right)F_{\mathrm{el}}^{\mathrm{nl}}\right]^2,\ (C_A^{\mathrm{nuc}})^2=\tfrac{g_A^2}{4}\left[(Z_+-Z_-)-(N_+-N_-)\right]^2, \end{aligned}$$

where the $+$ $(-)$ stands for $\nu=\nu_e$ $(\nu=\nu_{\mu,\tau})$, and Z (N) is the number of protons (neutrons). $F_{\mathrm{el}}(q^2)$ is the Fourier transform of the electron density, $g_A=1.25$, and $Z_\pm$ and $N_\pm$ $(L_\pm^{\mathrm{nl}})$ are the numbers of protons and neutrons (electrons) with spin parallel $(+)$ or antiparallel $(-)$ to the nucleus spin (the total electron spin).

Atomic screening effect

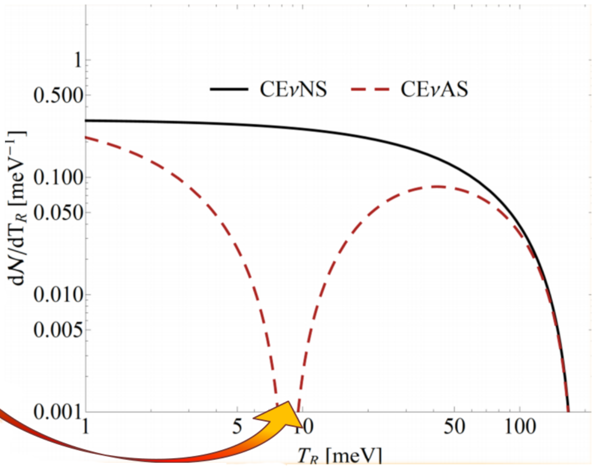
Interference condition

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

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

COMPLETE SCREENING AT

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



CEνAS cross section with account for μ_ν

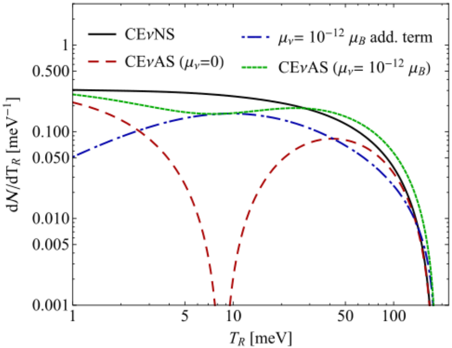
M. Cadeddu, F. Dordei, C. Giunti, K. Kouzakov, E. Picciau, A. Studenikin, Phys. Rev. D **100**, 073014 (2019)

$$\left(\frac{d\sigma}{dT}\right)_{\rm atom} = \frac{G_F^2 m}{\pi}\left[C_V^2\left(1-\frac{mT}{2E_\nu^2}\right)+C_A^2\left(1+\frac{mT}{2E_\nu^2}\right)\right]+\frac{\pi\alpha^2 Z^3}{m_e^2}|\mu_\nu|^2\left(\frac{1}{T}-\frac{1}{E_\nu}\right)F_{\rm scr}^2$$

$$\mathrm{F}_{\rm scr}^2 = (1-F_{el})^2$$

μ_ν-contribution

The effect of neutrino magnetic moment practically compensates the SM screening effect



Neutrino scattering on a system of atoms

The cross section for the transition of a system from $|i\rangle$ to $|f\rangle$

$$\frac{d\sigma_{i\to f}}{dT} = \int\limits_0^\infty dq^2 \int\limits_0^{2\pi} d\varphi_q \, \frac{d\sigma_{i\to f}}{dT dq^2 d\varphi_q}$$

In the case of a single atom

$$\frac{d\sigma_{i\to f}}{dT dq^2 d\varphi_q} = \left[\Sigma^{(w)} + \Sigma^{(\mu)}\right] \delta(T - \Delta E)$$

$\Delta E = E_f - E_i = \frac{q^2}{2m}$,
where $|i\rangle$, $|f\rangle$ are the initial and final states of the system, E_i, E_f are the corresponding energies.

