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ON SENSITIVITY OF NEUTRINO-HELIUM IONIZING COLLISIONS TO NEUTRINO MAGNETIC MOMENTS

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We theoretically consider ionization of a helium atom by impact of an electron antineutrino. The sensitivity of this process to neutrino magnetic moments is analyzed. In contrast to the recent theoretical prediction, no considerable enhancement of the electromagnetic contribution with respect to the free-electron case is found. The stepping approximation is shown to be well applicable practically down to the ionization threshold.

Теоретически рассматривается ионизация атома гелия ударом электронного антинейтрино. Анализируется чувствительность этого процесса к нейтринным магнитным моментам. В отличие от недавнего теоретического предсказания не обнаружено сколько-нибудь значительного увеличения электромагнитного вклада. Показано, что ступенчатое приближение хорошо применимо практически вплоть до ионизационного порога.

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INTRODUCTION

Electromagnetic properties of neutrinos are of particular interest, for they open a door to «new physics» beyond the Standard Model (SM) (see, for instance, review articles [1, 2]). Among these nontypical neutrino features the most studied and well-understood theoretically are neutrino magnetic moments (NMM). The latter are also being intensively searched in reactor [3,4], accelerator [5,6] and solar [7,8] experiments on low-energy elastic (anti)neutrino–electron scattering. The current best upper limit on the NMM value obtained in such direct laboratory measurements is

$$\mu_\nu \leqslant 2.9 \cdot 10^{-11} \mu_B,$$

where $\mu_B = e/(2m_e)$ is a Bohr magneton. This bound, which is due to the GEMMA experiment [4] with a HPGe detector at Kalinin Nuclear Power Station, is by an order of magnitude larger than the constraint obtained in astrophysics [9]:

$$\mu_\nu \leqslant 3 \cdot 10^{-12} \mu_B.$$

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And it by many orders of magnitude exceeds the value derived in the minimally extended SM with right-handed neutrinos [10]:

$$\mu_\nu \leqslant 3 \cdot 10^{-19} \mu_B \left(\frac{m_\nu}{1\,\mathrm{eV}} \right),$$

where m_ν is a neutrino mass. At the same time, there are different theoretical scenarios beyond the SM that predict much higher μ_ν values, thus giving hope to observe NMM experimentally in the not too distant future. Therefore, the major task faced by experiments is to enhance their sensitivity to the μ_ν value.

The strategy of experiments searching for NMM is as follows. One studies an inclusive cross section for (anti)neutrino–electron scattering, which is differential in the energy transfer T. In the ultrarelativistic limit $m_\nu \to 0$, it is given by an incoherent sum of the SM contribution, which is due to weak interaction that conserves the neutrino helicity, and the helicity-flipping contribution, which is due to μ_ν,

$$\frac{d\sigma}{dT} = \frac{d\sigma_{\mathrm{SM}}}{dT} + \frac{d\sigma_{(\mu)}}{dT}. \tag{1}$$

In the case of reactor experiments, where one deals with electron antineutrinos, the SM term is given by

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

where E_ν is the incident antineutrino energy, $g_A = -1/2$ and $g_V = (4\sin^2\theta_W + 1)/2$, with θ_W being the Weinberg angle. The μ_ν cross section is given by [11, 12]:

$$\frac{d\sigma_{(\mu)}}{dT} = 4\pi\alpha\mu_\nu^2 \left(\frac{1}{T} - \frac{1}{E_\nu} \right), \tag{3}$$

where α is the fine-structure constant. Thus, the two components of cross section (1) exhibit quite different dependencies on the recoil-electron kinetic energy T. Namely, at low T values the SM cross section is practically constant in T, while that due to μ_ν behaves as $1/T$. This means that the experimental sensitivity to the NMM value critically depends on lowering the energy threshold of the detector employed for measurement of the recoil-electron spectrum.

