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Energy–momentum tensor form factors of the nucleon in nuclear matter

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ABSTRACT

The nucleon form factors of the energy–momentum tensor are studied in nuclear medium in the framework of the in-medium modified Skyrme model. We obtain a negative D-term, in agreement with results from other approaches, and find that medium effects make the value of d_1 more negative.

1. Understanding the structure of the nucleon has been one of fundamental issues well over decades. While the scalar, vector and axial-vector properties of the nucleon have been studied extensively and comprehended to a great extent, its energy–momentum tensor (EMT) form factors have been drawn to attention only quite recently, long after Pagels proposed them [1]. The reason can be found in the fact that it is very difficult to get direct access to these form factors experimentally. However, the generalized parton distributions (GPDs) [2–5], which are accessible via hard exclusive reactions [6–15], make it possible to extract information on the EMT form factors of the nucleon. In particular, certain Mellin moments of the GPDs can be expressed in terms of the EMT form factors [3,16,17].

The nucleon matrix element of the total symmetric EMT are parameterized by three form factors as follows [16,17]

$$\begin{aligned}\langle p'|\hat{T}_{\mu\nu}(0)|p\rangle &= \bar{u}(p',s')\bigg[M_2(t)\frac{P_\mu P_\nu}{M_N} + J(t)\frac{i(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M_N} \\ &\quad + d_1(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M_N}\bigg]u(p,s), \qquad (1)\end{aligned}$$

where $P=(p+p')/2$, $\Delta=(p'-p)$ and $t=\Delta^2$. M_N is the nucleon mass, and $u(p,s)$ denotes the nucleon spinor with the polarization vector s defined such that it is given as $(0,\boldsymbol{s})$ in the rest frame in which $\boldsymbol{s}$ designates the axis of the spin quantization. The recent interest about the EMT form factors was stimulated by the fact that it is possible to define in QCD and to access in experiment the separate quark and gluon contributions to the form factors. The only presently known non-trivial piece of information is the decomposition of $M_2(t)$ at the zero-momentum transfer, which reveals that about 1/2 of the momentum of a fast moving nucleon is carried by quarks, and the other half by gluons. $J(t)$ provides analogous information on how the total angular momentum of quarks and gluons makes up the nucleon spin, but this information is presently not known. The interpretation of the last form factor $d_1(t)$ in Eq. (1) is less trivial but of equal significance for understanding the nucleon structure. It provides information on how the strong forces are distributed and stabilized in the nucleon [17,18].

In all theoretical approaches where it was studied so far, the so-called D-term $d_1 \equiv d_1(0)$ was found negative. This feature is expected to be deeply rooted in the spontaneous breakdown of chiral symmetry [19–21]. The form factor $d_1(t)$ can be extracted from the beam charge asymmetry in deeply virtual Compton scattering [20]. The EMT form factors of the nucleon have been studied in a variety of theoretical approaches: in lattice QCD [22–29], in chiral perturbation theory [30–34], in the chiral quark–soliton model [35–42] as well as in the Skyrme model [43]. Those of nuclei have also been studied [17,44–46].

It is also of great importance to understand how the nucleon undergoes changes in nuclear matter. Studying the EMT form factors of the nucleon in medium offers a new perspective on the

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internal structure of the nucleon, and an important step towards the understanding of how nucleon properties are modified in nuclei. The first experimental study of deeply virtual Compton scattering on (gaseous) nuclear targets (H, He, N, Ne, Kr, Xe) was reported in [47]. The admittedly sizable error bars of this first experiment did not allow to observe nuclear modifications. More precise future experiments of this type can in principle provide information on nuclear modifications of EMT form factors.

