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# Hadrons with charmed quarks in matter

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**Abstract.** We investigate the $D\bar{D}$ decay width of excited charmonium states at finite nuclear density with simultaneous modification of both $D$- and $\bar{D}$-mesons in nuclear matter. The strongest effect is found for the $\Psi'$-meson. The medium modification can be detected by dilepton spectroscopy as substantial $\Psi'$ broadening and anomalous $\Psi'$ absorption.

**PACS.** 13.25.Gv Decays of $J/\Psi$, $\Upsilon$, and other quarkonia – 14.40.Lb Charmed mesons – 14.65.Dw Charmed quarks – 24.85.+p Quarks, gluons, and QCD in nuclei and nuclear processes

## 1 Introduction

In dense and hot nuclear matter the light-quark condensates $q\bar{q}$ might be substantially reduced. This affects the light-quark content of mesons and baryons and therefore results in-medium modification of hadron properties [1–3]. Even if the changes in quark condensates are small, the absolute difference between the in-medium and bare masses of hadrons is expected [3,4] to be larger for heavier hadrons.

The charmed mesons, which consist of light $q$, $\bar{q}$ and heavy $c$, $\bar{c}$ quarks, are considered suitable probes of in-medium modification of hadron properties. Similarly to $\bar{K}$ ($\bar{q}s$) and $K$ ($q\bar{s}$) mesons, the $D$ ($\bar{q}c$) and $\bar{D}$ ($q\bar{c}$) satisfy different dispersion relations in matter because of the different sign of $q$ and $\bar{q}$ vector couplings [3]. While the $D$-meson mass is reduced in nuclear matter, the $\bar{D}$ mass is raised, as is illustrated by fig. 1a). Calculations with the Quark-Meson Coupling model (QMC) [5] show that already at normal nuclear density $\rho_0$ the mass splitting between $D$- and $\bar{D}$-mesons is about 160 MeV.

It was proposed [4] that the modification of the $D$-meson in nuclear matter can be identified by enhanced subthreshold production of open charm in $\bar{p}A$ annihilation. Because of charm conservation, $D$- and $\bar{D}$-mesons are produced pairwise. As is shown in fig. 1b) the sum of $D$ and $\bar{D}$ masses depends substantially on nuclear density. The downward shift of the $D\bar{D}$ threshold at $\rho_0$ is $\simeq -100$ MeV. A QCD sum rule estimate [6] predicts about the same shift.

Furthermore, an attractive $D$-nucleus potential can be measured by investigating charmed mesic nuclei [3]. The reduction of $D$ mass in matter might affect open-charm production [7] and $J/\Psi$ suppression [8] in relativistic heavy-ion collisions.

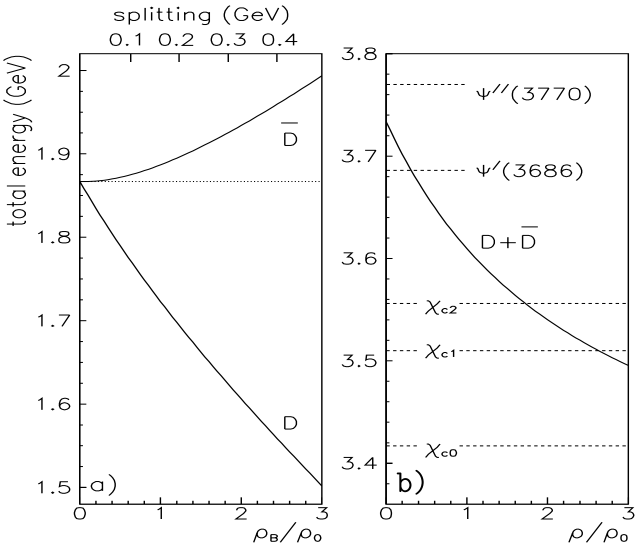


**Fig. 1.** a) The in-medium mass of $D$- and $\bar{D}$-mesons as a function of nuclear density $\rho/\rho_0$, with $\rho_0 = 0.16\,\mathrm{fm}^{-3}$ and the $D\bar{D}$ mass splitting (upper axis). b) The solid line shows the overall $D\bar{D}$ mass as a function of density. The dashed lines indicate the masses of excited charmonia.

In contrast to open charm, charmonium mesons consist of heavy $c\bar{c}$ quarks and can be affected only by gluonic condensates. It was expected that the modification of properties of heavy quarkonia in matter would be almost negligible [9]. In that case, the overall $D\bar{D}$ mass at some nuclear density might cross the masses of excited charmonium states, as is illustrated by fig. 1b).

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The crossing of the charmonium states levels and the $D\bar{D}$ threshold in nuclear medium might result in the melting [10] of excited charmonium mesons.

