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The interaction of D mesons and nucleons at finite density

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We present results on the the influence of changes in the masses and sizes of D mesons and nucleons on elastic DN scattering cross sections and phase shifts in a hadronic medium composed of confined quarks in nucleons. We evaluate the changes of the hadronic masses due to changes of the light constituent quarks at finite baryon density using a chiral quark model based on Coulomb gauge QCD. The model contains a confining Coulomb potential and a transverse hyperfine interaction consistent with a finite gluon propagator in the infrared. We present results for the total cross section and the s-wave phase shift at low energies for isospin I=1 – for I=0 and other partial waves the results are similar.

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1. Introduction

The study of temperature (T) and baryon density (ρ_B) dependence of the interaction of D mesons with nucleons is relevat for understanding the phenomenon of dynamical chiral symmetry breaking in hadronic matter. D mesons seem to be particularly suited for such studies in view of their heavy-light nature which allows to treat them approximately as one-body bound states. The mass of the light constituent quark in a D meson is sensitive to T and ρ_B and because of this the properties of these mesons will change in a hot and dense medium. One hopes to learn a good deal about these changes studying the propagation of D mesons in hadronic matter [1] and therefore it is important to develop models for describing their interactions with ordinary hadrons. In Refs. [2, 3] a model was developed for the interaction of D mesons with nucleons in free space, in which the long-distance part of the interaction was described by meson-baryon exchange, and the short-distance part was described by quark-gluon-interchange in the context of a nonrelativistic quark model. Possible changes in the internal structure of the mesons will affect mostly the short distance part of the interaction where quarks and gluons are the relevant degrees of freedom. Now, in order to access T and ρ_B effects on chiral properties of hadrons one needs a chiral quark model that goes beyond the nonrelativistic quark model. Such a chiral quark model was developed in Ref. [4]. The model is based on the QCD Hamiltonian in Coulomb gauge [5], it confines color and realizes dynamical chiral symmetry breaking. The model allows to construct a practical calculational scheme to construct hadronic bound-state wave functions and to derive effective hadron-hadron interactions that can be used in a Lippmann-Schwinger equation to obtain cross-sections and phase-shifts [6].

In Ref. [4] the model was used to investigate the short-distance part of the low energy interaction of D-mesons and nucleons in free space. In the present communication we preset results for the baryon density dependence of the DN interaction using this model.

2. Dynamical chiral symmetry breaking in a medium with confined quarks

The Hamiltonian of the model is based on the QCD Hamiltonian in Coulomb gauge [5]. The quark part of the Hamiltonian – see Eq. (2.1) of Ref. [4] – is written in terms of the quark field operator $\Psi(\mathbf{x})$ expanded as (suppressing color and flavor indices)

$$\Psi(\mathbf{x}) = \int \frac{d\mathbf{k}}{(2\pi)^{3/2}} \sum_{s=\pm 1/2} [u_s(\mathbf{k}) Q_s(\mathbf{k}) + v_s(\mathbf{k}) \bar{Q}_s^\dagger(-\mathbf{k})] e^{i\mathbf{k}\cdot\mathbf{x}} \tag{2.1}$$

where $Q_s^\dagger(\mathbf{k})$, $\bar{Q}_s^\dagger(-\mathbf{k})$, $Q_s(\mathbf{k})$ and $\bar{Q}_s(-\mathbf{k})$ are the creation and annihilation operators of *constituent quarks*, and $u_s(\mathbf{k})$ and $v_s(\mathbf{k})$ are Dirac spinors given by

$$u_s(\mathbf{k}) = \sqrt{\frac{E_k + M_k}{2E_k}} \begin{pmatrix} 1 \\ \frac{\sigma\cdot\mathbf{k}}{E_k+M_k} \end{pmatrix} \chi_s, \qquad v_s(\mathbf{k}) = \sqrt{\frac{E_k + M_k}{2E_k}} \begin{pmatrix} -\frac{\sigma\cdot\mathbf{k}}{E_k+M_k} \\ 1 \end{pmatrix} \chi_s^c \tag{2.2}$$