Thus, in the present Letter, we aim at investigating the form factors of the total EMT of the nucleon in nuclear matter within the framework of an in-medium modified SU(2) Skyrme model, extending the previous work [43]. The Skyrme model [48,49] provides a simple framework for the nucleon and connects chiral dynamics to the baryonic sector explicitly. Hence, the model can be easily extended to nuclear matter, modifications of chiral properties of the pion being taken into account. The changes of the nucleon in nuclear matter have been already examined within the in-medium modified Skyrme model [50,51]. In Ref. [52], the model has been further elaborated, the stabilizing term being refined in medium, which we will take as our framework to study the EMT form factors of the nucleon in nuclear matter.

2. We start with the in-medium modified chiral Lagrangian [52][1]

$$\mathcal{L}^* = \frac{F_\pi^2}{16}\mathrm{Tr}\big(\partial_0 U \partial^0 U^\dagger\big) - \alpha_p \frac{F_\pi^2}{16}\mathrm{Tr}(\nabla U)\cdot\big(\nabla U^\dagger\big) + \frac{1}{32e^2\gamma}\mathrm{Tr}\big[U^\dagger(\partial_\mu U), U^\dagger(\partial_\nu U)\big]^2 + \alpha_s \frac{m_\pi^2 F_\pi^2}{8}\mathrm{Tr}(U-2), \tag{2}$$

where U denotes the SU(2) pion field, F_π the pion decay constant, e a dimensionless parameter, and m_π the pion mass. The medium modifications are contained in the following functions [50–53]

$$\alpha_p(\rho) = 1 - \chi_p(\rho), \quad \chi_p(\rho) = \frac{4\pi c_0 \rho}{\eta + 4\pi c_0 g'\rho}, \quad \eta = 1 + \frac{m_\pi}{M_N}, \tag{3}$$

$$\alpha_s(\rho) = 1 + \frac{\chi_s(\rho)}{m_\pi^2}, \quad \chi_s(\rho) = -4\pi\eta b_0 \rho, \tag{4}$$

$$\gamma(\rho) = \exp\left(-\frac{\gamma_{\mathrm{num}}\rho}{1+\gamma_{\mathrm{den}}\rho}\right). \tag{5}$$

The $\alpha_{s,p}$ depend on the S- and P-wave pion–nucleus scattering lengths, volumes (b_0 and c_0), and the density ρ of nuclear matter [50,53], and g' is the Lorentz–Lorenz or correlation parameter. Similarly, the function γ in Eq. (5) describes the modification of the Skyrme term in nuclear matter proposed in Ref. [52] with γ_{num} and γ_{den} fitted to the coefficient of the volume term in the semiempirical mass formula. We can treat the modified chiral Lagrangian in terms of the renormalized effective constants $F_{\pi,t}^* = F_{\pi,t} = F_\pi$, $F_{\pi,s}^* = \alpha_p^{1/2} F_\pi$, $e^* = \gamma^{1/2} e$, and $m_\pi^* = (\alpha_s/\alpha_p)^{1/2} m_\pi$. The behavior of these parameters in nuclear matter is consistent with those in chiral perturbation theory [54] and QCD sum rules [55].

Homogeneous nuclear matter allows us to keep the hedgehog Ansatz for the pion field, i.e. $U = \exp[i\tau\frac{\mathbf{r}}{r}F(r)]$ with a profile function $F(r)$ in contrast to the case of local-density approximations for finite nuclei [56,57]. Consequently, one can immediately write the classical mass functional as

$$M_{\mathrm{sol}}^*[F] = 4\pi\int_0^\infty dr\, r^2\left[\frac{F_{\pi,s}^{*2}}{8}\left(\frac{2\sin^2 F}{r^2} + F'^2\right) + \frac{\sin^2 F}{2e^{*2}r^2}\left(\frac{\sin^2 F}{r^2} + 2F'^2\right) + \frac{m_\pi^{*2}F_{\pi,s}^{*2}}{4}(1-\cos F)\right], \tag{6}$$

where $F' = dF/dr$. The minimization of the mass functional (6) leads to the equation for $F(r)$ as follows

