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In-medium pion valence distributions in a light-front model

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ABSTRACT

Pion valence distributions in nuclear medium and vacuum are studied in a light-front constituent quark model. The in-medium input for studying the pion properties is calculated by the quark-meson coupling model. We find that the in-medium pion valence distribution, as well as the in-medium pion valence wave function, are substantially modified at normal nuclear matter density, due to the reduction in the pion decay constant.

Introduction One of the most exciting and challenging topics in hadronic and nuclear physics is to study the modifications of hadron properties in nuclear medium (nuclear environment), and also how such modifications affect the observables differently from those in vacuum. Since hadrons are composed of quarks, antiquarks and gluons, it is natural to expect that hadron internal structure would change when they are immersed in nuclear medium or in atomic nuclei [1–5]. This question, to study the medium modification of hadron internal structure, is particularly interesting when it comes to that of pion. To be able to study the properties of pion in nuclear medium, one first needs, simpler, effective quark-antiquark models of pion, which are successful in describing its properties in vacuum. Among such models, light-front constituent quark model has been very successful in describing the hadronic properties in vacuum, in particular, the electromagnetic form factors, electromagnetic radii and decay constants of pion and kaon [6–12]. Recent advances in experiments, indeed suggest to make it possible to access to the pion (hadronic) properties in a nuclear medium [3–5,13,14].

Among the all hadrons, pion is the lightest, and it is believed as a Nambu–Goldstone boson, which is realized in nature emerged by the spontaneous breaking of chiral symmetry. This Nambu–Goldstone boson, pion, plays very important and special roles in hadronic and nuclear physics [15–26]. However, because of its special properties, particularly the unusually light mass, it is not easy to describe the pion properties in medium as well as in vacuum based on naive quark models, even though such models can be successful in describing the other hadrons.

Despite of this difficulty, some important studies were made [27–29] on the pion structure and its role in a nuclear medium. Recently, we also studied the properties of pion in nuclear medium [13,14], namely, the electromagnetic form factor, charge radius and weak decay constant, by using a light-front constituent quark model. There, the in-medium input was calculated by the quark-meson coupling (QMC) model [3,30]. We have predicted the in-medium changes of pion properties [13,14]: (i) faster falloff of the pion charge form factor as increasing the negative of the four-momentum transfer squared, (ii) increasing of the root mean-square charge radius as increasing nuclear density, and (iii) decreasing of the decay constant as increasing nuclear density. The purpose of this work is, to extend our work for the pion in medium made in Refs. [13,14], and study the pion valence distribution amplitude in symmetric nuclear matter. We find substantial modification of the pion valence wave function and distribution amplitude in symmetric nuclear matter at normal nuclear matter density.

The QMC model First, we briefly review the QMC model, the quark-based model of nuclear matter, to study the pion properties in medium. The effective Lagrangian density for a uniform,

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spin-saturated, and isospin-symmetric nuclear system (symmetric nuclear matter) at the hadronic level is given by [30,31],

$$\mathcal{L} = \bar{\psi}[i\gamma \cdot \partial - m_N^*(\hat{\sigma}) - g_\omega \hat{\omega}^\mu \gamma_\mu]\psi + \mathcal{L}_{\text{meson}} , \tag{1}$$

where ψ, $\hat{\sigma}$ and $\hat{\omega}$ are respectively the nucleon, Lorentz-scalar-isoscalar σ, and Lorentz-vector-isoscalar ω field operators with,

$$m_N^*(\hat{\sigma}) \equiv m_N - g_\sigma(\hat{\sigma})\hat{\sigma}. \tag{2}$$

Note that, in symmetric nuclear matter isospin-dependent ρ-meson mean filed is zero, and thus we have omitted it. Then the relevant free meson Lagrangian density is given by,

$$\mathcal{L}_{\text{meson}} = \frac{1}{2}(\partial_\mu \hat{\sigma} \partial^\mu \hat{\sigma} - m_\sigma^2 \hat{\sigma}^2) - \frac{1}{2}\partial_\mu \hat{\omega}_\nu (\partial^\mu \hat{\omega}^\nu - \partial^\nu \hat{\omega}^\mu) + \frac{1}{2} m_\omega^2 \hat{\omega}^\mu \hat{\omega}_\mu. \tag{3}$$

