

Theory of neutrino-atom collisions: the history, present status and BSM physics

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Neutrinos are very intriguing objects in particle physics. They interact very weakly and their masses are much smaller than those of the other fundamental fermions (charged leptons and quarks). In the Standard Model (SM), neutrinos are massless and have only weak interactions. However, the observation of neutrino oscillations by many experiments implies that neutrinos are massive and mixed. Therefore, the SM must be extended to account for neutrino masses. In many extensions of the SM, neutrinos also acquire electromagnetic properties through quantum loop effects (see Fig. 1). Hence, the theoretical and experimental study of neutrino electromagnetic interactions is a promising tool to search for the fundamental theory beyond the SM (BSM). The most recent and comprehensive review on the neutrino electromagnetic properties can be found in [1].

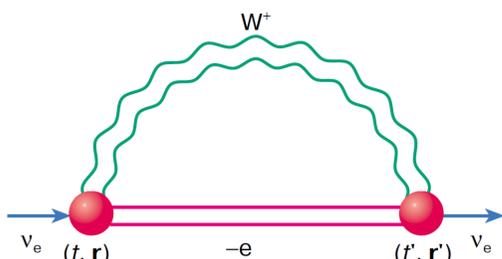


Fig. 1. The Feynman diagram illustrating how the electron neutrino can interact with an external electromagnetic field. There is a nonzero probability that, due to the SM weak interaction, the neutrino can be "converted" into the virtual W^+ boson and electron for a short time ($\Delta t=t'-t$). These virtual charged particles interact with the electromagnetic field, thus changing the state of the neutrino.

The most theoretically studied electromagnetic properties of neutrinos are the dipole magnetic and electric moments. The neutrino magnetic moments expected in the minimally extended SM are very small and proportional to the neutrino masses: $\mu_\nu=3\times 10^{-19}\mu_B(m_\nu/1\text{ eV})$ (in units $\hbar=c=1$), with $\mu_B=e/(2m_e)$ being the electron Bohr magneton, and m_e is the electron mass. Any larger value of μ_ν can arise only from the BSM physics [1,2]. Current direct experimental searches for a magnetic moment of the electron (anti)neutrinos from reactors [3] have lowered the upper limit on its value down to $\mu_\nu<2.9\times 10^{-11}\mu_B$. These ultra low background experiments use germanium crystal detectors exposed to the neutrino flux from a reactor and search for scattering events by measuring the energy deposited by the neutrino scattering in the detector. Their sensitivity to μ_ν crucially depends on lowering the threshold for the energy transfer T . This is because the electromagnetic contribution to the inclusive differential cross section for the neutrino scattering on a free electron (FE) is given by [4]

$$\frac{d\sigma_{EM}^{FE}}{dT} = 4\pi e^2 \mu_\nu^2 \left(\frac{1}{T} - \frac{1}{E_\nu} \right), \quad (1)$$

where E_ν is the incident electron energy, while that induced by weak interaction is practically constant in T (at $T\ll E_\nu$):

$$\frac{d\sigma_W^{FE}}{dT} = \frac{G_F^2 m_e}{2\pi} (1 + 4\sin^2\theta_W + 8\sin^4\theta_W) \left[1 + O\left(\frac{T}{E_\nu}\right) \right] \approx 10^{-47} \text{ cm}^2/\text{keV}, \quad (2)$$

where G_F is the Fermi coupling constant and θ_W is the Weinberg angle.

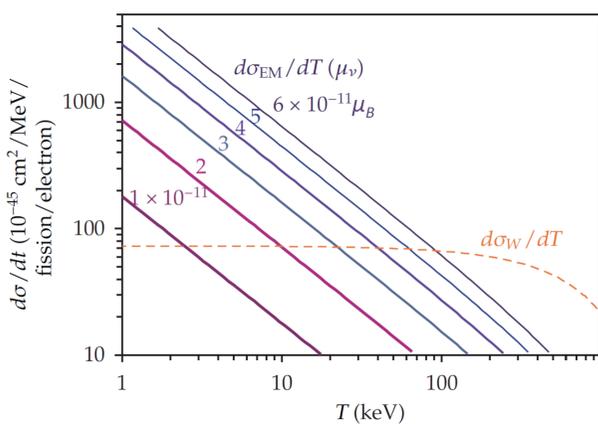


Fig. 2. Weak (W) and electromagnetic (EM) cross sections calculated for several μ_ν values (in units of the Bohr magneton μ_B).

The current experiments using germanium detectors have reached threshold values of T as low as few keV, where one can expect modifications of the FE formulas (1) and (2) due to the binding of electrons in the germanium atoms. Our theoretical analysis [5-7], involving the WKB and Thomas-Fermi models, has shown that the so-called stepping approximation, introduced in [8] from an interpretation of numerical data, works with a very good accuracy. According to the stepping approach, the SM and electromagnetic contributions are simply given by

$$\frac{d\sigma_W}{dT} = \frac{d\sigma_W^{FE}}{dT} \sum_i n_i \theta(T - \varepsilon_i), \quad \frac{d\sigma_{EM}}{dT} = \frac{d\sigma_{EM}^{FE}}{dT} \sum_i n_i \theta(T - \varepsilon_i), \quad (3)$$

where the i sum runs over all atomic sublevels, with n_i and ε_i being their occupations and binding energies.