Here, we investigate the modification of widths of charmonium states at finite nuclear density with $D$ and $\bar{D}$ in-medium masses predicted by QMC [3]. We consider simultaneous modification of both $D$- and $\bar{D}$-mesons, as is illustrated in fig. 1 and study $\Psi''(3770)$, $\Psi'(3686)$ and $\chi_{c2}$ decay into $D\bar{D}$ in nuclear matter. The $\chi_{c0}$ modification is not discussed since the $D\bar{D}$ threshold does not cross its mass even at $\rho = 3\rho_0$, as is shown in fig. 1. The $\chi_{c1} \to D\bar{D}$ decay is suppressed by parity conservation.

## 2 $\Psi''(3770)$

The $\Psi''$-charmonium lies above the $D\bar{D}$ threshold in free space and its dominant decay width into $D\bar{D}$ channel is given by

$$\Gamma_{\Psi'' \to D\bar{D}} = \frac{g^2_{\Psi'' D\bar{D}}}{3\pi} \frac{q^3}{m^2_{\Psi}}\,, \tag{1}$$

where $m_\Psi$ is the $\Psi''(3770)$ mass and $q$ is the $D$-meson momentum in the charmonium rest frame,

$$q = \frac{\left[\left(m^2_\psi - m^2_D - m^2_{\bar{D}}\right)^2 - 4m^2_D m^2_{\bar{D}}\right]^{1/2}}{2m_\Psi}\,, \tag{2}$$

with $m_D$ and $m_{\bar{D}}$ the masses of $D$- and $\bar{D}$-mesons, respectively, while the coupling constant $g_{\Psi'' D\bar{D}} = 14.89$ is fixed by the vacuum decay width $\Gamma_{\Psi'' \to D\bar{D}} = 23.6\,\text{MeV}$.

If $\Psi'' D\bar{D}$ coupling does not change in matter the modification of the $\Psi(3770)$ width is entirely given by $D$ and $\bar{D}$ in-medium masses and is determined by the phase space dependence of the charmonium decay width. In that case the in-medium $\Psi(3770)$ width depends substantially on nuclear-matter density, as is shown by the solid line in fig. 2a).

Within the $^3P_0$ model [11] the $\Psi'' D\bar{D}$ coupling itself depends on the $D$ and $\bar{D}$ masses via

$$g^2_{\Psi'' D\bar{D}} = \frac{\pi^{3/2} 2^{11} \gamma^2 m_\Psi}{5\beta^7 3^{10}} \left[\left(q^2 + m^2_D\right)\left(q^2 + m^2_{\bar{D}}\right)\right]^{1/2} \times \left(15\beta^2 - 2q^2\right)^2 \exp\left(-q^2/6\beta^2\right), \tag{3}$$

where the oscillator length scale $\beta = 360\,\text{MeV}$ is fixed by light-mesons decays [11], while the interaction strength $\gamma = 0.33$ is determined by $\Psi'' \to D\bar{D}$ decay.

Finally, the dashed line in fig. 2 shows the dependence of the $\Psi'' \to D\bar{D}$ decay width on nuclear-matter density resulting from the $^3P_0$ model. At normal nuclear density $\rho_0 = 0.16\,\text{fm}^{-3}$ the $\Psi''(3770)$ in-medium width almost saturates $\Gamma_{\Psi'' \to D\bar{D}} \simeq 90\,\text{MeV}$, which is $\simeq 3.8$ times larger than in vacuum. Furthermore, the $^3P_0$ result substantially differs from the phase space estimate.

The $\Psi''$ modification in nuclear matter might be studied by dilepton spectroscopy from $AA$ as well as $\bar{p}A$ interactions, since the effect is measurable already at normal nuclear densities. The $\Psi''(3770)$-charmonium does not decay into $J/\Psi$ and thus its modification in matter cannot be considered as an additional source of $J/\Psi$ suppression in heavy-ion collisions.