with $E_k = (k^2 + M_k^2)^{1/2}$, $\chi_s^c = -i\sigma^2\chi_s^*$, and χ_s is a Pauli spinor. The annihilation operators $Q_s(\mathbf{k})$ and $\bar{Q}_s(-\mathbf{k})$ annihilate the vacuum state with chiral symmetry dynamically broken. The momentum dependent function M_k is the constituent quark mass function. Meson and baryon states are constructed in terms of the creation operators of quarks and antiquarks acting on the dynamically broken chiral vacuum. The dependence on T and ρ_B of the quark condensate and meson and baryon states come in through the T and ρ_B dependence of the mass function M_k, and through the Pauli exclusion principle. This last effect is due the fact that quarks and antiquarks will not have all momentum states available to form a bound state as in free space. For example, for a medium with deconfined quarks forming a Fermi gas, the effect enters via Fermi-Dirac distributions of quarks and antiquarks. For a medium that is a *Fermi gas of nucleons*, i.e. with the quarks confined in the interior of hadrons, the Pauli exclusion effect comes in via quark distributions in the hadrons convoluted with the hadron thermal distribution in the medium.

Specifically, the gap equation for the quark mass function M_k can be written as

$$M_k = m_0 + \frac{2}{3}\int \frac{d^3q}{(2\pi)^3} F_q \left\{ V_C(\mathbf{k}-\mathbf{q}|) \left(\frac{M_q}{E_q} - \frac{M_k}{E_q}\frac{q}{k}\hat{k}\cdot\hat{q} \right) \right. \\ \left. + \, 2V_T(|\mathbf{k}-\mathbf{q}|) \left[\frac{M_q}{E_q} + \frac{M_k}{E_q}\frac{q}{k}\frac{(\mathbf{k}\cdot\mathbf{q}-k^2)(\mathbf{k}\cdot\mathbf{q}-q^2)}{kq|\mathbf{k}-\mathbf{q}|^2} \right] \right\} \tag{2.3}$$

where $F_q = 1 - n_q - \bar{n}_q$ is the Pauli blocking function, with n_q and $\bar{n}_q$ being the in medium quark and antiquark distributions

$$n_q = \langle\Omega|Q_q^\dagger Q_q|\Omega\rangle, \qquad \bar{n}_q = \langle\Omega|\bar{Q}_q^\dagger \bar{Q}_q|\Omega\rangle \tag{2.4}$$

where $|\Omega\rangle$ is the state of the many-body system.

Next we consider a medium of nonoverlapping nucleons at equilibrium with temperature $T = 1/\beta$ and chemical potential μ_B occupying single-particle energy levels E_P. For the internal structure of the nucleon we use the model of Ref. [4], where the nucleon wave function is given by a variational Gaussian wave function [7] with width α – the r.m.s. radius of the nucleon is $\sqrt{\langle r^2\rangle} = 1/\alpha$. For such a wave function, the Pauli blocking function F_q is given by

$$F_q(T,\mu_B) = 1 - \left(\frac{3}{2\pi\alpha^2}\right)^{3/2} g_B \int d^3P \, e^{-3(\vec{q}-\vec{P}/3)^2/2\alpha^2} \left[n_B(P) + \bar{n}_B(P)\right] \tag{2.5}$$

