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Elastic neutrino-nucleon scattering: The effects of neutrino electromagnetic properties and polarization

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1 Introduction

There are a large number of experiments investigating both neutrino oscillations and their interactions. In both cases, it is important to theoretically investigate neutrino scattering on various targets [1–3], since scattering processes are either a tool for detecting neutrino fluxes: the processes of neutrino scattering on a nucleon or a nucleus contribute to the signals of such experiments as MiniBooNE [5], COHERENT [6,7] and registration of supernova neutrinos in JUNO [8]; or a tool for studying fundamental interactions of neutrinos. Also, the beyond Standard-Model theories discuss properties of right-handed neutrinos [4]. In this work, the contribution of the electromagnetic properties and polarization effects of neutrinos is studied. The neutrino electromagentic properties emerge in different extensions of the Standard Model, and they include [9]: millicharges, charge radii, electric, magnetic and anapole moments.

2 Cross sections

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 an nucleon in a detector at energy-momentum transfer $q = (T, \mathbf{q})$. In the most general case the neutrino state in the detector can be mixed both in flavour/mass space and in spin space. In our work we assume that neutrino was born in the source in flavour state ℓ and in spin mixed state such that its density matrix is diagonal with respect to the helicity basis, which coincides with the chirality basis in the tiny neutrino mass limit. Considering vacuum oscillations on the source-detector distance $\mathcal{L}$, the neutrino state in the detector is

$$|\nu_\ell^{L,R}(\mathcal{L})\rangle = \sum_{k=1}^{3} U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}\mathcal{L}} |\nu_k^{L,R}\rangle, \tag{1}$$

with probabilities α_L for left-handed (L) and $\alpha_R = 1 - \alpha_L$ for right-handed (R) neutrinos. We assume the target nucleon to be free and at rest in the lab frame. The matrix element of the transition $\nu_\ell(L)+N \to \nu_j+N$ due to weak interaction is given by

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

where $J_\lambda^{(\mathrm{NC})}$ is a weak neutral current of a nucleon, $\bar{u}_{j,\lambda'}^{(\nu)}(k') = u_{j,\lambda'}^{(\nu)\dagger}(k')\gamma^0$, 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

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

where $\Lambda_{jk}^{(\mathrm{EM};\nu)\mu}(q)$ is the electromagnetic neutrino vertex and $J_\mu^{(\mathrm{EM})}$ is the electromagnetic current of the nucleon. Assuming the target to be a free nucleon, these currents can be expanded as follows:

$$\begin{aligned} J_\lambda^{(\mathrm{NC})}(q) &= \bar{u}_{s'}^{(N)}(p')\Lambda_\lambda^{(\mathrm{NC};N)}(-q)u_s^{(N)}(p), \\ J_\lambda^{(\mathrm{EM})}(q) &= \bar{u}_{s'}^{(N)}(p')\Lambda_\lambda^{(\mathrm{EM};N)}(-q)u_s^{(N)}(p), \end{aligned} \tag{4}$$

where $\Lambda_\lambda^{(\mathrm{NC};N)}(q)$ and $\Lambda_\lambda^{(\mathrm{EM};N)}(-q)$ are the nucleon NC weak and EM vertexes, respectively. We consider the following vertexes:

$$\begin{aligned} \Lambda_\mu^{(\mathrm{EM};\nu)fi}(q) &= (\gamma_\mu - q_\mu \not{q}/q^2)[f_Q^{fi}(q^2) + f_A^{fi}(q^2)q^2\gamma_5] - i\sigma_{\mu\nu}q^\nu[f_M^{fi}(q^2) + if_E^{fi}(q^2)\gamma_5], \\ \Lambda_\mu^{(\mathrm{EM};N)}(q) &= \gamma_\mu F_Q^N(q^2) - \frac{i}{2m_N}\sigma_{\mu\nu}q^\nu F_M^N(q^2) \\ &\quad + \frac{1}{2m_N}\sigma_{\mu\nu}q^\nu\gamma_5 F_E^N(q^2) - \left(q^2\gamma_\mu - q_\mu\not{q}\right)\gamma_5\frac{F_A^N(q^2)}{m_N^2}, \\ \Lambda_\mu^{(\mathrm{NC};N)}(q) &= \gamma_\mu F_1^N(q^2) - \frac{i}{2m_N}\sigma_{\mu\nu}q^\nu F_2^N(q^2) - \gamma_\mu\gamma_5 G_A^N(q^2) + \frac{1}{m_N}G_P^N(q^2)q_\mu\gamma_5. \end{aligned} \tag{5}$$