Hereafter, we consider the symmetric nuclear matter at rest. Then, within Hartree mean-field approximation, the nuclear (baryon) and scalar densities are respectively given by,

$$\rho = \frac{4}{(2\pi)^3}\int d\vec{k}\,\theta(k_F - |\vec{k}|) = \frac{2k_F^3}{3\pi^2},$$
$$\rho_s = \frac{4}{(2\pi)^3}\int d\vec{k}\,\theta(k_F - |\vec{k}|)\frac{m_N^*(\sigma)}{\sqrt{m_N^{*2}(\sigma) + \vec{k}^2}}, \tag{4}$$

here, $m_N^*(\sigma)$ is the value (constant) of effective nucleon mass at given density (see also Eq. (2)). In the standard QMC model [3,30, 31] the MIT bag model is used, and the Dirac equations for the light quarks inside a nucleon (bag) composing nuclear matter, are given by,

$$\left[i\gamma \cdot \partial_x - (m_q - V_\sigma^q) \mp \gamma^0 \left(V_\omega^q + \frac{1}{2}V_\rho^q\right)\right]\begin{pmatrix}\psi_u(x)\\ \psi_{\bar{u}}(x)\end{pmatrix} = 0, \tag{5}$$

$$\left[i\gamma \cdot \partial_x - (m_q - V_\sigma^q) \mp \gamma^0 \left(V_\omega^q - \frac{1}{2}V_\rho^q\right)\right]\begin{pmatrix}\psi_d(x)\\ \psi_{\bar{d}}(x)\end{pmatrix} = 0\,. \tag{6}$$

Because the nuclear matter interactions are strong interactions, the Coulomb interaction is neglected as usual, and SU(2) symmetry is assumed, $m_{u,\bar{u}} = m_{d,\bar{d}} \equiv m_{q,\bar{q}}$. The corresponding effective (constituent) quark masses are defined by, $m_{u,\bar{u}}^* = m_{d,\bar{d}}^* = m_{q,\bar{q}}^* \equiv m_{q,\bar{q}} - V_\sigma^q$, to be explained later.

As mentioned already, in symmetric nuclear matter within Hartree approximation, the ρ-meson mean field is zero, $V_\rho^q = 0$, in Eq. (6), and we ignore it. The constant mean-field potentials are defined as, $V_\sigma^q \equiv g_\sigma^q \sigma = g_\sigma^q < \sigma >$, and, $V_\omega^q \equiv g_\omega^q \omega = g_\omega^q < \omega >$, with g_σ^q, and g_ω^q, are the corresponding quark-meson coupling constants, where the quantities with the brackets stand for the expected values in symmetric nuclear matter [3]. Since the average velocity is zero, $< \bar{\psi}_q \vec{\gamma} \psi_q >= 0$, in the nuclear matter rest frame, no spacial-dependent source for the vector-meson mean fields arise, and only the terms proportional to γ^0 are kept in Eq. (6). (More details are given in Ref. [3].)

The same meson mean fields σ and ω for the quarks in Eqs. (5) and (6), satisfy self-consistently the following equations at the nucleon level:

$$\omega = \frac{g_\omega \rho}{m_\omega^2}, \tag{7}$$

$$\sigma = \frac{g_\sigma}{m_\sigma^2} C_N(\sigma) \frac{4}{(2\pi)^3}\int d\vec{k}\,\theta(k_F - |\vec{k}|)\frac{m_N^*(\sigma)}{\sqrt{m_N^{*2}(\sigma) + \vec{k}^2}} = \frac{g_\sigma}{m_\sigma^2} C_N(\sigma)\rho_s, \tag{8}$$

