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How deep is the antinucleon optical potential at FAIR energies

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ABSTRACT

The key question in the interaction of antinucleons in the nuclear medium concerns the deepness of the antinucleon–nucleus optical potential. In this work we study this task in the framework of the non-linear derivative (NLD) model which describes consistently bulk properties of nuclear matter and Dirac phenomenology of nucleon–nucleus interactions. We apply the NLD model to antinucleon interactions in nuclear matter and find a strong decrease of the vector and scalar self-energies in energy and density and thus a strong suppression of the optical potential at zero momentum and, in particular, at FAIR energies. This is in agreement with available empirical information and, therefore, resolves the issue concerning the incompatibility of G-parity arguments in relativistic mean-field (RMF) models. We conclude the relevance of our results for the future activities at FAIR.

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1. Introduction

The in-medium nucleon–nucleon interaction has been an object of intensive theoretical and experimental research of modern nuclear physics over the last few decades, see for a review [1]. The main finding was a softening of the nuclear equation of state at densities reached in intermediate energy nucleus–nucleus collisions, which was consistent with a variety of phenomenological [2] and microscopic [3] models. In addition the empirical saturation of the proton–nucleus optical potential turned out to be consistent with heavy-ion theoretical studies [4].

While the bare antinucleon–nucleon ($\bar{N}N$) interaction has been actively studied, see Ref. [5] and references therein, empirical information on the in-medium interactions of antinucleons is still very poor. Antiproton production has been investigated theoretically in reactions induced by protons [6] and heavy ions in the SIS-energy region [7], where some data on antiprotons were available. Complementary studies of antiproton annihilation in nuclei [8] and antiprotonic atoms [9] provided further insight on the optical potential at very low energies, however, with rather big uncertainties in the nuclear interior due to the strong annihilation cross section at the surface of the nucleus.

In the near future the FAIR facility intends to study the still controversial and empirically less known high energy domain of the (anti)nuclear interactions in more details than before. For instance, the nuclear equation of state for strangeness degrees of freedom and also the in-medium antinucleon–nucleon interaction are some of the key projects [10]. They are relevant for the formation of exotic (anti)matter systems such as double-strange hypernuclei and $\bar{\Lambda}$-hypernuclei in antiproton-induced reactions in the $\bar{\text{P}}$ANDA experiment at FAIR [11].

The microscopic Brueckner–Hartree–Fock calculations of the in-medium $\bar{N}N$-scattering have been carried out in [12]. On the other hand, a complementary theoretical background for phenomenological models builds the relativistic hadrodynamics (RHD). It is based on the relativistic mean-field (RMF) theory, which is a well established tool for infinite and finite nuclear systems [13]. However, as already shown many years ago [7], there are still unresolved problems in RMF models, when applying them to antiproton–nucleus scattering and to heavy ion collisions. By just imposing G-parity arguments, like in microscopic models [12,14], the RMF do not describe the experimental data [7,15,16]. This incompatibility of mean-field models with respect to G-parity symmetry has been also shown in recent transport studies [15], where one had to largely decrease the antinucleon–meson couplings by hand in order to reproduce the empirical data.

In this work we address this issue why the conventional RMF models do not describe antiproton–nucleus Dirac phenomenology. To be more specific, our studies are based on the non-linear derivative (NLD) model [17] to RMF. The NLD model describes simultaneously the density dependence of the nuclear equation of state and the energy dependence of the proton–nucleus optical potential. Latter feature is missing in standard RMF models. Then applying G-parity transformation it is shown that the real part of the proton *and simultaneously* the real part of the antiproton optical potentials are reproduced fairly well in comparison

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with phenomenological studies. We finally make predictions for the deepness of the real part of the antiproton optical potential and estimate its imaginary part at low energies and energies relevant for the forthcoming experiments at FAIR.

2. NLD formalism

The NLD approach [17] to nuclear matter is based essentially on the Lagrangian density of RHD [13]. It describes the interaction of nucleons through the exchange of auxiliary meson fields (Lorentz-scalar, σ, and Lorentz-vector meson fields ω^{μ}) [18]

$$\mathcal{L} = \mathcal{L}_{Dirac} + \mathcal{L}_{mes} + \mathcal{L}_{int}. \tag{1}$$

The Lagrangian in Eq. (1) consists of the free Lagrangians for the Dirac field Ψ and for the meson fields σ and ω^{μ}. The isovector meson ρ is not considered here, for simplicity.