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

$$\frac{d\sigma}{dT} = \frac{|\mathcal{M}|^2}{32\pi E_\nu^2 m_N}, \tag{6}$$

with the following absolute matrix element squared:

$$|\mathcal{M}|^2 = \sum_{j=1}^{3}\left|\mathcal{M}_j^{(w)} + \mathcal{M}_j^{(\gamma)}\right|^2, \tag{7}$$

where averaging over initial and summing over final spin polarizations of the nucleon and summing over final neutrino polarisations are assumed. Taking into account the initial neutrino mixed spin state, the cross section can be presented as

$$\frac{d\sigma}{dT} = \alpha_L\frac{d\sigma^L}{dT} + \alpha_R\frac{d\sigma^R}{dT}, \tag{8}$$

$\frac{d\sigma^K}{dT}$ are cross sections for the initial left-handed $(K = L)$ and right-handed $(K = R)$ neutrino spin states, respectively. Both of them can be split into helicity-preserving (hp) and helicity-flipping (hf) components (for the sake of brevity, we omit the argument $q^2 = -2m_N T$ in the expressions for the form factors); that is,

$$\begin{aligned} \frac{d\sigma^K}{dT} &= \frac{d\sigma^K_{\mathrm{hp}}}{dT} + \frac{d\sigma^K_{\mathrm{hf}}}{dT}, \\ \frac{d\sigma^K_{\mathrm{hp}}}{dT} &= \frac{G_F^2 m_N}{2\pi}\Bigg[\left(C_V^K - 2\mathrm{Re}\,C_{V\&A}^K + C_A^K\right) + \left(C_V^K + 2\mathrm{Re}\,C_{V\&A}^K + C_A^K\right)\left(1 - \frac{T}{E_\nu}\right)^2 \\ &\quad + \left(C_A^K - C_V^K\right)\frac{m_N T}{E_\nu^2} + C_M^K\frac{T}{2m_N}\left(2 + \frac{m_N T}{E_\nu^2} - \frac{2T}{E_\nu}\right) - C_E^K\frac{T}{2m_N}\left(2 - \frac{m_N T}{E_\nu^2} - \frac{2T}{E_\nu}\right) \\ &\quad + 2\frac{T}{E_\nu}\mathrm{Re}\,C_{A\&M}^K\left(2 - \frac{T}{E_\nu}\right) - 2\mathrm{Re}\,C_{V\&M}^K\frac{T^2}{E_\nu^2}\Bigg], \\ \frac{d\sigma^K_{\mathrm{hf}}}{dT} &= \frac{\pi\alpha^2}{m_e^2}|\mu_\nu^K(\mathcal{L}, E_\nu)|^2\Bigg[\left(\frac{1}{T} - \frac{1}{E_\nu}\right)F_Q^2 + \left(\frac{1}{T} - \frac{1}{E_\nu} - \frac{m_N}{2E_\nu^2}\right)\frac{T^2}{4m_N^2}F_A^2 \\ &\quad - \frac{T}{2E_\nu^2}F_Q F_M + \frac{\left(2 - \frac{T}{E_\nu}\right)^2 - \frac{2m_N T}{E_\nu^2}}{8m_N}F_M^2 - \frac{\left(2 - \frac{T}{E_\nu}\right)^2}{8m_N}F_E^2\Bigg], \end{aligned} \tag{9}$$

where [1]