Recently, Martemyanov and Tsinoev [9] deduced by means of numerical calculations that the cross section $d\sigma_{EM}/dT$ for ionization of helium by neutrino impact strongly departs from the stepping approximation (3), exhibiting large enhancement relative to the FE case. They thus suggested that this finding may have an impact on searches for μ_ν , provided that its value falls within the range 10^{-13} - $10^{-12}\mu_B$. According to Martemyanov and Tsinoev, at the T values close to the ionization threshold in helium, $T_i=24.5874\text{ eV}$, the relative enhancement as large as almost seven orders of magnitude (see Fig. 3).

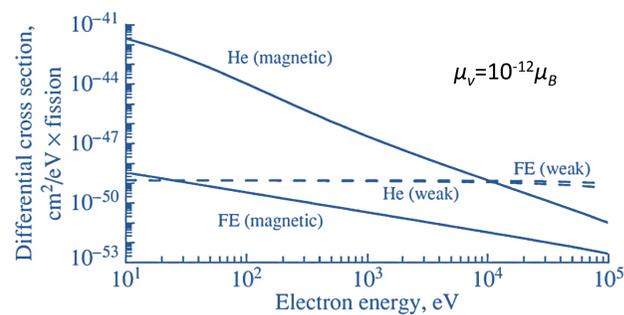


Fig. 3. Calculations of Martemyanov and Tsinoev for $d\sigma_W/dT$ (weak) and $d\sigma_{EM}/dT$ (magnetic) in the case of ionization of helium by reactor-antineutrino impact. The figure is borrowed from Ref. [9].

To inspect the conclusion of Martemyanov and Tsinoev, we carried out numerical estimates of the weak and electromagnetic components of the inclusive differential cross section for the ionizing neutrino-helium collision [10]. The general formulas for these cross sections are

$$\frac{d\sigma_W}{dT} = \frac{G_F^2}{4\pi} (1 + 4\sin^2\theta_W + 8\sin^4\theta_W) I_W(T), \quad \frac{d\sigma_{EM}}{dT} = 4\pi e^2 \mu_\nu^2 I_{EM}(T), \quad (4)$$

where the functions $I_W(T)$ and $I_{EM}(T)$ are given by (when $T\ll E_\nu$)

$$I_W(T) = \int_{T^2}^{4E_\nu^2} S(T, q^2) dq^2, \quad I_{EM}(T) = \int_{T^2}^{4E_\nu^2} S(T, q^2) \frac{dq^2}{q^2}, \quad (5)$$

where q is the momentum transfer, and $S(T, q^2)$ is the so-called dynamical structure factor:

$$S(T, q^2) = \sum_f \left| \langle \Phi_f(\mathbf{r}_1, \mathbf{r}_2) | e^{i\mathbf{q}\cdot\mathbf{r}_1} + e^{i\mathbf{q}\cdot\mathbf{r}_2} | \Phi_0(\mathbf{r}_1, \mathbf{r}_2) \rangle \right|^2 \delta(T - E_f + E_0), \quad (6)$$

Here the f sum runs over all final helium states Φ_f , with E_f being their energies. The function (6) is even in q due to the rotational symmetry of the He atom. For its evaluation we employed the same models of the helium states as in Ref. [9]. Numerical results for atomic factors ($f = d\sigma/d\sigma^{FE}$) are shown in Fig. 4.

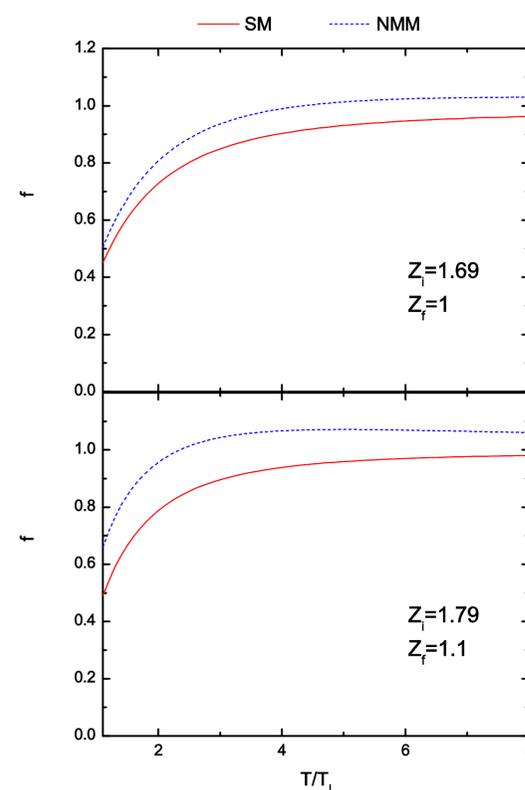


Fig. 4. Atomic factors for neutrino-impact ionization of helium as functions of energy transfer T (measured in units of the helium ionization energy $T_i=24.5874\text{ eV}$). Two sets of effective nuclear charges in the initial and final states of the He atom are inspected. The value $Z_f=1.69$ minimizes the He ground-state energy E_0 , while the value $Z_i=1$ ensures the correct asymptotic behavior of the final He state. The values $Z_f=1.79$ and $Z_i=1.1$ were utilized by Martemyanov and Tsinoev in their calculations [9]. They derived these values from fitting the photoionization cross-section data for helium.

The results presented in Fig. 4 are in qualitative agreement with the stepping approximation (3). Thus, they disconfirm the giant enhancement of the EM contribution shown in Fig. 3.

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