Heavy mesons in dense matter

Laura Tolos[1,2], Daniel Gamermann[3], Carmen Garcia-Recio[4], Raquel Molina[5],
Juan Nieves[5], Eulogio Oset[5], Angels Ramos[3]

[1]*Theory Group. KVI. University of Groningen, Zernikelaan 25, 9747 AA Groningen, The Netherlands*
[2] *Instituto de Ciencias del Espacio (IEEC/CSIC), Campus Universitat Autónoma de Barcelona,*
Facultat de Ciències, Torre C5, E-08193 Bellaterra (Barcelona), Spain
[3]*Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona,*
Diagonal 647, 08028 Barcelona, Spain
[4]*Departamento de Física Atómica, Molecular y Nuclear, Universidad de Granada, E-18071 Granada, Spain*
[5]*Instituto de Física Corpuscular (centro mixto CSIC-UV), Institutos de Investigación de Paterna,*
Aptdo. 22085, 46071, Valencia, Spain

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
PACS: 11.10.St,14.20.Lq,14.20.Pt,14.40.Lb,21.65.-f

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 [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 [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. [3, 4]). Then, the meson spectral function reads

$$S_{D(D^*)}(q_0,\vec{q},\rho,T) = -\frac{1}{\pi}\frac{\mathrm{Im}\,\Pi_{D(D^*)}(q_0,\vec{q},\rho,T)}{\mid q_0^2-\vec{q}^{\,2}-m^2_{D(D^*)}-\Pi_{D(D^*)}(q_0,\vec{q},\rho,T)\mid^2}\ , \quad (1)$$

with $\Pi_{D(D^*)}$ being the self-energy at given energy q_0, momentum $\vec{q}$, density ρ 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 $SU(4)$ s-wave Weinberg-Tomozawa (WT) interaction supplemented by an attractive isoscalar-scalar term and using a cutoff regularization scheme. We fix this cutoff by generating dynamically the $I=0$ $\Lambda_c(2595)$ resonance. A new resonance in $I=1$ channel, $\Sigma_c(2800)$, is generated [5, 6].

The in-medium solution incorporates Pauli blocking, baryon mean-field bindings and meson self-energies [3]. In l.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

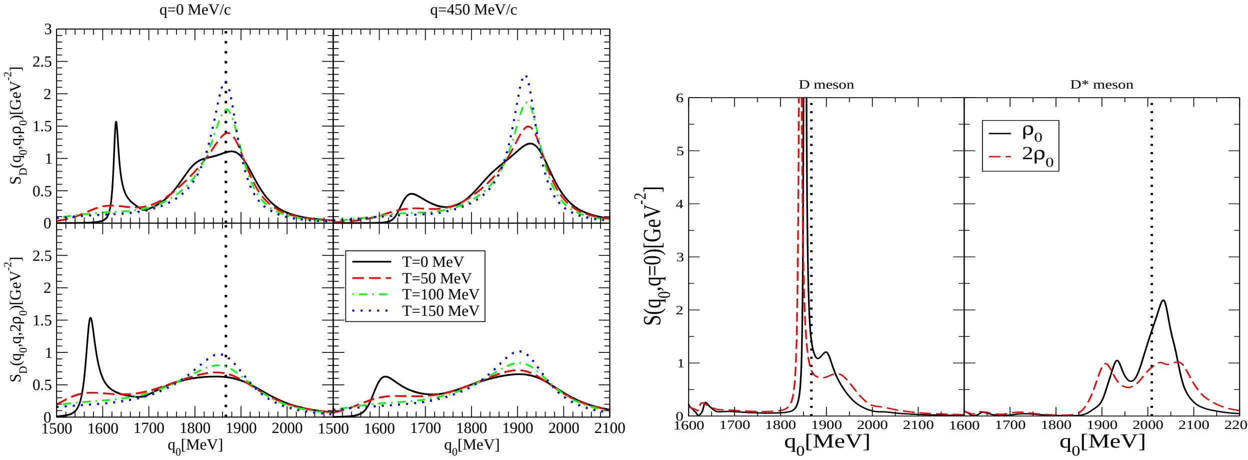

FIGURE 1. Left: D meson spectral function for the SU(4) model. Right: D and D^* spectral functions in the SU(8) scheme. We show the D and D^* meson free masses for reference (dotted lines).

$\Lambda_c(2595)N^{-1}$ 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 implemented 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 meson decay constants. We also improve on the regularization 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 nuclear matter is crucial in order to understand their nature, 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 $D_{s0}(2317)$ [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 $D_{s0}(2317)$ 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 important effect on these resonances. The D meson self-energy is given in the $SU(4)$ model without the phenomenological isoscalar-scalar term, but supplemented by the p-wave self-energy [14].

In Fig. 2 the $D_{s0}(2317)$ (left) and $X(3700)$ (middle) resonances are displayed via the squared transition amplitude for the corresponding dominant channel at different densities. The $D_{s0}(2317)$ and $X(3700)$ resonances, which have a zero and small width, develop widths of the order of 100 and 200 MeV at normal nuclear matter density, respectively. This is due to the opening of new many-body decay channels as the D meson gets absorbed 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].