Formulas (2) and (3) assume the electron to be free and initially at rest. The energy threshold reached so far in the aforementioned GEMMA experiment with a HPGe detector is 2.8 keV [4]. This value is already much lower than the binding energy of K-electrons in Ge atoms ($\sim$ 10 keV). This fact makes it necessary to take into account the atomic effects beyond the free-electron (FE) approximation. The results of the corresponding treatment performed in [13] suggested that the electron binding in atoms can dramatically increase the μ_ν contribution to differential cross section (1) as compared with the FE case. However, the careful and detailed theoretical analysis [14–16] has found no evidence of the claimed «atomic ionization effect». Moreover, it provided general arguments supporting the so-called stepping approximation formulated in [17] on the basis of numerical calculations for various targets. According to the stepping approximation, the cross section $d\sigma/dT$ for knocking out an electron from an atomic orbital follows the FE dependence on T all the way down to the ionization threshold T_I for this orbital with a very small (at most a few percent) deviation. And the orbital becomes «inactive» when $T < T_I$, thus producing a sharp step in the T dependence of $d\sigma/dT$ summed over all occupied atomic levels.

Recently, the authors of [18] deduced by means of numerical calculations that the μ_ν contribution to ionization of the He target by impact of electron antineutrinos from reactor and tritium sources strongly departures from the stepping approximation, exhibiting large enhancement relative to the FE approximation. According to [18], the effect is maximal when the T value approaches the ionization threshold in helium, $T_I = 24.5874$ eV, where the relative enhancement is as large as almost eight orders of magnitude. It was thus suggested that this finding might have an impact on searches for μ_ν, provided that its value falls within the range 10^{-13}–$10^{-12}\mu_B$. The purpose of the present article is to show that (i) the result of [18] is erroneous and (ii) the stepping approximation for helium is well applicable, except the energy region $T \sim T_I$, where the differential cross section substantially decreases relative to the FE case.

1. THEORY OF NEUTRINO-IMPACT IONIZATION OF HELIUM

We consider the process where an electron antineutrino with energy E_ν scatters on a He atom at energy and spatial-momentum transfers T and $\mathbf{q}$, respectively. In what follows we focus on the ionization channel of this process in the kinematical regime $T \ll E_\nu$, which mimics a typical situation with reactor ($E_\nu \sim 1$ MeV) and tritium ($E_\nu \sim 10$ keV) antineutrinos when the case $T \to T_I$ is concerned. The He target is assumed to be in its ground state $|\Phi_i\rangle$ with the corresponding energy E_i. Since for helium one has $\alpha Z \ll 1$, where $Z = 2$ is the nuclear charge, the state $|\Phi_i\rangle$ can be treated nonrelativistically. As we are interested in the energy region $T \sim T_I$, the final He state $|\Phi_f\rangle$ (with one electron in continuum) can also be treated in the nonrelativistic approximation.

Under the above assumptions, the SM and μ_ν components of the differential cross section for the discussed ionization process can be presented as [16]:

$$\frac{d\sigma_{\rm SM}}{dT} = \frac{G_F^2}{4\pi}(1 + 4\sin^2\theta_W + 8\sin^4\theta_W)\int\limits_{T^2}^{4E_\nu^2} S(T,q^2)\,dq^2, \tag{4}$$

$$\frac{d\sigma_{(\mu)}}{dT} = 4\pi\alpha\mu_\nu^2\int\limits_{T^2}^{4E_\nu^2} S(T,q^2)\,\frac{dq^2}{q^2}, \tag{5}$$

where $S(T,q^2)$ is the dynamical structure factor given by

$$S(T,q^2) = \sum_f \left|\langle\Phi_f(\mathbf{r}_1,\mathbf{r}_2)|\mathrm{e}^{i\mathbf{q}\mathbf{r}_1} + \mathrm{e}^{i\mathbf{q}\mathbf{r}_2}|\Phi_i(\mathbf{r}_1,\mathbf{r}_2)\rangle\right|^2 \delta(T - E_f + E_i). \tag{6}$$

Here the f sum runs over all final He states having one electron ejected in continuum, with E_f being their energies.