Table 1
Coupling constants, and calculated properties for symmetric nuclear matter at normal nuclear matter density $\rho_0 = 0.15$ fm^{-3}, for $m_q = 5$ and 220 MeV (the latter values is used in this study and was used in Refs. [12,13]). The effective nucleon mass, m_N^*, and the nuclear incompressibility, K, are quoted in MeV. (See Ref. [3] for details.)

m_q (MeV)	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	m_N^*	K
5	5.39	5.30	754.6	279.3
220	6.40	7.57	698.6	320.9

$$C_N(\sigma) = \frac{-1}{g_\sigma(\sigma = 0)}\left[\frac{\partial m_N^*(\sigma)}{\partial \sigma}\right], \tag{9}$$

where $C_N(\sigma)$ is the constant value of the scalar density ratio [3,30, 31]. Because of the underlying quark structure of the nucleon used to calculate $M_N^*(\sigma)$ in nuclear medium (see Eq. (2)), $C_N(\sigma)$ gets nonlinear σ-dependence, whereas the usual point-like nucleon-based model yields unity, $C_N(\sigma) = 1$.

It is this $C_N(\sigma)$ or $g_\sigma(\sigma)$ that gives a novel saturation mechanism in the QMC model, and contains the important dynamics which originates in the quark structure of the nucleon. Without an explicit introduction of the nonlinear couplings of the meson fields in the Lagrangian density at the nucleon and meson level, the standard QMC model yields the nuclear incompressibility of $K \simeq 280$ MeV with $m_q = 5$ MeV, which is in contrast to a naive version of quantum hadrodynamics (QHD) [32] (the point-like nucleon model of nuclear matter), results in the much larger value, $K \simeq 500$ MeV; the empirically extracted value falls in the range $K = 200$–300 MeV. (See Ref. [33] for the updated discussions on the incompressibility.)

Once the self-consistency equation for the σ including the quark Dirac equations, Eqs. (5), (6), and Eq. (8) have been solved, one can evaluate the total energy per nucleon:

$$E^{\text{tot}}/A = \frac{4}{(2\pi)^3 \rho}\int d\vec{k}\,\theta(k_F - |\vec{k}|)\sqrt{m_N^{*2}(\sigma) + \vec{k}^2} + \frac{m_\sigma^2 \sigma^2}{2\rho} + \frac{g_\omega^2 \rho}{2m_\omega^2}. \tag{10}$$

We then determine the coupling constants, g_σ and g_ω, so as to fit the binding energy of 15.7 MeV at the saturation density $\rho_0 = 0.15$ fm^{-3} ($k_F^0 = 1.305$ fm^{-1}) for symmetric nuclear matter.

In Refs. [12,13], the quark mass in vacuum was used $m_{q,\bar{q}} = 220$ MeV to study the pion properties in symmetric nuclear matter. With this value the model can reproduce the electromagnetic form factor and the decay constant well in vacuum [8]. Thus, we use the same value in this study. The corresponding coupling constants and some calculated properties for symmetric nuclear matter at the saturation density ρ_0, with the standard values of $m_\sigma = 550$ MeV and $m_\omega = 783$ MeV, are listed in Table 1. For comparison, we also give the corresponding quantities calculated in the standard QMC model with a vacuum quark mass of $m_q = 5$ MeV (see Ref. [3] for details). Thus we have obtained the necessary properties of the light-flavor constituent quarks in symmetric nuclear matter with the empirically accepted data for a vacuum constituent light-quark mass of $m_q = 220$ MeV; namely, the density dependence of the effective mass (scalar potential) and vector potential. The same in-medium constituent quark properties which reproduce the nuclear saturation properties (and used in Refs. [13, 14]) will be used as input to study the pion properties in symmetric nuclear matter.

In Figs. 1 and 2 we respectively show our results for the negative of the binding energy per nucleon ($E^{\text{tot}}/A - m_N$), effective constituent light-quark mass, m_q^*, in symmetric nuclear matter (left panel of Fig. 2), and the in-medium pion decay constant, f_π^* (right