The weak interaction contribution

$$\Sigma^{(w)} = \frac{G_F^2}{2\pi^2}\left[C_V^2\left(1-\frac{q^2}{4E_\nu^2}\right)+C_A^2\left(1+\frac{q^2}{4E_\nu^2}\right)\right],$$

$$C_V = Z\left(\tfrac{1}{2}-2\sin^2\theta_W\right)-\tfrac{1}{2}N+Z\left(\mp\tfrac{1}{2}+2\sin^2\theta_W\right)F_{\mathrm{el}}(q^2),$$

$$C_A^2 = (C_A^{\mathrm{nuc}})^2+\frac{1}{4}\sum_{n,l}\left[\left(L_+^{\mathrm{nl}}-L_-^{\mathrm{nl}}\right)F_{\mathrm{el}}^{\mathrm{nl}}(q^2)\right]^2,\ (C_A^{\mathrm{nuc}})^2=\frac{g_A^2}{4}\left[(Z_+-Z_-)-(N_+-N_-)\right]^2$$

μ_ν-interaction contribution

$$\Sigma^{(\mu)} = \frac{\alpha^2 Z^3}{2m_e^2}|\mu_\nu|^2\left(\frac{2m}{q^2}-\frac{1}{E_\nu}\right)F_{\mathrm{scr}}^2(q^2),$$

where $\mu_\nu \sim 10^{-12}\mu_B$ is the neutrino dipole magnetic moment and $F_{\mathrm{scr}}^2(q^2) = \left[1-F_{el}(q^2)\right]^2$.

The case of $\mathcal{N}$ atoms

$$C_V^2 \to \left| C_V^{(\mathcal{N})} \right|^2 = \left| \langle f | \sum_{j=1}^{\mathcal{N}} e^{i\mathrm{q}\mathrm{R}_j} C_V | i \rangle \right|^2$$
$$C_A^2 \to \left| C_A^{(\mathcal{N})} \right|^2 = \left| \langle f | \sum_{j=1}^{\mathcal{N}} e^{i\mathrm{q}\mathrm{R}_j} C_A | i \rangle \right|^2$$
$$F_{\mathrm{scr}}^2 \to \left| F_{\mathrm{scr}}^{(\mathcal{N})} \right|^2 = \left| \langle f | \sum_{j=1}^{\mathcal{N}} e^{i\mathrm{q}\mathrm{R}_j} C_A | i \rangle \right|^2$$

R_j – the radius vector of the j-th atom.

General formula

$$\frac{d\sigma}{dT} = \int_0^\infty dq^2 \int_0^{2\pi} d\varphi_q \left[\Sigma^{(w)} + \Sigma^{(\mu)} \right] S(T,\mathrm{q})$$

$$S(T,\mathrm{q}) = \sum_{i,f} w_i \left| \langle f | \sum_{j=1}^{\mathcal{N}} e^{i\mathrm{q}\mathrm{R}_j} | i \rangle \right|^2 \delta(T - E_f + E_i),$$

$S(T,\mathrm{q})$ is a dynamic structure factor, w_i is the probability to find the target in the state $|i\rangle$.

Neutrino scattering on liquid ^{4}He

$\mathcal{N}$ free atoms $\quad S(T,\mathrm{q}) = \mathcal{N}\delta\left(T - \frac{q^2}{2m}\right)$

$$\frac{d\sigma}{dT} = \mathcal{N}\left[C_V^2\,\frac{G_F^2 m}{\pi}\left(1 - \frac{mT}{2E_\nu^2}\right) + \frac{\pi\alpha^2 Z^3}{m_e^2}|\mu_\nu|^2\left(\frac{1}{T} - \frac{1}{E_\nu}\right)F_{\mathrm{scr}}^2\right],$$

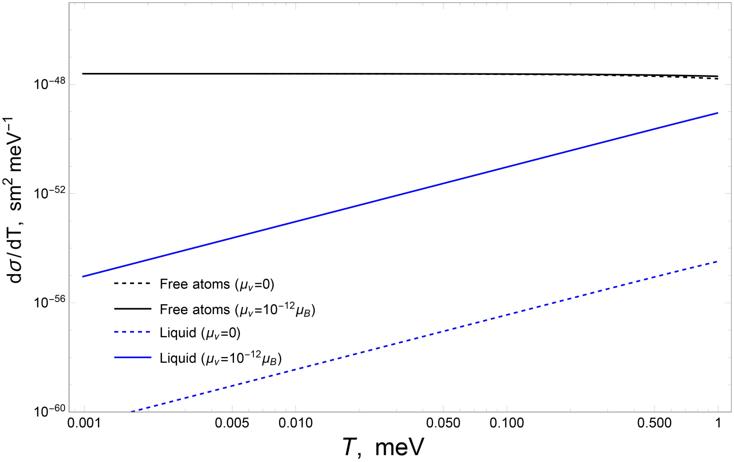
where $C_V^2 = C_V^2(q^2 = 2mT)$ and $F_{\mathrm{scr}}^2 = F_{\mathrm{scr}}^2(q^2 = 2mT)$.