For evaluation of dynamical structure factor (6) we employ the same models of the initial and final He states as in [18]. The initial state is given by a product of two $1s$ hydrogen-like wave functions with an effective charge Z_i,

$$\Phi_i(\mathbf{r}_1,\mathbf{r}_2)=\varphi_{1s}(Z_i,\mathbf{r}_1)\varphi_{1s}(Z_i,\mathbf{r}_2),\qquad \varphi_{1s}(Z_i,\mathbf{r})=\sqrt{\frac{Z_i^3}{\pi a_0^3}}\,\mathrm{e}^{-Z_i r/a_0},\tag{7}$$

where $a_0=1/(\alpha m_e)$ is the Bohr radius. The final state has the form

$$\Phi_f(\mathbf{r}_1,\mathbf{r}_2)=\frac{1}{\sqrt{2}}[\varphi^-_{\mathbf{k}}(Z_f,\mathbf{r}_1)\varphi_{1s}(Z,\mathbf{r}_2)+\varphi^-_{\mathbf{k}}(Z_f,\mathbf{r}_2)\varphi_{1s}(Z,\mathbf{r}_1)],\tag{8}$$

where $\varphi^-_{\mathbf{k}}(Z_f,\mathbf{r})$ is an outgoing Coulomb wave for the ejected electron with spatial momentum $\mathbf{k}$. Z_f is the effective charge experienced by the ejected electron in the field of the final He^+ ion. Contributions to the dynamical structure factor from the excited He^+ states are neglected due to their very small overlap with the K-electron state in the He atom.

To avoid nonphysical effects connected with nonorthogonality of states (7) and (8), we use the Gram–Schmidt orthogonalization

$$|\Phi_f\rangle\to|\Phi_f\rangle-\langle\Phi_i|\Phi_f\rangle|\Phi_i\rangle.$$

Substitution of (7) and (8) into (6) thus yields

$$S(T,q^2)=\int\frac{d\mathbf{k}}{(2\pi)^3}|F(\mathbf{k},\mathbf{q})|^2\delta\left(T-\frac{k^2}{2m_e}+2\alpha^2 m_e-Z_i^2\alpha^2 m_e\right),\tag{9}$$

where $k=\sqrt{2m_e(T+2\alpha^2 m_e-Z_i^2\alpha^2 m_e)}$, and

$$F(\mathbf{k},\mathbf{q})=\sqrt{2}\langle\varphi^-_{\mathbf{k}}(Z_f,\mathbf{r}_1)\varphi_{1s}(Z,\mathbf{r}_2)|\,\mathrm{e}^{i\mathbf{q}\mathbf{r}_1}+\mathrm{e}^{i\mathbf{q}\mathbf{r}_2}-2\rho_{1s}(\mathbf{q})|\varphi_{1s}(Z_i,\mathbf{r}_1)\varphi_{1s}(Z_i,\mathbf{r}_2)\rangle\tag{10}$$

is the inelastic form factor, with

$$\rho_{1s}(\mathbf{q})=\int\varphi_{1s}(Z_i,\mathbf{r})\,\mathrm{e}^{i\mathbf{q}\mathbf{r}}\varphi_{1s}(Z_i,\mathbf{r})\,d\mathbf{r}.\tag{11}$$

It is straightforward to perform the further calculation of the dynamical structure factor analytically[1] (see, for instance, textbook [19]).

Finally, the usual choice of the effective charges is $Z_i=27/16\approx1.69$ and $Z_f=1$ (see, for instance, [20] and references therein). The value $Z_i=27/16$ follows from the variational procedure that minimizes the ground-state energy E_i, while the value $Z_f=1$ ensures the correct asymptotic behavior of the final state. However, the authors of [18] utilized in their calculations the values $Z_i=1.79$ and $Z_f=1.1$ derived from fitting the photoionization cross-section data on helium with the present model of the He states.

[1]The resulting expressions are omitted for the sake of brevity.