$$\begin{aligned} C_V^K &= \sum_j\left|\sum_k U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}\mathcal{L}}(\delta_L^K\delta_{jk}F_1 - F_Q Q_{jk}^K)\right|^2, \quad Q_{jk}^{L,R} = \frac{2\sqrt{2}\pi\alpha}{G_F q^2}\left(f_Q^{jk} \mp q^2 f_A^{jk}\right), \\ C_{V\&A}^K &= \sum_j\left(\sum_k U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}\mathcal{L}}(\delta_L^K\delta_{jk}F_1 - F_Q Q_{jk}^K)\right)\left(\sum_n U_{\ell n}e^{i\frac{m_n^2}{2E_\nu}\mathcal{L}}\left(-\delta_L^K\delta_{jn}G_A + \frac{q^2 F_A Q_{jn}^K}{m_N^2}\right)\right), \\ C_A^K &= \sum_j\left|\sum_k U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}\mathcal{L}}\left(\delta_L^K G_A\delta_{jk} - \frac{q^2 F_A Q_{jk}^K}{m_N^2}\right)\right|^2, \\ C_M^K &= \sum_j\left|\sum_k U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}\mathcal{L}}(\delta_L^K F_2\delta_{jk} - F_M Q_{jk}^K)\right|^2, \qquad C_E^K = \sum_j\left|\sum_k U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}\mathcal{L}}F_E Q_{jk}^K\right|^2, \\ C_{A\&M}^K &= \sum_j\left(\sum_k U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}\mathcal{L}}\left(\delta_L^K\delta_{jk}G_A - \frac{q^2 F_A Q_{jk}^K}{m_N^2}\right)\right)\left(\sum_n U_{\ell n}e^{i\frac{m_n^2}{2E_\nu}\mathcal{L}}(\delta_L^K F_2\delta_{jn} - F_M Q_{jn}^K)\right), \\ C_{V\&M}^K &= \sum_j\left(\sum_k U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}\mathcal{L}}(-\delta_L^K\delta_{jk}F_1 + F_Q Q_{jk}^K)\right)\left(\sum_n U_{\ell n}e^{i\frac{m_n^2}{2E_\nu}\mathcal{L}}(\delta_L^K F_2\delta_{jn} - F_M Q_{jn}^K)\right), \\ |\mu_\nu^{L,R}(\mathcal{L}, E_\nu)|^2 &= \sum_j\left|\sum_k U_{\ell k}^* e^{-i\frac{m_k^2}{2E_\nu}\mathcal{L}}2m_e(f_M^{jk} \mp if_E^{jk})\right|^2. \end{aligned} \tag{10}$$

It is important to note that in the case of right-handed neutrino scattering cross section $\frac{d\sigma^R}{dT}$ only electromagnetic interactions can contribute. The differential cross section in (8) determines the shape of the recoil-nucleon spectrum, which can be measured in experiment.

3 Numerical results

Obviously, manifestations of neutrino electromagnetic properties should be much more pronounced in neutrino–proton rather than in neutrino–neutron scattering. In order to illustrate the characteristic effects of these properties, we present below the results of numerical calculations of the differential cross sections for elastic neutrino–proton scattering.

