Heavy mesons in dense matter

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Abstract. Charmed mesons in dense matter are studied within a unitary coupled-channel approach which takes into account Pauli-blocking effects and meson self-energies in a self-consistent manner. We obtain the open-charm meson spectral functions in this dense medium, and discuss their implications on hidden charm and charm scalar resonances and on the formation of $D$-mesic nuclei.

Keywords: charm meson, dynamically generated resonance, mesic nuclei, heavy-quark symmetry

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INTRODUCTION

The properties of open and hidden charm mesons in a hot dense environment are being the focus of recent analysis. Indeed, part of the physics program of the PANDA and CBM experiments at the future FAIR facility at GSI \cite{1} will search, among others, for in-medium modification of hadrons in the charm sector, providing a first insight into the charm-nucleus interaction.

The in-medium modification of the properties of open-charm mesons may lead to formation of $D$-mesic nuclei \cite{2}, and will also affect the renormalization of charm and hidden-charm scalar hadron resonances in nuclear matter, providing information not only about their nature but also about the interaction of the open-charm mesons with nuclei. In the present paper we obtain the open-charm spectral functions in dense matter within a self-consistent approach in coupled channels, and analyze the effect on the properties of dynamically-generated charm and hidden charm scalar resonances and provide some insight into the formation of $D$-nucleus bound states.

CHARMED MESONS IN MATTER

The self-energy in symmetric nuclear matter for open-charm pseudoscalar ($D$) and vector ($D^*$) mesons is obtained following a self-consistent coupled-channel procedure. The transition potential of the Bethe-Salpeter equation for different isospin, total angular momentum, and finite density and temperature is derived from effective lagrangians, which will be discussed in the next subsection. The $D$ and $D^*$ self-energies are then obtained summing the transition amplitude for the different isospins over the nucleon Fermi distribution at a given temperature (see details in Refs. \cite{3, 4}). Then, the meson spectral function reads

$$S_{D(D^*)}(q_0, \vec{q}, \rho, T) = \frac{1}{\pi} \left| \frac{\text{Im} \Pi_{D(D^*)}(q_0, \vec{q}, \rho, T)}{q_0^2 - \vec{q}^2 - m_{D(D^*)}^2 - \Pi_{D(D^*)}(q_0, \vec{q}, \rho, T)} \right|^2,$$

with $\Pi_{D(D^*)}$ being the self-energy at given energy $q_0$, momentum $\vec{q}$, density $\rho$ and temperature $T$.

SU(4) and SU(8) schemes

The open-charm meson spectral functions are obtained from the Bethe-Salpeter equation in coupled-channels taking, as bare interaction, two kinds of bare potential.

First, we consider a type of broken $SU(4)$-wave Weinberg-Tomozawa (WT) interaction supplemented by an attractive isoscalar-scalar term and using a cutoff regularization scheme. We fix this cutoff by generating dynamical the $I = 0$ $\Lambda_c(2595)$ resonance. A new resonance in $I = 1$ channel, $\Sigma_c(2800)$, is generated \cite{5, 6}.

The in-medium solution incorporates Pauli blocking, baryon mean-field bindings and meson self-energies \cite{3}. In I.h.s. of Fig. 1 we display the $D$ meson spectral function for different momenta, temperatures and densities. At $T = 0$ the spectral function shows two peaks: the
$\Lambda_c(2595)N^{-1}$ and the quasi(D)-particle peak mixed with 
the $\Sigma_c(2880)N^{-1}$. Those states dilute with increasing 
temperature while the quasiparticle peak gets closer to 
its free value. Finite density results in a broadening of 
the spectral function because of the increased phase space.

Secondly, heavy-quark symmetry (HQS) is imple-
mented by treating on equal footing heavy pseudoscalar 
and vector mesons, such as the $D$ and $D^*$ mesons. The 
$SU(8)$ WT includes pseudoscalars and vector mesons 
together with $J = 1/2^+$ and $J = 3/2^+$ baryons [7, 8]. 
This symmetry is, however, strongly broken in nature and 
we adopt the physical hadron masses and different weak 
non-charmed and charmed pseudoscalar and vector me-
son decay constants. We also improve on the regulariza-
tion scheme in matter beyond the cutoff method [4].

In this scheme, all resonances in the $SU(4)$ model 
are reproduced and new resonant states are generated 
[7] due to the enlarged Fock space. However, the nature 
of some of those resonances is different regarding the 
model. While the $\Lambda_c(2595)$ emerges as a $DN$ quasibound 
state in the $SU(4)$ model, it becomes predominantly a 
$D^*N$ quasibound state in the $SU(8)$ scheme.

