PROCEEDINGS OF SCIENCE

Neutrino electromagnetic interactions in elastic neutrino-nucleus scattering

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The nonzero neutrino masses open the door for neutrino electromagnetic interactions. We study how these interactions may manifest themselves in elastic neutrino-nucleus scattering processes. Following our approach developed for the case of elastic neutrino-electron and neutrino-proton collisions, in our formalism we account for possible electromagnetic form factors of massive neutrinos: the charge, magnetic, electric, and anapole form factors of both diagonal and transition types. We give an illustration of how a nonzero neutrino millicharge can influence the differential cross section of elastic neutrino scattering on a spin-0 nuclear target.

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1. Introduction

There are a large number of experiments investigating neutrino oscillations and their interactions. In both cases, it is important to theoretically investigate neutrino scattering on various targets [1, 2], since scattering processes are either a tool for detecting neutrino fluxes: the process of neutrino scattering on a nucleus studied in this work contributes to the signals of such experiments as COHERENT [3, 4], registration of supernova neutrinos [5], etc.; or a tool for studying fundamental interactions of neutrinos: in this work, the contribution of the neutrino electromagnetic properties is in focus. The latter neutrino properties emerge in different extensions of the Standard Model, and they include [6]: millicharges and charge radii, electric, magnetic and anapole moments.

2. The differential cross section of elastic neutrino-nucleus scattering

We consider the process where an ultrarelativistic neutrino with energy E_ν originates from a source (reactor, accelerator, the Sun, etc.) and elastically scatters on a nucleus in a detector at energy-momentum transfer $q = (T, \mathbf{q})$. If the neutrino is born in the source in the flavor state $|\nu_\ell\rangle$, then its state in the detector is $|\nu_\ell(\mathcal{L})\rangle = \sum_{k=1}^{3} U_{\ell k}^* \exp(-i\frac{m_k^2}{2E_\nu}\mathcal{L})|\nu_k\rangle$, where $\mathcal{L}$ is the source-detector distance. We assume the target nucleus to be free and at rest in the lab frame. The matrix element of the transition $\nu_\ell(\mathcal{L}) + X \to \nu_j + X$, where X is a nucleus, due to weak interaction is given by

$$\mathcal{M}_j^{(w)} = \frac{G_F}{\sqrt{2}} U_{\ell j}^* e^{-i\frac{m_j^2}{2E_\nu}\mathcal{L}} \bar{u}_{j,\lambda'}^{(\nu)}(k')\gamma^\mu(1-\gamma^5)u_{j,\lambda}^{(\nu)}(k) J_\mu^{(NC)}(q). \tag{1}$$

Here $J_\lambda^{(NC)}$ is a weak neutral current of a nucleus, $\bar{u}_{j,\lambda'}^{(\nu)}(k') = u_{j,\lambda'}^{(\nu)\dagger}(k')\gamma^0$, where $u_{j,\lambda}^{(\nu)}(k)$ is the bispinor amplitude of the massive neutrino state $|\nu_j\rangle$ with 4-momentum k and spin state λ. The matrix element due to electromagnetic interaction is

$$\mathcal{M}_j^{(\gamma)} = -\frac{4\pi\alpha}{q^2} \sum_{k=1}^{3} U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}\mathcal{L}} \bar{u}_{j,\lambda'}^{(\nu)}(k')\Lambda_{jk}^{(\mathrm{EM};\nu)\mu}(q) u_{k,\lambda}^{(\nu)}(k) J_\mu^{(EM)}(q), \tag{2}$$

where $J_\mu^{(EM)}$ is the electromagnetic current of the nucleus and $\Lambda_{jk}^{(\mathrm{EM};\nu)\mu}$ is the neutrino electromagnetic vertex [6]. The nuclear currents can be expanded as follows:

$$J_\mu^{(NC)}(q) = 2M[g_{\mu 0}\mathcal{F}_1(\vec{q}) - g_{\mu i}\mathcal{G}_A^i(\vec{q})], \qquad J_\mu^{(EM)}(q) = 2M g_{\mu 0}\mathcal{F}_Q(\vec{q}). \tag{3}$$

Here M is the nuclear mass, and $\mathcal{F}_1, \mathcal{G}_A^i$ and $\mathcal{F}_Q$ are nuclear vector, axial and charge form factors respectively:

$$\begin{aligned}
\mathcal{F}_1(\vec{q}) &= \frac{1}{(2\pi)^3}\int d^3r e^{i\vec{q}\cdot\vec{r}} \langle n, J, M_J'| \sum_{k=0}^{Z+N} g_V^{N_{(k)}} \delta^3(\vec{r}-\vec{r}_k)|n, J, M_J\rangle, \\
\mathcal{G}_A^i(\vec{q}) &= \frac{1}{(2\pi)^3}\int d^3r e^{i\vec{q}\cdot\vec{r}} \langle n, J, M_J'| \sum_{k=0}^{Z+N} g_A^{N_{(k)}} \sigma_{(k)}^i \delta^3(\vec{r}-\vec{r}_k)|n, J, M_J\rangle, \\
\mathcal{F}_Q(\vec{q}) &= \frac{1}{(2\pi)^3}\int d^3r e^{i\vec{q}\cdot\vec{r}} \langle n, J, M_J'| \sum_{k=0}^{Z} \delta^3(\vec{r}-\vec{r}_k)|n, J, M_J\rangle.
\end{aligned} \tag{4}$$