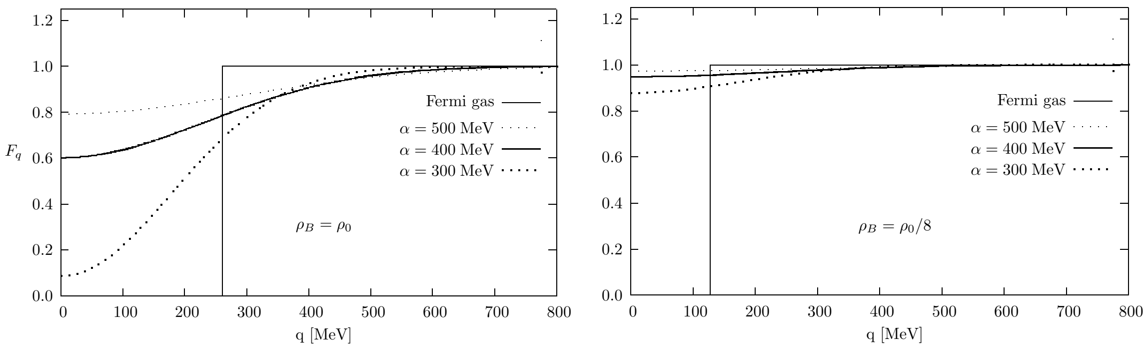

Figure 1: The Pauli blocking function for different nucleon sizes and two baryon densities. Also shown is the function for a Fermi gas of deconfined quarks.

where g_B is the degeneracy of the energy level E_P and $n_B(P)$ and $\bar{n}_B(P)$ are the Fermi-Dirac distributions of nucleons and antinucleons

$$n_B(P) = \frac{1}{e^{\beta[E_P-\mu_B]}+1}, \qquad \bar{n}_B(P) = \frac{1}{e^{\beta[E_P+\mu_B]}+1} \tag{2.6}$$

In the present communication we present results for $T = 0$ only – for this case $n_B(P) = \theta(P_F - P)$ and $\bar{n}_B(P) = 0$. Fig. 1 presents the function F_q for different nucleon sizes and two baryon densities. One clearly sees that at a given baryon density ρ_B the Pauli blocking effect is much less effective in a medium with confined quarks than in a medium with deconfined quarks. This means that the breaking of chiral symmetry is much less affected in clustered matter than in deconfined matter and therefore changes in the quark and hadron masses, quark condensate, hadron sizes and interaction strengths are not so much changed.

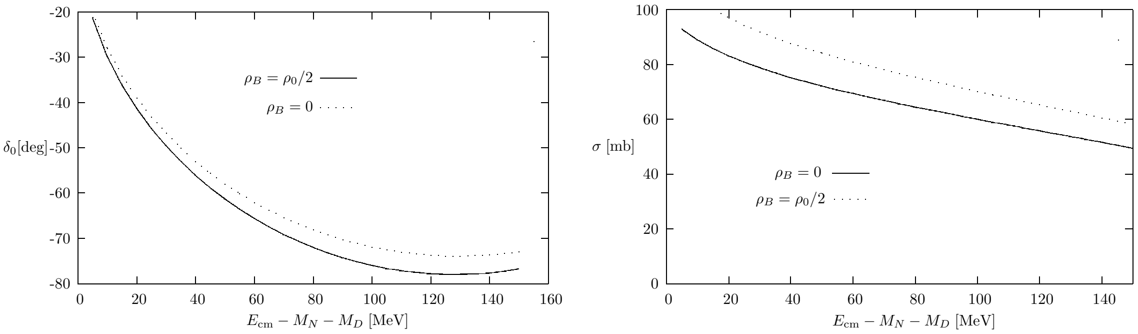

Figure 2: S-wave isospin $I = 0$ phase shift and total cross section of elastic DN scattering in medium (at $\rho_B = \rho_0/2$) and in free space.

In Fig. 2 we present results for the DN total cross section and s-wave phase-shift for isospin $I = 1$ – the density effect on isospin $I = 0$ is similar. We use the parameters of the model named *SS* in Ref. [4]. The effect on the masses of the light quark mass and hadron masses and sizes is of the order of 5%. The effective interaction increases in medium essentially because of the increase of transverse gluon interaction in medium, which is inversly proportional to the light quark mass. Also, it is important to note that phase space for scattering also changes in medium because the hadron masses change.

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