The modifications of these resonances in the nuclear 
medium strongly depend on the coupling to $D, D^*$ and $N$ 
and are reflected in the spectral functions. On the r.h.s of 
Fig. 1 we display the $D$ and $D^*$ spectral functions, which 
show then a rich spectrum of resonance ($Y_c$)-hole($N^{-1}$) 
states. As density increases, these $Y_cN^{-1}$ modes tend 
to smear out and the spectral functions broaden with 
increasing phase space, as seen for the $SU(4)$ model [6].

SCALAR RESONANCE IN MATTER

The analysis of the properties of scalar resonances in nu-
clear matter is crucial in order to understand their na-
ture, whether they are $q\bar{q}$, molecules, mixtures of $q\bar{q}$ 
with meson-meson components, or dynamically generated 
resonances from meson-meson scattering.

In the following we study the charmed resonance 
$D_{(0)}(2317)$ [9, 10, 11] together with a hidden charm 
scalar meson, $X(3700)$, predicted in Ref. [11], which 
might have been observed [12] by the Belle collaboration 
[13]. Those resonances are generated dynamically by 
solving the coupled-channel Bethe-Salpeter equation for 
two pseudoscalar mesons [14]. The $D_{(0)}(2317)$ mainly 
couples to the $DK$, while the hidden charm state $X(3700)$ 
couples most strongly to $D\bar{D}$. Thus, any change in the 
$D$ meson properties in nuclear matter will have an im-
portant effect on these resonances. The $D$ meson self-energy 
is given in the $SU(4)$ model without the phenomenolog-
ical isoscalar-scalar term, but supplemented by the $p$-
wave self-energy [14].

In Fig. 2 the $D_{(0)}(2317)$ (left) and $X(3700)$ (middle) 
resonances are displayed via the squared transition am-
plitude for the corresponding dominant channel at differ-
ent densities. The $D_{(0)}(2317)$ and $X(3700)$ resonances, 
which have a zero and small width, develop widths of 
the order of 100 and 200 MeV at normal nuclear mater-
density, respectively. This is due to the opening of 
new many-body decay channels as the $D$ meson gets ab-
sorbed in the nuclear medium via $DN$ and $DNN$ inelastic 
reactions. We do not extract any clear conclusion for 
the mass shift. We suggest to look at the transparency ratio 
to investigate those in-medium widths, since it is very 
sensitive to the in-medium width of the resonance.

D-MESIC NUCLEI

$D$-meson bound states in $^{208}$Pb were predicted [2] relying 
upon an attractive $D$ meson potential. The observation 
of those bound states might be, though, problematic due 
to their widths, as in the case of the $SU(4)$ model [3].

FIGURE 1. Left: $D$ meson spectral function for the $SU(4)$ model. Right: $D$ and $D^*$ spectral functions in the $SU(8)$ scheme. We show the $D$ and $D^*$ meson free masses for reference (dotted lines).
However, for the scheme with HQS [4] the \(D\) meson in nuclear matter has a sufficiently small width with respect to the mass shift to form bound states in nuclei.

In order to compute de \(D\)-nucleus bound states, we solve the Schrödinger equation. We concentrate on \(D^0\)-nucleus bound states [15]. The potential that enters in the equation is an energy-dependent one that results from the zero-momentum \(D\)-meson self-energy within the SU(8) model [4]. In Fig. 2 (right) we show \(D^0\) meson bound states in different nuclei. We observe that the \(D^0\)-nucleus states are weakly bound, in contrast to previous results [2]. Their experimental detection is, though, difficult.

**CONCLUSIONS**

Open-charm mesons (\(D\) and \(D^0\)) in dense matter have been studied within a self-consistent coupled-channel approach taking, as bare interaction, different effective lagrangians. The in-medium solution accounts for Pauli blocking effects and meson self-energies. We have analyzed the evolution in matter of the open-charm meson spectral functions and discussed their effects on the \(D_{s0}(2317)\) and the predicted \(X(3700)\) in nuclear matter, and suggested to look at transparency ratios to investigate the in-medium width of those resonances. We have finally analyzed the possible formation of \(D\)-mesic nuclei. Only weakly bound \(D^0\)-nucleus states seem to be feasible within the \(SU(8)\) scheme that incorporates heavy-quark symmetry. However, its experimental detection is most likely a challenging task.

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