When evaluating the cross section, we neglect the neutrino masses. Since the final massive state of the neutrino is not resolved in the detector, the differential cross section measured in the scattering experiment is given by

$$\frac{d\sigma}{dT} = \frac{|\mathcal{M}|^2}{32\pi E_\nu^2 m_N}, \qquad |\mathcal{M}|^2 = \sum_{j=1}^{3} \left| \mathcal{M}_j^{(w)} + \mathcal{M}_j^{(\gamma)} \right|^2, \tag{5}$$

where averaging over initial and summing over final spin polarizations is assumed. The cross section for elastic neutrino-nucleus scattering is

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} \left[\mathcal{C}_V \left(2 - \frac{MT}{E_\nu^2} \right) + \frac{1}{2J+1} \sum_{M_J M_{J'}} |\mathcal{G}_A^z|^2 \left(2 + \frac{MT}{E_\nu^2} \right) \right] + \frac{\pi\alpha^2}{m_e^2} \frac{|\mathcal{F}_Q|^2}{T} |\mu_\nu(\mathcal{L}, E_\nu)|^2,$$
$$\mathcal{C}_V = \sum_j \left| \sum_k U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}\mathcal{L}} (\delta_{jk}\mathcal{F}_1 - \mathcal{F}_Q Q_{jk}) \right|^2, \qquad Q_{jk} = \frac{2\sqrt{2}\pi\alpha}{G_F q^2} \left[(e_\nu)_{jk} + \frac{1}{6} q^2 \langle r_\nu^2 \rangle_{jk} \right], \tag{6}$$

with $|\mu_\nu(\mathcal{L}, E_\nu)|^2 = \sum_{j=1}^3 \left| \sum_{k=1}^3 U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}\mathcal{L}} (\mu_\nu)_{jk} \right|^2$ [1], where μ_ν, e_ν, and $\langle r_\nu^2 \rangle$ are, respectively, the neutrino magnetic moment (in units of μ_B), millicharge (in units of e) and charge radius.

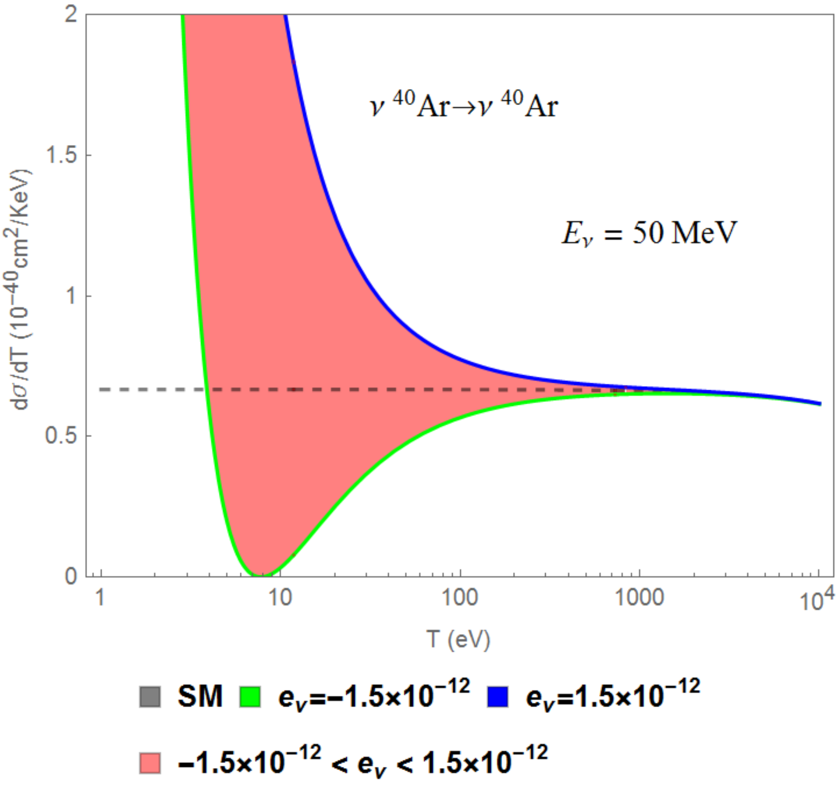

Figure 1: The differential cross section of elastic neutrino scattering on ^{40}Ar with account for the diagonal neutrino millicharge.

For illustrative purposes we present numerical calculations for elastic neutrino scattering on the ^{40}Ar nucleus with parametrization of the nuclear form factors that can be found in [7] and references

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therein. In Fig. 1 we show our results in the case of $E_\nu = 50$ MeV and a zero source-detector distance, with or without diagonal neutrino millicharge at the level of $|e_\nu| \leq 1.5 \times 10^{-12}$ [8, 9].

3. Summary and conclusions

Elastic neutrino-nucleus scattering has been considered theoretically, taking into account the electromagnetic interactions of massive neutrinos. Thus, the process under consideration has two channels: through the exchange of a Z boson and a photon. In both cases, the nuclear form factors are taken into account. In addition, neutrino oscillations on the source-detector base are taken into account. We have performed numerical calculations for the neutrino energy and nuclear target relevant to the COHERENT experiment and have accounted for the neutrino millicharge.

The developed formalism contains information about both neutrino electromagnetic form factors and nuclear form factors. This feature allows the expression derived for the differential cross section to be used in various studies. Among them are neutrino experiments with short and long baselines, the study of neutrino interactions and oscillations in matter, registration of neutrinos from supernova explosions, the search for the electromagnetic characteristics of neutrinos.

The results of this work contribute to the development of a systematic approach to studying the properties of neutrinos in their elastic scattering on complex targets (nuclei, atoms, condensed matter systems).

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