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Transverse charge densities in the nucleon in nuclear matter

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ABSTRACT

We investigated the transverse charge densities in the nucleon in nuclear matter within the framework of the in-medium modified Skyrme model. The medium modification of the nucleon electromagnetic form factors are first discussed. The results show that the form factors in nuclear matter fall off faster than those in free space, as the momentum transfer increases. As a result, the charge radii of the nucleon become larger, as the nuclear matter density increases. The transverse charge densities in the nucleon indicate that the size of the nucleon tends to bulge out in nuclear matter. This salient feature of the swelling is more clearly observed in the neutron case. When the proton is transversely polarized, the transverse charge densities exhibit the distortion due to the effects of the magnetization.

1. It is of utmost importance to understand the structure of the nucleon in particle and nuclear physics, since the nucleon consists of the basic building block of matter. In particular, the nucleon electromagnetic (EM) form factors are the fundamental issue in that they reveal how the electric charge and magnetization of the quarks are distributed inside the nucleon. While the EM form factors have been studied well over several decades, their understanding is still not complete.

Recently, a series of new measurements of the free nucleon EM form factors has been carried out and has produced the remarkably precise data [1–8]. These new experimental results have subsequently intrigued both experimental and theoretical works (see, for example, the following reviews [9–11]). The experimental data with high precision enable one to make a flavor decomposition of the nucleon EM form factors with isospin and charge symmetries taken into account [12,13]. Moreover, generalized parton distributions (GPDs) have unveiled a novel aspect of the nucleon EM structure: The Fourier transforms of the nucleon EM form factors in the transverse plane, as viewed from a light front frame moving towards a nucleon, paint a tomographic picture of how the charge densities of quarks are distributed [14,15] transversely. These transverse charge densities of the quarks inside a nucleon have been already investigated for the unpolarized [16] and transversely polarized [17] nucleons.

It is of equal importance to examine how the EM structure of the nucleon is changed in nuclear matter. Studying the EM form factors of the nucleon in medium provides a new perspective on EM properties of the nucleon modified in nuclei [18–26]. In fact, the first experimental study of deeply virtual Compton scattering on (gaseous) nuclear targets (H, He, N, Ne, Kr, Xe) was reported in Ref. [27]. While uncertainties of the first measurement are so large that one is not able to observe nuclear modifications of the nucleon structure, future experiments will bring about more information on medium modifications of the EM properties of the nucleon.

In the present work, we want to investigate the nucleon EM form factors and the transverse charge densities of quarks inside a nucleon in nuclear matter within the framework of an in-medium modified Skyrme model. The Skyrme model has certain virtues: it is simple but respects chiral symmetry and its spontaneous symmetry breaking. Moreover, one can easily extend it to the study of nuclear matter, based on modifications of the pion in medium [28,29]. The energy-momentum tensor form factors of the nucleon, which are yet another fundamental form factors that are related to the generalized EM form factors, have been investigated in nuclear matter within this framework [30]. The results have explained certain interesting features of the modifications of the nucleon in nuclear matter such as the pressure and angular momentum. Indeed, we will also show in this work how the EM properties of the nucleon are changed in nuclear matter in a simple manner. We will also see that the transverse charge densities expose noticeably how the distribution of quarks undergo changes in the presence of nuclear medium.

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2. We begin with the in-medium modified effective chiral Lagrangian [29]:

$$\mathcal{L}^* = \frac{F_\pi^2}{16}\mathrm{Tr}\left(\frac{\partial U}{\partial t}\right)\left(\frac{\partial U^\dagger}{\partial t}\right) - \frac{F_\pi^2}{16}\alpha_p(\mathbf{r})\mathrm{Tr}(\nabla U)\cdot(\nabla U^\dagger) + \frac{1}{32e^2\gamma(\mathbf{r})}\mathrm{Tr}\left[U^\dagger\partial_\mu U, U^\dagger\partial_\nu U\right]^2 + \frac{F_\pi^2 m_\pi^2}{16}\alpha_s(\mathbf{r})\mathrm{Tr}\left(U+U^\dagger-2\right), \tag{1}$$

where $F_\pi = 108.78$ MeV denotes the pion decay constant, $e = 4.85$ the Skyrme parameter, and m_π the experimental value of the pion mass $m_{\pi^0} = 134.98$ MeV. This set of the parameters reproduce qualitatively well the experimental data for the nucleon and Δ-isobar in free space.

The medium functionals, α_s, α_p and γ, are expressed as

$$\alpha_s = 1 - \frac{4\pi b_0\rho(\mathbf{r})f}{m_\pi^2},$$
$$\alpha_p = 1 - \frac{4\pi c_0\rho(\mathbf{r})}{f + g_0' 4\pi c_0\rho(\mathbf{r})},$$
$$\gamma = \exp\left(-\frac{\gamma_{\mathrm{num}}\rho(\mathbf{r})}{1+\gamma_{\mathrm{den}}\rho(\mathbf{r})}\right). \tag{2}$$

They encode information on how the surrounding environment influences properties of the single skyrmion. The parameters α_s and α_p are related to the corresponding phenomenological S- and P-wave pion–nucleus scattering lengths and volumes, i.e. $b_0 = -0.024m_\pi^{-1}$ and $c_0 = 0.06m_\pi^{-3}$, respectively, which describe the pion physics in a nucleus [31]. The last functional γ is parameterized in the form of an exponential function and represents the medium modification of the Skyrme parameter. This simple form with two variational parameters $\gamma_{\mathrm{num}} = 0.47m_\pi^{-3}$ and $\gamma_{\mathrm{den}} = 0.17m_\pi^{-3}$ reproduce the correct position of the saturation point of symmetric nuclear matter [29]. The ρ stands for the density of nuclear matter. The $g_0' = 0.7$ denotes the Lorentz–Lorenz or correlation parameter and $f = 1 + m_\pi/m_N^{\mathrm{free}}$ is the kinematical factor.