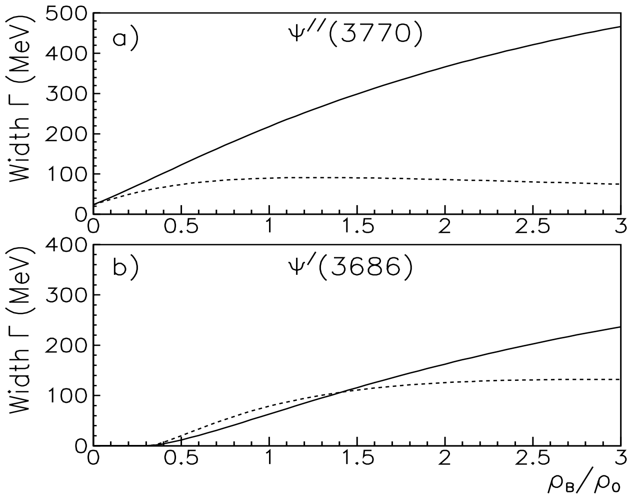


**Fig. 2.** Decay widths of $\Psi''(3770)$ (a) and $\Psi'(3686)$ (b) charmonium states into $D\bar{D}$ as a function of nuclear-matter density in units of $\rho_0$. The solid lines show the phase space dependence, while the dashed lines are the results from the $^3P_0$ model. In both calculations the $D$ and $\bar{D}$ in-medium masses are given by the QMC model.

## 3 $\Psi'(3686)$

The $\Psi'$-charmonium lies below the $D\bar{D}$ threshold in free space, but the $D\bar{D}$ decay channel becomes open at nuclear density $\rho \simeq 0.05\,\text{fm}^{-3}$, as illustrated by fig. 1. The $\Psi'$ is narrow, its total width is 0.277 MeV and partial decay into $J/\Psi$ accounts for $\simeq 54\%$ of the total width.

Although, the $\Psi(3686)$ coupling to $D\bar{D}$ is not directly accessible, it can be estimated within the framework of Vector Meson Dominance model as

$$g^2_{\Psi' D\bar{D}} = \frac{16\pi\alpha^2}{27} \frac{m_\Psi}{\Gamma_{\Psi' \to e^+e^-}}\,, \tag{4}$$

where $\alpha$ is the fine-structure constant, $m_\Psi$ is the $\Psi'(3686)$ mass and $\Gamma_{\Psi' \to e^+e^-} = 2.35\,\text{keV}$ is the radiative $\Psi' \to e^+e^-$ decay width. Finally, the $\Psi' D\bar{D}$ coupling constant is 12.84; the $\Psi'' D\bar{D}$ coupling from VMD is to 19.94, which is close to the result from direct $\Psi'' \to D\bar{D}$ decay given by eq. (1).

The phase space dependence of the $\Psi'$ in-medium width from eq. (1) is shown by the solid line in fig. 2b). This result again can be compared with the prediction of the $^3P_0$ model given by [11]

$$\Gamma_{\Psi' \to D\bar{D}} = \frac{\pi^{1/2} 2^9 \gamma^2}{m_\Psi \beta^7 3^{11}} \left[\left(q^2 + m^2_D\right)\left(q^2 + m^2_{\bar{D}}\right)\right]^{1/2} \times q^3 \left(15\beta^2 - 2q^2\right)^2 \exp\left(-q^2/6\beta^2\right) \tag{5}$$

and shown by the dashed line in fig. 2b). Here the calculations were done with parameters $\beta$ and $\gamma$ evaluated

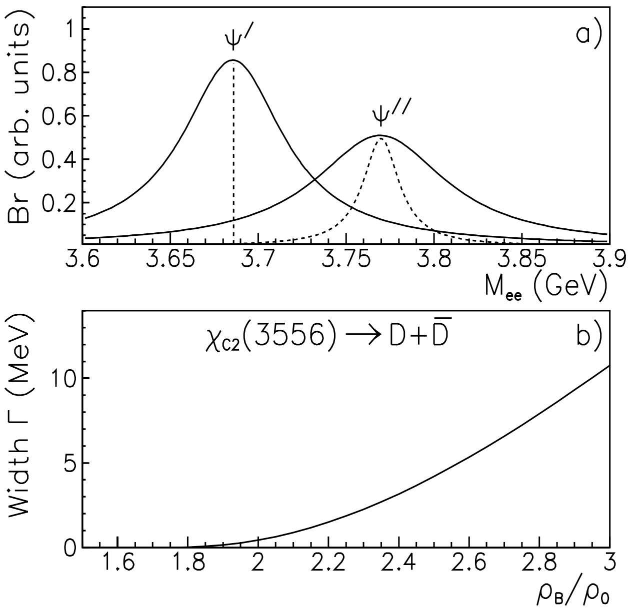


**Fig. 3.** a) Dilepton spectra from $\Psi'$ and $\Psi''$ decays at normal nuclear density $\rho = \rho_0 = 0.16\,\mathrm{fm}^{-3}$ (solid lines) and in vacuum (dashed lines). b) Decay width of the $\chi_{c2}(3556)$-charmonium into $D\bar{D}$ as a function of nuclear-matter density in units of $\rho_0$ predicted by the $^3P_0$ model with $D$ and $\bar{D}$ in-medium masses given by QMC.

above. Note that at nuclear densities $\rho \leq 1.5\rho_0$ both the $^3P_0$ model and VMD phase space estimates are in reasonable agreement. An exciting observation is that at normal nuclear density $\rho_0 = 0.16\,\mathrm{fm}^{-3}$ the $\Psi'$ width is $\simeq 70\,\mathrm{MeV}$, which is $\simeq 250$ times larger than that in vacuum.