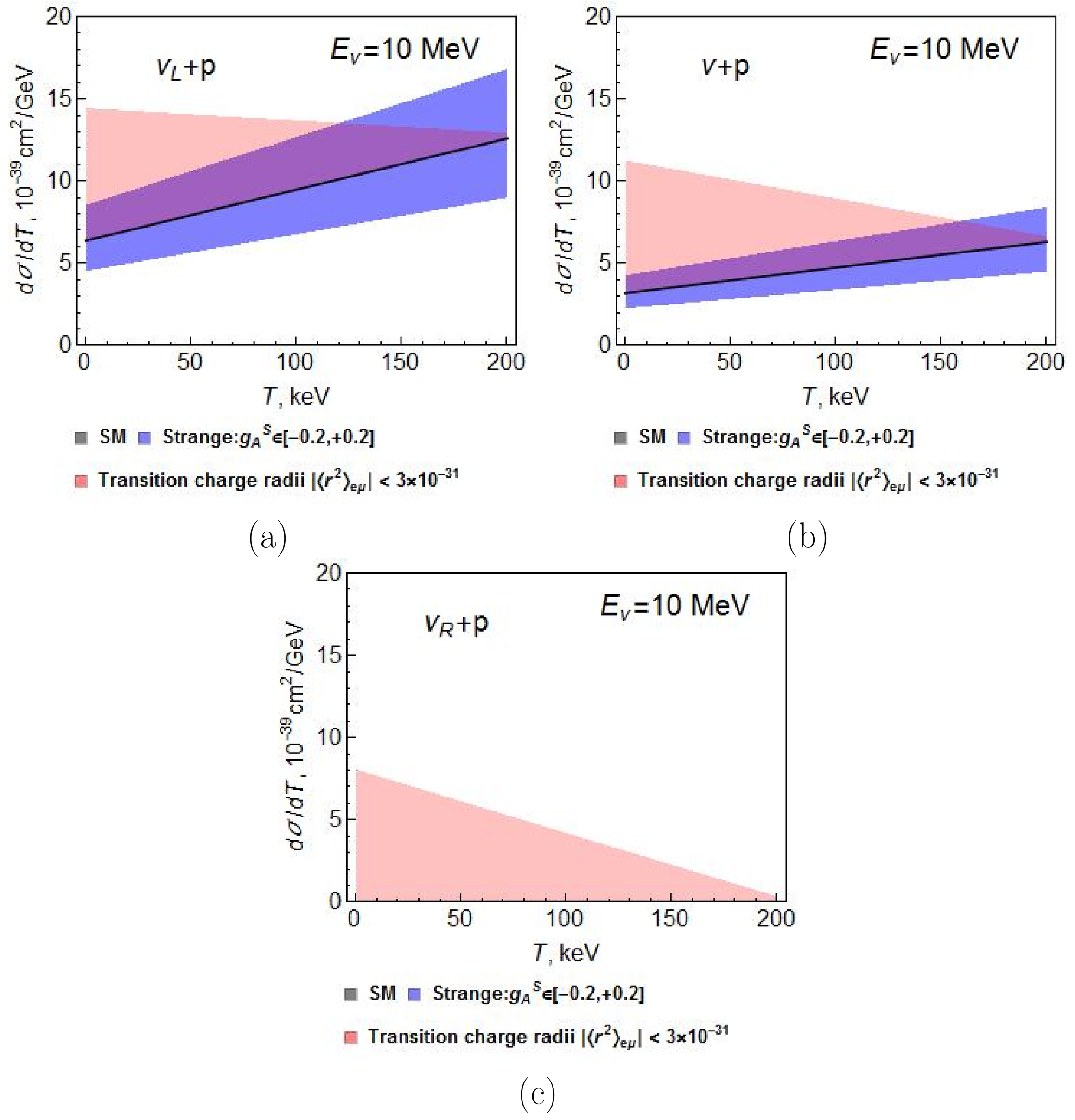

Figure 1: The differential cross sections of elastic neutrino-proton scattering for incident (a) left-handed, (b) unpolarazed and (c) right-handed neutrinos at $E_\nu = 10$ MeV.