Since we consider isospin symmetric infinite nuclear matter in the present work, the density can be regarded as a homogeneous and constant one. Thus, we can simply choose the spherically symmetric "hedgehog" for the soliton:

$$U = \exp\{i\boldsymbol{n}\cdot\boldsymbol{\tau}F(r)\}, \tag{3}$$

where $\boldsymbol{n}$ denotes the unit radial vector in coordinate space and $\boldsymbol{\tau}$ the usual Pauli isospin matrices.

3. We refer to Ref. [29] for the details of the minimization procedure and other useful formulas. In this work, we concentrate on EM properties of the nucleon.

The nucleon matrix element of the EM current is expressed in terms of the Dirac and Pauli form factors:

$$\langle N(p',S')|J_\mu^{EM}(0)|N(p,S)\rangle = \bar{u}_N(p',S')\left[\gamma_\mu F_1^*(q^2) + i\frac{\sigma_{\mu\nu}q^\nu}{2m_N}F_2^*(q^2)\right]u_N(p,S), \tag{4}$$

where the EM current is defined in terms of the baryon current B_μ and the isovector current $J_\mu^{(3)}$

$$J_\mu^{EM}(0) = \frac{1}{2}\left(B_\mu(0) + J_\mu^{(3)}(0)\right). \tag{5}$$

The γ_μ denotes the Dirac matrices and $u_N(p,S)$ stands for the Dirac spinor for the nucleon with mass m_N, momentum p, and the third component of its spin S. The $\sigma_{\mu\nu}$ is the spin operator $i[\gamma_\mu,\gamma_\nu]/2$ and q^2 the square of the momentum transfer $q^2 = -Q^2$ with $Q^2 > 0$. The asterisk means the form factors in medium. In the Breit frame, the in-medium modified Sachs EM form factors of the nucleon are defined as

$$G_E^*(Q^2) = \frac{1}{2}\int d^3r\, e^{i\boldsymbol{q}\cdot\boldsymbol{r}} J_0^{EM}(\mathbf{r}),$$
$$G_M^*(Q^2) = \frac{m_N}{2}\int d^3r\, e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\left[\mathbf{r}\times\boldsymbol{J}^{EM}(\mathbf{r})\right]_3, \tag{6}$$

where J^0 and $\boldsymbol{J}$ correspond respectively to the temporal and spatial components of the properly normalized sum of the baryonic (topological) current B_μ and the third component of the isovector (Noether) current V_μ^*.

The isoscalar (S) and isovector (V) EM formfactors are generically expressed as

$$G_{E,M}^{S,V,*}(Q^2) = \int d^3r\, e^{iqr\cos\theta}\rho_{E,M}^{S,V}(r,\theta), \tag{7}$$

where $\rho_E^{S,V}$ and $\rho_M^{S,V}$ denote the three-dimensional Fourier transforms of the corresponding form factors, which are written, respectively, as

$$\rho_{\mathrm{E}}^{\mathrm{S}}(r,\theta) = -\frac{F'\sin^2 F}{4\pi^2 r^2},$$
$$\rho_{\mathrm{M}}^{\mathrm{S}}(r,\theta) = -\frac{m_N}{8\pi^2\lambda^*}F'\sin^2 F\sin^2\theta,$$
$$\rho_{\mathrm{E}}^{\mathrm{V}}(r,\theta) = \frac{\sin^2 F}{12\lambda^*}\left\{F_\pi^2 + \frac{4}{e^2\gamma}\left(F_r^2 + \frac{\sin^2 F}{r^2}\right)\right\},$$
$$\rho_{\mathrm{M}}^{\mathrm{V}}(r,\theta) = \frac{m_N}{3}\left\{F_\pi^2\alpha_p + \frac{4}{e^2\gamma}\left(F'^2 + \frac{\sin^2 F}{r^2}\right)\right\} \times \sin^2 F\sin^2\theta. \tag{8}$$

Here, λ^* stands for the medium-modified moment of inertia of the soliton. Note that because of the modification of the Skyrme term, all of the electromagnetic charge distributions except for the isoscalar electric charge depend explicitly on the medium density. Moreover, the medium functional α_p appears in the expression for the isovector distribution of the magnetization.

The charges of the proton (p) and neutron (n) are defined as

$$\begin{pmatrix} Q^p \\ Q^n \end{pmatrix} := \int d^3r\left\{\rho_E^S(r,\theta) \pm \rho_E^V(r,\theta)\right\}, \tag{9}$$

where the distributions include the prefactor $1/2$. Similarly, the magnetic moments of the nucleon are defined in terms of the distributions of the magnetization

$$\begin{pmatrix} \mu_p \\ \mu_n \end{pmatrix} := \int d^3r\left\{\rho_M^S(r,\theta) \pm \rho_M^V(r,\theta)\right\}. \tag{10}$$

The Fourier transforms of the Laplacian with respect to the momentum transfer of the electric form factor are expressed as

$$\langle r^2\rangle_{I=0}^* = -\frac{2}{\pi}\int_0^\infty F'\sin^2 F r^2\,dr,$$
$$\langle r^2\rangle_{I=1}^* = \frac{2\pi}{3\lambda^*}\int_0^\infty\left[F_\pi^2 + \frac{4}{e^2\gamma}\left(F'^2 + \frac{\sin^2 F}{r^2}\right)\right]\sin^2 F r^4\,dr. \tag{11}$$