In conventional RHD the interaction Lagrangian $\mathcal{L}_{int}$ contains meson fields which couple to the Dirac field via the corresponding Lorentz-density operators $g_\sigma\overline{\Psi}\Psi\sigma$ and $-g_\omega\overline{\Psi}\gamma^\mu\Psi\omega_\mu$ for the scalar and vector parts, respectively. Such interactions describe rather successfully the saturation properties of nuclear matter, but they miss the energy dependence of the mean field. A possible solution to this problem has been proposed in [6] where the momentum-dependent phenomenological form factors were introduced. In [17] this idea has been generalized in a manifestly covariant way. In particular, the symmetrized interaction in the NLD model is given by

$$\mathcal{L}_{int} = \frac{g_\sigma}{2}\left[\overline{\Psi}\overleftarrow{\mathcal{D}}\Psi\sigma + \sigma\overline{\Psi}\overrightarrow{\mathcal{D}}\Psi\right] - \frac{g_\omega}{2}\left[\overline{\Psi}\overleftarrow{\mathcal{D}}\gamma^\mu\Psi\omega_\mu + \omega_\mu\overline{\Psi}\gamma^\mu\overrightarrow{\mathcal{D}}\Psi\right]. \tag{2}$$

The interaction between the Dirac and the meson fields has a similar functional form as in standard RHD [13]. However, now new operators $\mathcal{D}$ acting on the nucleon fields appear, which are the non-linear functionals of partial derivatives

$$\overrightarrow{\mathcal{D}} := \exp\left(\frac{-v^\beta i\overrightarrow{\partial}_\beta + m}{\Lambda}\right), \qquad \overleftarrow{\mathcal{D}} := \exp\left(\frac{i\overleftarrow{\partial}_\beta v^\beta + m}{\Lambda}\right). \tag{3}$$

In Eq. (3) v^β denotes a dimensionless auxiliary 4-vector and Λ stands for the cut-off parameter. The latter has been adjusted to the saturation properties of nuclear matter [17]. In the limiting case of $\Lambda \to \infty$ the standard Walecka model is retained.

The NLD Lagrangian $\mathcal{L}$ is a functional of not only Ψ, $\overline{\Psi}$ and their first derivatives, but it depends on all higher order covariant derivatives of Ψ and $\overline{\Psi}$. For such a generalized functional the Euler–Lagrange equations take the form [17]

$$\frac{\partial\mathcal{L}}{\partial\phi} - \partial_{\alpha_1}\frac{\partial\mathcal{L}}{\partial(\partial_{\alpha_1}\phi)} + \partial_{\alpha_1}\partial_{\alpha_2}\frac{\partial\mathcal{L}}{\partial(\partial_{\alpha_1}\partial_{\alpha_2}\phi)} + \cdots + (-)^n\partial_{\alpha_1}\partial_{\alpha_2}\cdots\partial_{\alpha_n}\frac{\partial\mathcal{L}}{\partial(\partial_{\alpha_1}\partial_{\alpha_2}\cdots\partial_{\alpha_n}\phi)} = 0. \tag{4}$$

Contrary to the standard expressions for the Euler–Lagrange equation, now infinite series of terms ($n \to \infty$) proportional to higher order derivatives of the Dirac field ($\phi = \Psi, \overline{\Psi}$) appear. They can be evaluated by a Taylor expansion of the non-linear derivative operators (3). As shown in [17], in nuclear matter an infinite series of terms can be resumed exactly and the following Dirac equation is obtained

$$\left[\gamma_\mu\left(i\partial^\mu - \Sigma^\mu\right) - (m - \Sigma_s)\right]\Psi = 0, \tag{5}$$

with Lorentz-vector and Lorentz-scalar self-energies defined as follows

$$\Sigma^\mu = g_\omega\omega^\mu e^{\frac{-v^\beta i\overrightarrow{\partial}_\beta + m}{\Lambda}}, \qquad \Sigma_s = g_\sigma\sigma e^{\frac{-v^\beta i\overrightarrow{\partial}_\beta + m}{\Lambda}}. \tag{6}$$