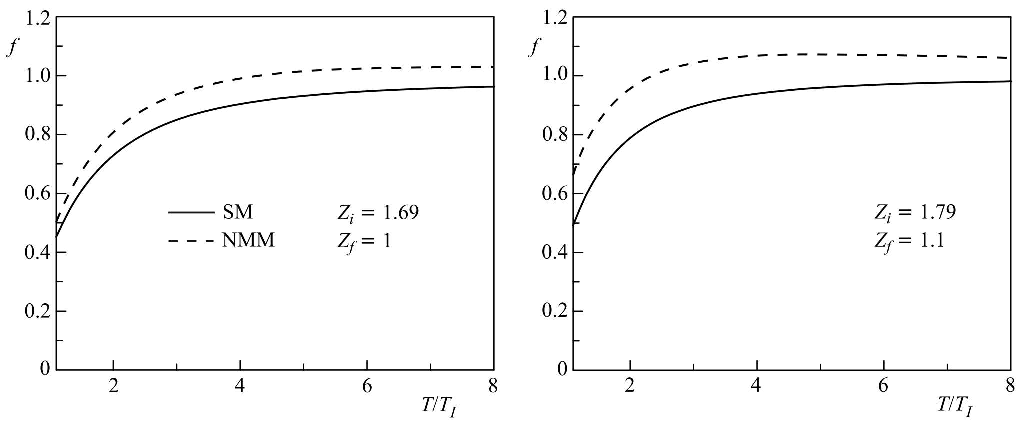
2. RESULTS AND DISCUSSION

The departures of differential cross sections (4) and (5) from the FE approximation are characterized by the respective atomic factors

$$f_{\rm SM} = \frac{d\sigma_{\rm SM}/dT}{d\sigma_{\rm SM}^{\rm FE}/dT}, \qquad f_{\rm NMM} = \frac{d\sigma_{(\mu)}/dT}{d\sigma_{(\mu)}^{\rm FE}/dT}, \tag{12}$$

where $d\sigma_{\rm SM}^{\rm FE}/dT$ and $d\sigma_{(\mu)}^{\rm FE}/dT$ are the SM and μ_ν contributions to the differential cross section for scattering of an electron antineutrino on two free electrons. Let us recall that following [18] one should expect the $f_{\rm NMM}$ value to be of about 10^8 at $T \to T_I$.

Numerical results for atomic factors (12) are shown in the Figure. They correspond to the kinematical regime $T \ll \alpha m_e \ll 2E_\nu$, which is typically realized both for reactor and for tritium antineutrinos when $T < 200$ eV. Note that in such a case one can safely set the upper limit of integrals in (4) and (5) to infinity, as the dynamical structure factor $S(T, q^2)$ rapidly falls down when $q \gtrsim \alpha m_e$ and practically vanishes in the region $q \gg \alpha m_e$. It can be seen from the Figure that atomic factors exhibit similar behaviors for both sets of the Z_i and Z_f parameters discussed in the previous section. Namely, their values are minimal (~ 0.5) at the ionization threshold, $T = T_I$, and tend to unity with increasing T. The latter tendency is readily explained by approaching the FE limit. It can be also seen that a more or less serious deviation ($> 10\%$) of the present results from the stepping approximation is observed only in the low-energy region $T < 100$ eV.



Atomic factors as functions of the energy transfer

Thus, the present calculations do not confirm the huge enhancement of the μ_ν contribution with respect to the FE approximation. Moreover, in accord with various calculations for other atomic targets [14–17,21–24], we find that at small energy-transfer values the electron binding in helium leads to the appreciable reduction of the differential cross section relative to the FE case. We attribute the erroneous prediction of [18] to the incorrect dynamical model that draws an analogy between the NMM-induced ionization and photoionization. Indeed, as discussed in [14], the virtual photon in the NMM-induced ionization process can be treated as real only when $q \to T$. However, the integration in (5) involves the q values ranging from T up to $2E_\nu$. Since $E_\nu \gg T$, the real-photon picture appears to be applicable only in the vicinity of the lower integration limit. When moving away from that momentum region, one encounters a strong departure from the real-photon approximation, which treats the integrand as a constant in the whole integration range, assuming it to be equal to its value at $q = T$, that is,

$$\frac{1}{q^2}\, S(T, q^2) = \frac{1}{T^2}\, S(T, T^2).$$

Such an approach is manifestly unjustified, and it gives rise to the spurious enhancement of the μ_ν contribution to the differential cross section.

3. SUMMARY

We carried out a theoretical analysis of ionization of helium by electron-antineutrino impact. Our calculations showed no evidence of the enhancement of the electromagnetic contribution as compared with the FE case. In contrast, in line with the previous studies on other targets, we found that the magnitudes of the differential cross sections decrease relative to the FE approximation when the energy transfer is close to the ionization threshold. Thus, no sensitivity enhancement can be expected when using the He target in searches for NMM. And the stepping approximation appears to be valid, within a few-percent accuracy, down to the energy-transfer values as low as almost 100 eV.

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