Collective excitation effect (phonon) $\quad S(T,\mathrm{q}) = \dfrac{\mathcal{N}q}{2mu}\delta(T - uq)$

$$\frac{d\sigma}{dT} = \mathcal{N}\left[C_V^2\,\frac{G_F^2 T^2}{2\pi mu^3}\left(1 - \frac{T^2}{4u^2E_\nu^2}\right) + \frac{\pi\alpha^2 Z^3}{m_e^2}|\mu_\nu|^2\left(\frac{2mu^2}{T^2} - \frac{1}{E_\nu}\right)F_{\mathrm{scr}}^2\right],$$

where $C_V^2 = C_V^2(q^2 = T^2/u^2)$, $F_{\mathrm{scr}}^2 = F_{\mathrm{scr}}^2(q^2 = T^2/u^2)$
and u is the phonon speed in liquid ^{4}He.

Neutrino scattering on liquid ^{4}He



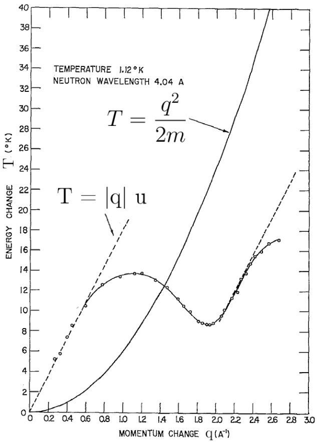
Differential cross section normalized to the number $\mathcal{N}$ of helium atoms for scattering of neutrinos with $E_\nu = 10$ keV

Conclusions

- The theory of low-energy neutrino scattering by condensed matter target with account for the neutrino magnetic moment is developed
- It is shown that taking collective effects into account in the neutrino scattering by superfluid ^{4}He qualitatively changes the dependence of the differential cross section on the energy transfer
- This fact must be taken into account both in the preparation and in the data analysis of future neutrino experiments with detectors based on liquid ^{4}He and other materials (e. g., graphene)
- The strong effect of neutrino magnetic moment is found for energy transfer values $\lesssim 1$ meV for liquid ^{4}He

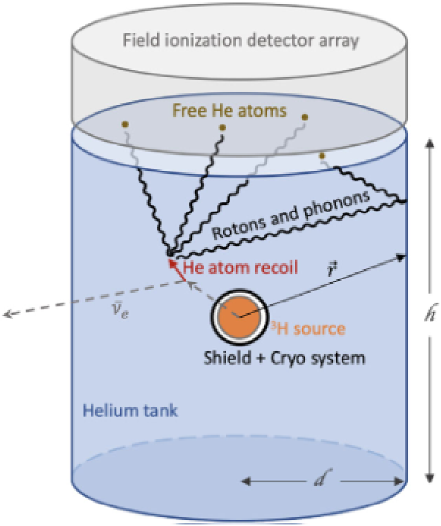
Thank you for the attention!

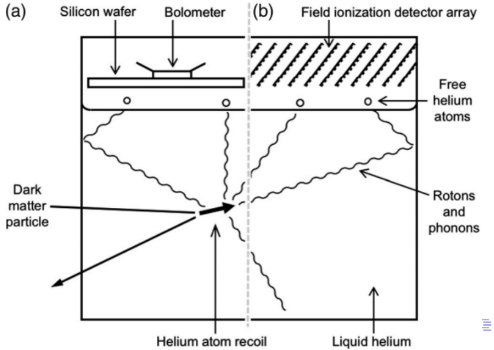
Backup slides



Dispersion curve for liquid ^{4} He (points - experiment).

Backup slides





Neutrino oscillations

The Effect of Neutrino Oscillations

$$\frac{d\sigma}{dT} = \sum_{\beta=e,\mu,\tau} P_{\nu_\alpha\to\nu_\beta}(L/L_{osc})\,\frac{d\sigma_{\nu_\beta}}{dT}$$

$$P_{\nu_\alpha\to\nu_\alpha}(L/L_{osc}\to 0)\to 1,$$

where $\frac{d\sigma_{\nu_\beta}}{dT}$ is the differential cross section for neutrino scattering of the β , $\alpha = e,\mu,\tau$, types

$$L_{osc} \geq \frac{4E_\nu}{\pi\Delta m^2_{32}},\ \text{где}\ \Delta m^2_{32} \simeq 2{,}45\times 10^{-3}\text{эВ}^2.$$

Qualitative Estimation of the Oscillation Length

- CEνNS reactor experiments: $L \lesssim 100$ m, $E_\nu \sim 1$ MeV
- COHERENT: $L \simeq 20 - 30$ m, $E_\nu \sim 10$ keV
- CEνAS: $L \lesssim 1$ m, $E_\nu \sim 10$ keV

Thus, $L/L_{osc} \ll 1$ for the experiments under consideration, and the probability of changing the original flavor tends to 0.