The Proca and Klein–Gordon equations for the meson fields can be also derived

$$\partial_\mu F^{\mu\nu} + m_\omega^2\omega^\nu = \frac{1}{2}g_\omega\left[\overline{\Psi}e^{\frac{i\overleftarrow{\partial}_\beta v^\beta + m}{\Lambda}}\gamma^\nu\Psi + \overline{\Psi}\gamma^\nu e^{\frac{-v^\beta i\overrightarrow{\partial}_\beta + m}{\Lambda}}\Psi\right], \tag{7}$$

$$\partial_\mu\partial^\mu\sigma + m_\sigma^2\sigma = \frac{1}{2}g_\sigma\left[\overline{\Psi}e^{\frac{i\overleftarrow{\partial}_\beta v^\beta + m}{\Lambda}}\Psi + \overline{\Psi}e^{\frac{-v^\beta i\overrightarrow{\partial}_\beta + m}{\Lambda}}\Psi\right], \tag{8}$$

with the field tensor $F^{\mu\nu} = \partial^\mu\omega^\nu - \partial^\nu\omega^\mu$. The meson field equations (7) and (8) show a similar form as in the linear Walecka model of RHD, except of the highly non-linear behavior of the source terms, which generate selfconsistent couplings between the meson-field equations.

Applying the usual RMF approximation to the idealized system of infinite nuclear matter, the Dirac equation (5) maintains its original form. However, we have to distinguish between nucleons (N) forming the nuclear matter and antinucleons ($\overline{N}$) which interact with the nuclear matter. For the description of antiparticles we require G-parity invariance of the Dirac equation and then follow the standard procedure of applying a G-parity transformation $\mathrm{G} = \mathrm{C}e^{i\pi I_2}$ to the negative energy states, where I_2 is the operator associated with the 2nd component of the isospin "vector" and C is the charge conjugation operator. The invariance of the Dirac equation under charge conjugation requires that the auxiliary vector v^β must be odd under C-parity transformation. With our choice of $v^\beta = (1, \vec{0})$ for positive energy solutions [17] this results in $v^\beta = (-1, \vec{0})$ for the charge conjugated Dirac field. This leads to the following Dirac equations for nucleons

$$\left[\gamma_\mu\left(i\partial^\mu - \Sigma^\mu\right) - (m - \Sigma_s)\right]\Psi_N = 0 \tag{9}$$

and antinucleons

$$\left[\gamma_\mu\left(i\partial^\mu + \Sigma^\mu\right) - (m - \Sigma_s)\right]\Psi_{\overline{N}} = 0 \tag{10}$$

interacting with nuclear matter, where $\Psi_N = \Psi^+$ and $\Psi_{\overline{N}} = \Psi_C$ denote the positive energy and the charge conjugated Dirac fields, respectively.

The nucleon and antinucleon self-energies entering Eqs. (9) and (10) are the same

$$\Sigma_v \equiv \Sigma^0 = g_\omega\omega_0 e^{-\frac{E-m}{\Lambda}}, \quad \Sigma_s = g_\sigma\sigma e^{-\frac{E-m}{\Lambda}}. \tag{11}$$

However, note the opposite signs in the Lorentz-vector interactions in Eqs. (9) and (10). Furthermore, the single particle energies E have to be obtained from the in-medium mass-shell conditions which are different for nucleons (N) and antinucleons ($\overline{N}$)

$$E_N(p) = \sqrt{p^2 + m^{*2}} + \Sigma_v, \qquad E_{\overline{N}}(p) = \sqrt{p^2 + m^{*2}} - \Sigma_v. \tag{12}$$

The in-medium (or effective) Dirac mass in Eq. (12) is given by $m^* = m - \Sigma_s$. Note, that m^* depends explicitly on particle momentum. Again, in the limiting case of $\Lambda \to \infty$, the exponential factor is equal to unity and the equations are reduced to the ones from the Walecka model. In the NLD model the cut-off parameter Λ is of natural size, i.e., of typical hadronic mass scale in this problem. In the following, $\Lambda = 770$ MeV is chosen, as in the original work [17].

In nuclear matter the NLD equations of motion for ω and σ simplify to standard algebraic equations

$$m_\omega^2\omega^0 = g_\omega\rho_v, \qquad m_\sigma^2\sigma = g_\sigma\rho_s \tag{13}$$

with the corresponding density sources $\rho_v = \langle\overline{\Psi}_N\gamma^0 e^{-\frac{E-m}{\Lambda}}\Psi_N\rangle$ and $\rho_s = \langle\overline{\Psi}_N e^{-\frac{E-m}{\Lambda}}\Psi_N\rangle$. The vector density ρ_v is not related to

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