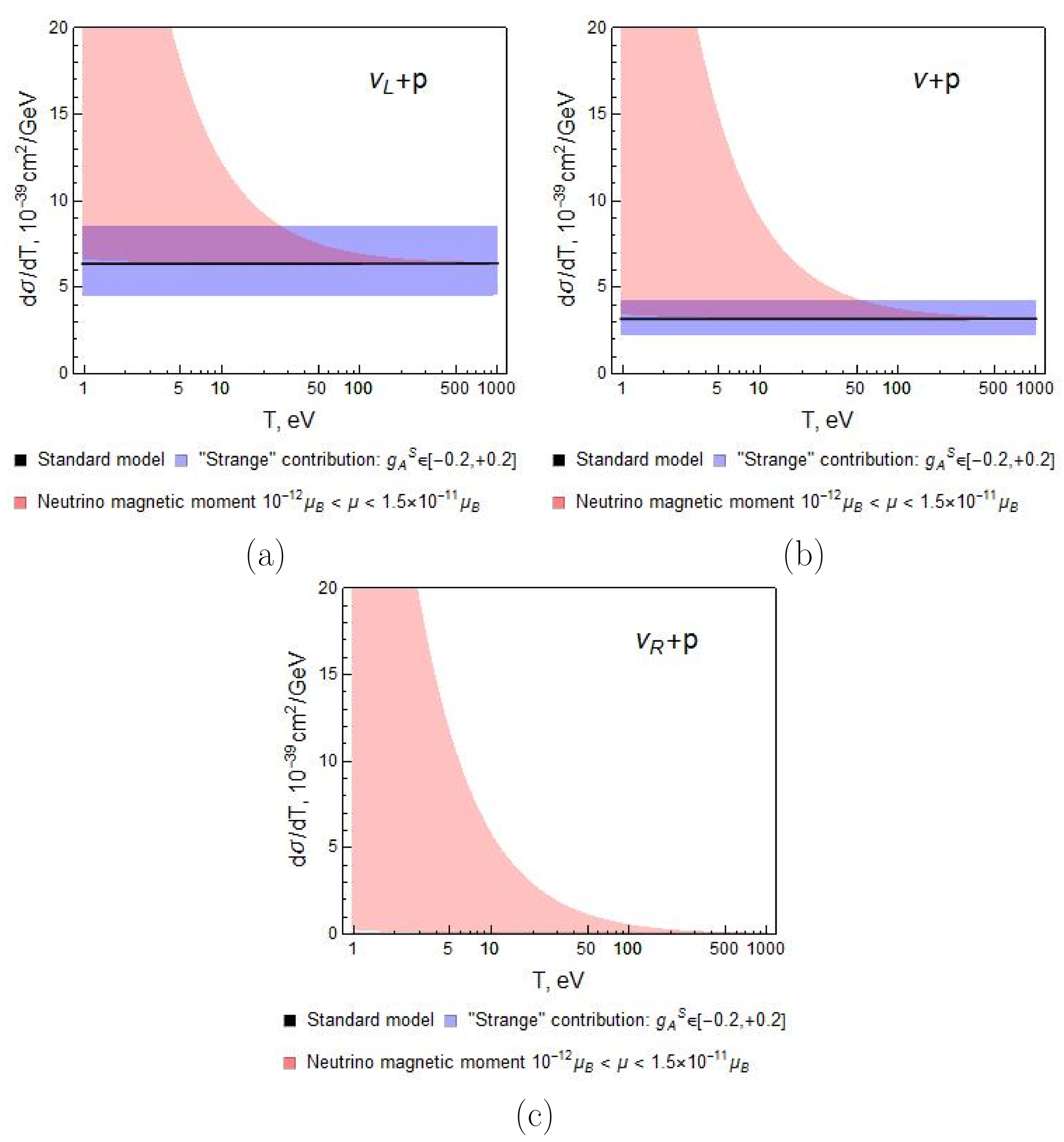

Figure 2: The differential cross sections of elastic neutrino-proton scattering for incident (a) left-handed, (b) unpolarazed and (c) right-handed neutrinos accounting for neutrino magnetic moments.

We restrict ourselves to the case of charge and magnetic electromagnetic form factors of a nucleon, accounting for the relation between the nucleon neutral weak and electromagnetic form factors

$$\begin{aligned} F_{1,2}^p(q^2) &= (\frac{1}{2} - 2\sin^2\theta_W)F_{Q,M}^p(q^2) - 1\frac{1}{2}F_{Q,M}^n(q^2) - \frac{1}{2}F_{1,2}^S(q^2), \\ F_{1,2}^n(q^2) &= (\frac{1}{2} - 2\sin^2\theta_W)F_{Q,M}^n(q^2) - 1\frac{1}{2}F_{Q,M}^p(q^2) - \frac{1}{2}F_{1,2}^S(q^2), \\ G_{A,P}^N(q^2) &= \frac{\tau_3}{2}G_{A,P}^{\mathrm{a}}(q^2) - \frac{1}{2}G_{A,P}^S(q^2), \end{aligned} \tag{11}$$

where $F_{1,2}^S$, $G_{A,P}^S$ are strange form factors of the nucleon. We use the parameterization that can be found in [10] (and references therein).
We present the numerical results for incident left-handed $(\alpha_L = 1)$, unpolarized $(\alpha_{L,R} = 1/2)$ and right-handed $(\alpha_R = 1)$ neutrino states, accounting for the nucleon strange form-factor contribution and the neutrino transition charge radii (Fig. 1) or the neutrino magnetic moments (Fig. 2).

4 Summary

Elastic neutrino-nucleon scattering has been considered theoretically, taking into account the electromagnetic interactions of massive neutrinos and their initial polarization. Thus, the processes under consideration have two channels: through the exchange of a Z^0 boson and a photon. The strange-quark contribution to the nucleon form factors that can have a similar effect as that due to the neutrino electromagnetic properties is taken into account. In addition, neutrino oscillations on the source-detector distance are taken into account in the formalism.
The derived cross sections contain information about the neutrino polarization and both the neutrino electromagnetic form factors and the nucleon form factors. This feature allows the obtained expressions 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 using elastic neutrino-proton scattering [8], the study of the anapole moment of the nucleon, the search for the electric dipole moment of the neutron, the search for the electromagnetic characteristics of neutrinos. We have performed numerical calculations for neutrino energies relevant for supernova explosions (Figs. 1,2), where one might expect neutrino spin oscuillations to take place. Thus, our results illustrate how electromagnetic neutrino properties can manifest themselves in the scattering of right-handed supernova 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).

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