$$\left(\frac{r^2}{4} + \frac{2F\sin^2 F}{e^{*2}F_{\pi,s}^{*2}}\right)F'' + \frac{rF'}{2} + \frac{F'^2\sin 2F}{e^{*2}F_{\pi,s}^{*2}} - \frac{\sin 2F}{4} - \frac{\sin^2 F\sin 2F}{e^{*2}F_{\pi,s}^{*2}r^2} - \frac{m_\pi^{*2}r^2\sin F}{4} = 0 \tag{7}$$

with the boundary conditions $F(0) = \pi$ and $F(r)\to 0$ as $r\to\infty$ imposed by the unit topological number of the chiral soliton. Having performed a collective quantization, we arrive at the modified collective Hamiltonian

$$H^* = M_{\mathrm{sol}}^* + \frac{\boldsymbol{J}^2}{2\Theta^*} = M_{\mathrm{sol}}^* + \frac{\boldsymbol{I}^2}{2\Theta^*},$$
$$\Theta^* = \frac{2\pi}{3}\int_0^\infty dr\, r^2 s^2\left[F_{\pi,t}^2 + \frac{4F'^2}{e^{*2}} + \frac{4s^2}{e^{*2}r^2}\right], \tag{8}$$

where $\boldsymbol{J}^2$ and $\boldsymbol{I}^2$ are the squared collective spin and isospin operators, respectively, which act on the nucleon or Δ wave functions obtained from the diagonalization of the collective Hamiltonian [49], and Θ^* is the moment of inertia of the soliton. A consistent description of the EMT form factors requires either to minimize the energy functional including rotational corrections, or to consider for the nucleon mass and other observables only the leading contribution in the limit of large number of colors N_c [43]. In this work we will follow Ref. [43] and choose the second option. In particular, this means that in our treatment the nucleon and Δ masses (in vacuum or in medium) are degenerate and given by the minimum of the mass functional (6).

Input parameters in the Skyrmion sector are fixed as $m_\pi = 135$ MeV, $F_\pi = 108.78$ MeV, $e = 4.854$ following Ref. [52]. Those relevant to nuclear matter are determined by reproducing the coefficient of the volume term in the semiempirical mass formula and the experimental data for the compressibility of nuclear matter [52]: $b_0 = -0.024m_\pi^{-1}$, $c_0 = 0.09m_\pi^{-3}$, $g' = 0.7$, $\gamma_{\mathrm{num}} = 0.797\ m_\pi^{-3}$ and $\gamma_{\mathrm{den}} = 0.496m_\pi^{-3}$. All observables will be given as functions of ρ/ρ_0 with normal nuclear matter density $\rho_0 = 0.5m_\pi^3$.

3. We are now in a position to calculate the EMT form factors of the nucleon in nuclear matter. Since the details of the general formalism have already been presented in Ref. [43] in free space, we briefly recapitulate only the necessary formulae here. The components of the static EMT [17] are given as follows:

$$T_{00}^*(r) = \frac{F_{\pi,s}^{*2}}{8}\left(\frac{2\sin^2 F}{r^2} + F'^2\right) + \frac{\sin^2 F}{2e^{*2}r^2}\left(\frac{\sin^2 F}{r^2} + 2F'^2\right) + \frac{m_\pi^{*2}F_{\pi,s}^{*2}}{4}(1-\cos F), \tag{9}$$

$$T_{0k}^*(\boldsymbol{r},\boldsymbol{s}) = \frac{\epsilon^{klm}r^l s^m}{(\mathbf{s}\times\mathbf{r})^2}\rho_J^*(r),$$

$$T_{ij}^*(\boldsymbol{r}) = s^*(r)\left(\frac{r_i r_j}{r^2} - \frac{1}{3}\delta_{ij}\right) + p^*(r)\delta_{ij}, \tag{10}$$

[1] From now on, the asterisks in expressions indicate the medium modified quantities which depend on the medium-dependent functions explicitly. Otherwise, we use the same symbol without any asterisk.