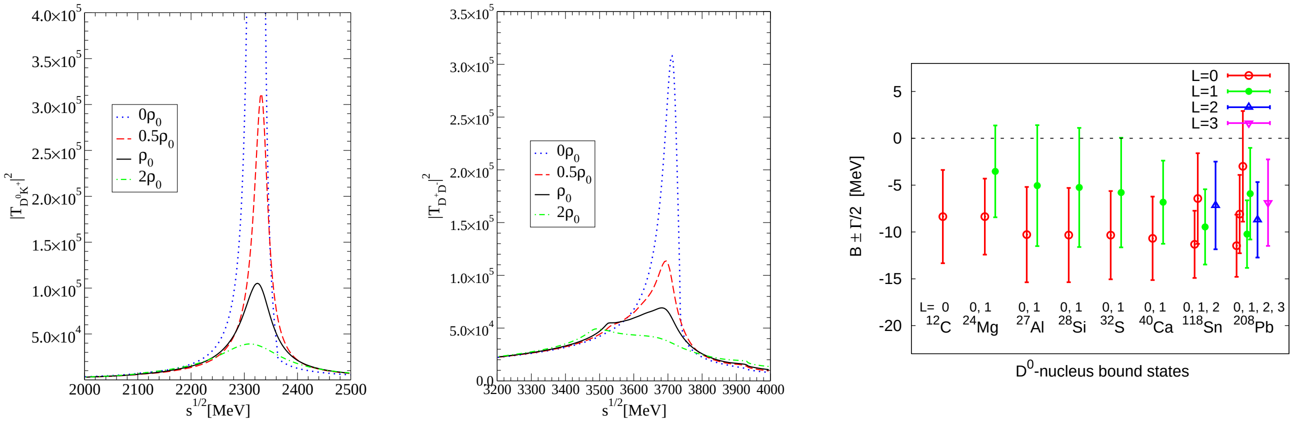

FIGURE 2. $D_{s0}(2317)$ (left) and $X(3700)$ (middle) resonances in nuclear matter. D^0 nucleus bound states (right)

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^*) 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.

L.T. acknowledges support from the RFF program of the University of Groningen. This work is partly supported by the EU contract No. MRTN-CT-2006-035482 (FLAVIAnet), by the contracts FIS2008-01661 and FIS2008-01143 from MICINN (Spain), by the Spanish Consolider-Ingenio 2010 Programme CPAN (CSD2007-00042), by the Generalitat de Catalunya contract 2009SGR-1289 and by Junta de Andalucía under contract FQM225. We acknowledge the support of the European Community-Research Infrastructure Integrating Activity “Study of Strongly Interacting Matter” (HadronPhysics2, Grant Agreement n. 227431) under the 7th Framework Programme of EU.

REFERENCES

1. http://www.gsi.de/ fair
2. K. Tsushima, D. H. Lu, A. W. Thomas, K. Saito, and R. H. Landau, *Phys. Rev. C* **59**, 2824 (1999).
3. L. Tolos, A. Ramos, and T. Mizutani, *Phys. Rev. C* **77**, 015207 (2008).
4. L. Tolos, C. Garcia-Recio, and J. Nieves, *Phys. Rev. C* **80**, 065202 (2009).
5. J. Hofmann, and M. F. M. Lutz, *Nucl. Phys. A* **763**, 90 (2005); M. F. M. Lutz, and C. L. Korpa, *Phys. Lett. B* **633**, 43 (2006).
6. T. Mizutani, and A. Ramos, *Phys. Rev. C* **74**, 065201 (2006).
7. C. Garcia-Recio, V. K. Magas, T. Mizutani, J. Nieves, A. Ramos, L. L. Salcedo, and L. Tolos, *Phys. Rev. D* **79**, 054004 (2009).
8. D. Gamermann, C. Garcia-Recio, J. Nieves, L. L. Salcedo and L. Tolos, *Phys. Rev. D* **81**, 094016 (2010).
9. E. E. Kolomeitsev, and M. F. M. Lutz, *Phys. Lett. B* **582**, 39 (2004).
10. F. K. Guo, P. N. Shen, H. C. Chiang, and R. G. Ping, *Phys. Lett. B* **641**, 278 (2006).
11. D. Gamermann, E. Oset, D. Strottman, and M. J. Vicente Vacas, *Phys. Rev. D* **76**, 074016 (2007).
12. D. Gamermann, and E. Oset, *Eur. Phys. J. A* **36**, 189 (2008).
13. K. Abe *et al.* [Belle Collaboration], *Phys. Rev. Lett.* **100**, 202001 (2008).
14. R. Molina, D. Gamermann, E. Oset, and L. Tolos, *Eur. Phys. J. A* **42**, 31 (2009).
15. C. Garcia-Recio, J. Nieves and L. Tolos, *Phys. Lett. B* **690**, 369 (2010).