Again, the $\Psi'$ modification in nuclear matter can be measured through dilepton spectroscopy. As we found, the dilepton spectrum from $\Psi'(3686)$ decay in matter might strongly overlap with $\Psi''(3770)$-charmonium decay. Figure 3a) shows dilepton spectra from $\Psi'$ and $\Psi''$ decays unfolded from the production cross-section. The solid lines show the results for matter at normal nuclear density, while the dashed lines indicate the spectra in free space. The measurement of a broad peak around $\Psi'$ pole might be considered as an direct indication of in-medium modification of charmonia.

On the other hand, a large $D\bar{D}$ component of $\Psi'$-charmonium should result in strong $\Psi'$ absorption in nuclear matter, similar to that found [8] for $J/\Psi$ dissociation. Moreover, $\Psi'$ melting in nuclear matter will additionally suppress $\Psi' \to J/\Psi$ decay and partially eliminate $J/\Psi$ yield in heavy-ion collisions.

## 4 $\chi_{c2}(3556)$

The $\chi_{c2}$-charmonium level crosses the $D\bar{D}$ threshold at a nuclear density of about $0.28\,\mathrm{fm}^{-3}$. In vacuum the $\chi_{c2}$ width is $2\,\mathrm{MeV}$ and partial decay into the $J/\Psi$ is $\simeq 13.5\%$. There is no reliable way to estimate $\chi_{c2}D\bar{D}$ coupling and to evaluate the phase space dependence of the $\chi_{c2}$ in-medium width.

In the $^3P_0$ model the $\chi_{c2} \to D\bar{D}$ width is given as [11]

$$\Gamma_{\chi_{c2}\to D\bar{D}} = \frac{\pi^{1/2}2^{12}\gamma^2}{5m_\chi\beta^5 3^8}\left[\left(q^2+m_D^2\right)\left(q^2+m_{\bar{D}}^2\right)\right]^{1/2} \times q^5 \exp\left(-q^2/6\beta^2\right), \qquad (6)$$

where $m_\chi$ is the $\chi_{c2}$ mass and parameters $\beta$ and $\gamma$ are listed above. The in-medium $\chi_{c2}$ width is shown in fig. 3b) as a function of nuclear-matter density. The $\chi_{c2}$ modification becomes significant only at large densities.

## 5 Conclusion

Modification of the $D$- and $\bar{D}$-meson masses in nuclear matter leads to a substantial increase of the $\chi_{c2}$, $\Psi'$ and $\Psi''$ decay widths into the $D\bar{D}$ channel.

The calculations with the density-independent coupling constants between the $\Psi'$- and $\Psi''$-charmonium and the $D\bar{D}$-pair results in strong and monotonic density dependence of the $\Psi'$ and $\Psi''$ in-medium widths due to the increase of the final-state phase space. Within the $^3P_0$ model these couplings are also considered as a function of the in-medium $D$ and $\bar{D}$ masses and as a result the $\Psi'$- and $\Psi''$-charmonium widths do not increase monotonically with nuclear density, but saturate at $\rho_0 = 0.16\,\mathrm{fm}^{-3}$. It was found that the saturation limits are $\Gamma_{\Psi'\to D\bar{D}} \simeq 70\,\mathrm{MeV}$ and $\Gamma_{\Psi''\to D\bar{D}} \simeq 90\,\mathrm{MeV}$, which can be compared with vacuum widths of $0.277\,\mathrm{MeV}$ and $23.6\,\mathrm{MeV}$, respectively.

The $\chi_{c2}$-charmonium level crosses the $D\bar{D}$ threshold at $\rho \simeq 1.25\rho_0$ and its width increases with nuclear-matter density. At $\rho \simeq 3\rho_0$ the $\chi_{c2}$ decay width into $D\bar{D}$ is about $11\,\mathrm{MeV}$, which may be compared with total $\Gamma_{\chi_{c2}} = 2\,\mathrm{MeV}$ width in vacuum.

We conclude that the modification of the $D$ and $\bar{D}$ in matter most dramatically affects the $\Psi'$-charmonium. This can be detected by dilepton spectroscopy as the appearance of a broad peak near the $\Psi'$ pole or as anomalous $\Psi'$ suppression in nuclear matter.

Our results are in agreement with the most recent findings [12] that both the mass and width of $\Psi''(3770)$ depend significantly on the $D$-meson mass.

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