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Neutrino magnetic moments in low-energy neutrino scattering on condensed matter systems

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Introduction

- The detectors for searching light particles of dark matter are actively discussed in the literature. To achieve the sensitivity to low-energy signals at a level of ∼1 meV, condensed matter targets are proposed [1].
- Such detectors can also be used to study the low-energy neutrino scattering in order both to test the Standard Model and to search for the physics beyond the Standard Model [2].

Background

Kinematical regime

$$E_\nu \ll m, \qquad T \leq \frac{2E_\nu^2}{m} \ll E_\nu, \qquad E_\nu \ll \frac{1}{R_{\text{nuc}}},$$

where T is the energy transfer, m is the atomic mass, and R_{nuc} is the nuclear radius.

The differential cross section for an atom

According to [3]:

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

The weak interaction contribution:

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

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

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

$$(C_A^{nuc})^2 = \tfrac{g_A^2}{4}\left[(Z_+ - Z_-) - (N_+ - N_-)\right]^2,$$

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

The electromagnetic interaction contribution:

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

where $\mu_\nu \sim 10^{-11}\mu_B$ is the neutrino dipole magnetic moment [4] and $F_{scr}^2(q^2) = [1 - F_{el}(q^2)]^2$.

General formalism

The differential cross section for the system of $\mathcal{N}$ atoms:

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

where $S(T,\mathbf{q}) = \sum_{i,f} w_i \left|\langle f|\sum_{j=1}^{\mathcal{N}} e^{i\mathbf{q}\mathbf{R}_j}|i\rangle\right|^2 \delta(T - E_f + E_i)$ is the dynamical structure factor, with $\mathbf{R}_j$ being the position of the jth atom and w_i the probability for the system to be in the initial state $|i\rangle$.

Neutrino scattering on liquid ^{4}He

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

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

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

$\mathcal{N}$ bound atoms (liquid) $\quad S(T,\mathbf{q}) = \frac{\mathcal{N}q}{2mu}\delta(T - uq)$

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

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

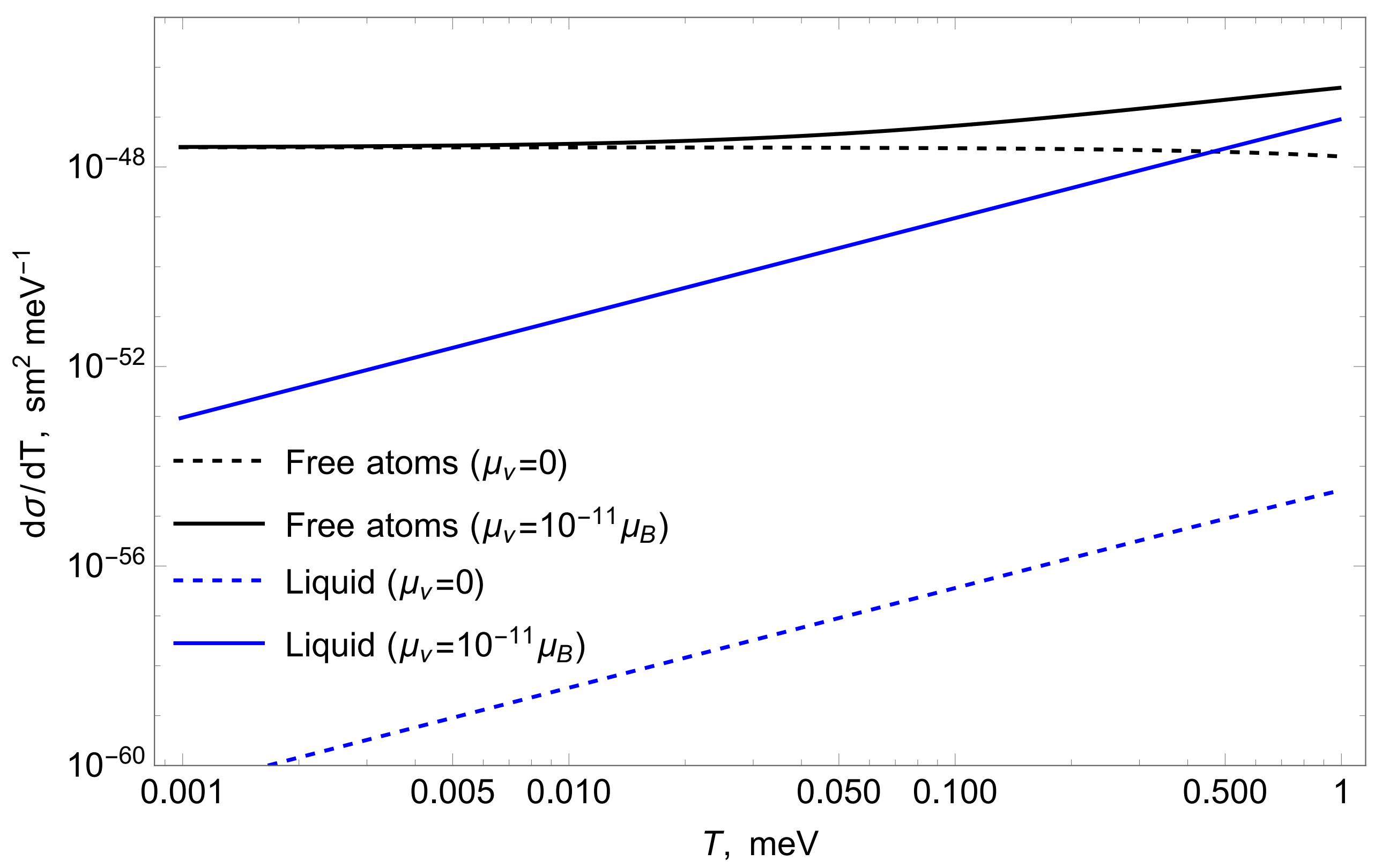

Figure: The differential cross section for tritium antineutrino scattering at $E_\nu = 10$ keV normalized to the number of helium atoms $\mathcal{N}$.

Conclusions

- The theory of low-energy neutrino scattering by a target in a condensed state with account for the neutrino anomalous magnetic moment is developed.
- It is shown that taking collective effects into account in the neutrino scattering by superfluid He-4 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 He-4 and other materials (e. g., graphene [5]).
- The obtained results will be used in the search for the electromagnetic properties of neutrinos [6].

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