The properties of the D-meson in dense matter

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Abstract. We study the D-meson spectral density in dense matter within the framework of a coupled-channel self-consistent calculation taking, as bare meson-baryon interaction, a separable potential. Our coupled-channel model generates dynamically the Λc(2593) resonance. The medium modifications of the D-meson properties due to Pauli blocking and the dressing of D-mesons, nucleons and pions are also discussed. We found that the coupled-channel effects in the self-consistent process reduce the in-medium effects on the D-meson compared to previous works.

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1. Introduction

The study of medium modifications of the D-meson has become a subject of recent interest because the important consequences for open-charm enhancement in nucleus-nucleus collisions [1] as well as for J/Ψ suppression [2]. The NA50 Collaboration [3] has observed an enhancement of dimuons in Pb+Pb collisions which has been attributed to an open-charm enhancement in nucleus-nucleus collisions relative to proton-nucleus reactions. On the other hand, an appreciable contribution for the J/Ψ suppression is expected to be due to the formation of the quark-gluon plasma [4]. However, the suppression could also be understood in an hadronic environment due to inelastic comover scattering and, therefore, the medium modification of the D-mesons should modify the J/Ψ absorption [5]. Finally, the D-mesic nuclei, predicted by the quark-meson coupling (QMC) model [6], could also give us information about the in-medium properties of the D-meson. It is shown that the D− meson forms narrow bound states with 208Pb while the D0 is deeply bound in nuclei. It is thus of importance to understand the interactions of the D-mesons in the hadronic medium.

Calculations based on the QCD sum-rule (QSR) approach [7] as well as on the QMC model [6] predict the mass drop of the D-meson to be of the order of 50-60 MeV at nuclear matter density. A similar drop at finite temperature is suggested from the lattice calculations for heavy-quark potentials [8] together with a recent work based on a chiral model [9]. In this paper, we study the spectral density of a D-meson embedded in dense matter incorporating the coupled-channel effects as well as the dressing of the intermediate propagators which have been ignored in the previous works. These effects will turn out to be crucial for describing the D-meson in dense matter [10].
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2. Formalism

In order to obtain the D-meson self-energy in dense matter and, hence, the spectral density, the knowledge of the in-medium DN interaction is required. This amplitude is obtained taking, as a bare interaction, a separable potential model

\[ V_{ij}(k, k') = \frac{g^2}{\Lambda^2} C_{ij} \Theta(\Lambda - k) \Theta(\Lambda - k') , \]  

where \( g \) and \( \Lambda \) are the coupling constant and cutoff, respectively. These two parameters will be determined by fixing the position and the width of the \( \Lambda_c(2593) \) resonance. For the interaction matrix \( C_{ij} \), we use the result derived from SU(3) flavor symmetry. We are, therefore, confronted with a coupled-channel problem since this interaction allows for the transition from DN to other channels, namely, \( \pi \Lambda_c \), \( \pi \Sigma_c \), \( \eta \Lambda_c \) and \( \eta \Sigma_c \), all having charm \( c = 1 \). With this structure in mind, the G-matrix is given by

\[ \langle M_1 B_1 | G(\Omega) | M_2 B_2 \rangle = \langle M_1 B_1 | V | M_2 B_2 \rangle + \sum_{M_3 B_3} \langle M_1 B_1 | V | M_3 B_3 \rangle \frac{Q_{M_3 B_3}}{\Omega - E_{M_2} - E_{B_3} + i\eta} \langle M_3 B_3 | G(\Omega) | M_2 B_2 \rangle , \]

where \( M_i \) and \( B_i \) represent the possible mesons (D, \( \pi \), \( \eta \)) and baryons (N, \( \Lambda_c \), \( \Sigma_c \)) respectively, and their corresponding quantum numbers, and \( \Omega \) is the starting energy. The function \( Q_{M_3 B_3} \) stands for the Pauli operator while \( E_{M_i(B_3)} \) is the meson (baryon) single-particle energy. Then, the D-meson single-particle potential in the Brueckner-Hartree-Fock approach reads

\[ U_D(k, E_{qp}^D) = \sum_{N \leq F} \langle DN | G_{DN\rightarrow DN}(\Omega = E_{np}^N + E_{np}^D) | DN \rangle , \]

where the summation over nucleonic states is limited by the nucleon Fermi momentum. As it can be seen from Eq. (3), since the DN interaction (G-matrix) depends on the D-meson single-particle energy, which in turn depends on the D-meson potential, we are confronted with a self-consistent problem. After self-consistency for the on-shell value \( U_D(k_D, E_{qp}^D) \) is achieved, one can obtain the full self-energy \( \Pi_D(k_D, \omega) = 2\sqrt{k_D^2 + m_D^2} U_D(k_D, \omega) \). This self-energy can then be used to determine the D-meson single-particle propagator and the corresponding spectral density.

3. Results and Conclusions

We start this section by showing in the l.h.s. of Fig. 1 the mass distribution of the \( \pi \Sigma_c \) state as a function of the C.M. energy for different sets of coupling constants \( g \) and cutoffs \( \Lambda \) (see the definition in Ref. [10]). Our coupled-channel calculation generates dynamically the \( \Lambda_c(2593) \) resonance. The position \( (2593.9 \pm 2 \text{ MeV}) \) and width \( (\Gamma = 3.6^{+2.0}_{-1.3} \text{ MeV}) \) are obtained for a given set of coupling constants and cutoffs.

Once the position and width of the \( \Lambda_c(2593) \) resonance are reproduced dynamically, we study the effect of the different medium modifications on the resonance. In the r.h.s. of Fig. 1 we display the real and imaginary parts of the s-wave DN amplitude for \( I = 0 \) and \( I = 1 \) within different approaches. When the nucleons and pions are dressed, the picture depicted is completely different to the case when only D-mesons are dressed self-consistently. In this case, for \( I = 0 \), we observe two structures: one structure around 2.5 GeV below the \( \pi \Sigma_c \) threshold and
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Figure 1. Left: $\Lambda_c(2593)$ mass spectrum for different sets of coupling constants and cutoffs. Right: Real and imaginary parts of the $s$-wave DN amplitude as functions of the center-of-mass energy at total momentum zero for $\Lambda = 1$ GeV and $g^2 = 13.4$ and for different approaches: T-matrix calculation (dotted lines), self-consistent calculation for the D-meson at $\rho = \rho_0$ (solid lines) and self-consistent calculation for the D-meson including the dressing of nucleons and the pion self-energy at $\rho = \rho_0$ (long-dashed lines).

In order to study the dependence on the cutoff and coupling constants together with the isospin dependence of the in-medium DN interaction, on the l.h.s. of Fig. 2 we show the real and imaginary parts of the D-meson potential at $k_D = 0$ as a function of the density. In the case that only the D-meson is dressed (left panels), and fixing $\Lambda = 1$ GeV, the D-meson potential is governed by the $I = 1$ component while, when nucleons and pions are dressed (right panels), the $I = 0$ component dominates due to the structure present at 2.8 GeV in the G-matrix. With regards to the dependence on the cutoff and coupling constant, we observe a weak dependence on the chosen set of parameters for both approaches. However, it is interesting to see that, for any chosen parameters, the coupled-channel effects seem to result in an overall reduction of the in-medium effects independent of the in-medium properties compared to previous works \[6, 7, 8, 9\]. For example, when nucleons and pions are dressed in the self-consistent process, the attraction lies in between $[2.6, -12.3]$ MeV for $\Lambda = [0.8, 1.4]$ GeV at normal nuclear matter density $\rho_0$.

Finally, the spectral density at zero momentum is shown on the r.h.s. of Fig. 2 for $\Lambda = 1$ GeV and for several densities in the two self-consistent approaches considered before. In the first approach (left panel), the quasiparticle peak moves slightly to lower energies while the $\Lambda_c$ resonance is seen for energies around 1.63-1.65 GeV. For the second approach (right panel), the structure around 2.8 GeV of Fig. 1 mixes with...
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Figure 2. Left: D-meson potential at $k_D = 0$ as a function of the density, including the isospin decomposition, for different sets of coupling constants and cutoffs and the two self-consistent approaches. Right: D-meson spectral density at $k_D = 0$ as a function of energy with $\Lambda = 1$ GeV and $g^2 = 13.4$ for different densities and for the two approaches.

We have performed a microscopic self-consistent coupled-channel calculation of the D-meson spectral density embedded in symmetric nuclear matter assuming, as bare interaction, a separable potential [10]. We have obtained the $\Lambda(2593)$ dynamically and we have concluded that the self-consistent coupled-channel effects result in a small attractive real part of the in-medium potential for D-mesons. However, the production of D-mesons in the nuclear medium will be still enhanced due to the broad D-meson spectral density. This effect is similar to the one obtained for the enhanced $\bar{K}$ production in heavy-ion collisions [11]. The in-medium effects seen in this work can be studied with the future PANDA experiment at GSI [12].

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References