\textit{D mesons and charmonium states in hot pion matter}

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(Dated:)

We calculate the in-medium D meson self-energies in a hot pion gas induced by resonance interactions with pions. The appropriate resonances in the s, p and d waves of the D meson-pion pair are represented by low lying scalar, vector and tensor D\textsuperscript{*} mesons. At temperatures around 200 MeV the D-meson mass drops by 30 MeV and the scattering width grows up to 60 MeV. Similar medium effects are found for the D\textsuperscript{*} vector mesons. This opens and/or enhances the decay and/or dissociation channels of the charmonium states \(\Psi, \chi_c\) and \(J/\Psi\) to \(DD, D^*D, DD^*, D^*D^*\) pairs in pion matter.

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Since the conjecture of the dissociation of charmonium states \(J/\Psi, \Psi', \ldots\) in a quark-gluon plasma (QGP) due to color screening \cite{1} \(J/\Psi\) suppression was considered as one of the key signals for the creation of a QGP phase in heavy ion reactions. An anomalous \(J/\Psi\) suppression has possibly been seen in central \(p\bar{p} + p\bar{p}\) reactions at CERN Super Proton Synchrotron (SPS) \cite{2}. However, the interpretation of data is strongly influenced by the final state interactions of charmonium states in a hadron gas. The dissociation of \(J/\Psi\)'s due to pion scattering \(J/\Psi + \pi \rightarrow DD, D^*D, DD^*, D^*D^*\) has extensively been discussed within the comover scenario \cite{3}, for a review see \cite{4}. The \(J/\Psi\) yield at Relativistic Heavy Ion Collider (RHIC) will be measured by the PHENIX Collaboration \cite{5}. On the other hand, recent lattice QCD calculations indicate that the \(J/\Psi\) might exists as a bound state even at temperatures above the critical temperature for a QGP phase transition \cite{6}.

Direct in-medium modifications of charmonium states, i.e. mass shifts and elastic collisional widths are expected to be small compared to those of the \(D\) mesons \cite{7}. Indirect modifications of charmonium state can, however, appear due to medium modifications of the \(D\)-meson states. With the lowering of \(D\) masses the inelastic collisional width of charmonium states (due to dissociation to open charm) or, in some cases, even the ordinary width (due to on-shell decays to open charm) is increased or is appeared as a result of the lowering of corresponding thresholds \cite{8}. These facts are important for both, the production and the survival probability of \(J/\Psi\) mesons. About 20\%, 14\% and 8\% of \(J/\Psi\)'s are produced in \(p\bar{p}, D\bar{D}, K\bar{K}\) channels in a quark-gluon plasma (QGP) due to color screening \cite{1}, while for the remaining \(J/\Psi\)'s, the 

\[
\Sigma = -\int (A^+dn_{s\pi^+} + A^0dn_{s\pi^0} + A^-dn_{s\pi^-})
\]  

Scalar \(n_{s\pi}\) and vector pion densities \(n_{v\pi} (dn_{s\pi} = dn_{s\pi}/2E_\pi)\) are given by Bose-Einstein distributions at fixed temperature \(T\):

\[
dn_{v\pi} = \frac{d^3p_\pi}{(2\pi)^3} \left( \exp\left(\frac{E_\pi - \mu_\pi}{T}\right) - 1 \right)^{-1} \]  

Here \(\mu_\pi^+ = -\mu_\pi^-\) is the \(\pi^+\) chemical potential, \(\mu_\pi^0 = 0\). In isotopically symmetric pion matter which is expected to be formed in ultra-relativistic heavy-ion collisions at RHIC energies the chemical potentials vanish \((\mu_\pi^\pm = 0)\).
0). Hence all pions (negative, neutral and positive) are equally distributed.

In an isotopically symmetric pion gas $D^+ + D^0$ obtain identical self-energies due to isospin symmetry and these are further equal to the $D^- + \overline{D}^0$ self-energies due to charge conjugation symmetry. Thus we can restrict ourselves in the following to the discussion of the $D^+$ self-energy. In this context it should be noticed that $D$ mesons show a close analogy to kaons. In both cases a mass splitting between $K$ and $\overline{K}$, respectively $D$ and $\overline{D}$ occurs at finite nuclear density whereas in isotopically symmetric pion matter kaons and antikaons obtain equal in-medium modifications.

The interaction of $D$ mesons with pions or more generally, the interaction of charmed heavy-light pseudoscalar and vector mesons with light pseudoscalar mesons has been already discussed in the literature. A local 4-particle interaction motivated by chiral symmetry and been already discussed in the literature. A local 4-particle interaction motivated by chiral symmetry and implemented for $s$-wave scattering in Ref. [26]. This tree level interaction has further been iterated for $s$-wave resonant effects in Ref. [26]. This tree level interaction has further been iterated for $s$-wave resonant effects in Ref. [26].

The $D\pi$ resonances in the $D\pi$ system with masses

\[
\begin{array}{cccc}
\text{Resonance} & \text{mass (MeV)} & \text{width (MeV)} \\
D^* & 2008.5 & \approx 0.1 \\
D_0^* & 2308 \pm 60 & 276 \pm 99 \\
D^*_1 & 2427 \pm 61 & 384^{+203}_{-169} \\
D_1 & 2421.4 \pm 2.7 & 23.7 \pm 6.9 \\
D_2^* & 2461.6 \pm 5.9 & 45.6 \pm 12.5 \\
\end{array}
\]

are further equal to the $D\pi$ resonances in the $D\pi$ system.

where $F \approx 93$ MeV is the pion decay constant. This result can be presented by isospin $1/2$ and isospin $3/2$ amplitudes

\[
\begin{align*}
A_{1/2} &= \frac{1}{2F^2}(s-u) \\
A_{3/2} &= -\frac{1}{2F^2}(s-u),
\end{align*}
\]

The first amplitude $A_{1/2}$ is positive and attractive, the second amplitude $A_{3/2}$ is negative and repulsive. Iterating the $A_{1/2}$ amplitude to all orders in ladder approximation leads to a large value for the $T$ matrix (at least in $s$ waves) and a pole corresponding to a $D\pi$ resonance. The $A_{3/2}$ amplitude after iteration decreases. The tree level amplitudes contain only $s$ and $p$ waves. Not discussing the reliability of such an approach in what follows we will not rely on these tree level amplitudes but instead will take only the observed $s$-, $p$- and $d$- wave resonances in the $D\pi$ system into account. For orbitally excited mesons we take the experimental data from the BELLE Collaboration [29] (see Fig.1) where for the first time all four orbitally excited $D$-meson states have been observed simultaneously. The information on the very narrow vector mesons $D^*$ (p-wave resonances close to threshold) is taken from Particle Data Group [30].

For resonance scattering we include only the isospin

![FIG. 1: (Color online) Levels of $D$-meson excitations which are taken into account as resonances in $D\pi$ system.](image)

TABLE I: Excited $D$-meson states which are taken into account as resonances in $D\pi$ system.

| Resonance | mass (MeV) | width (MeV) |
|-----------|------------|-------------|
| $D^*$     | 2008.5     | $\approx 0.1$ |
| $D_0^*$   | 2308 ± 60  | 276 ± 99    |
| $D^*_1$   | 2427 ± 61  | 384$^{+203}_{-169}$ |
| $D_1$     | 2421.4 ± 2.7 | 23.7 ± 6.9 |
| $D_2^*$   | 2461.6 ± 5.9 | 45.6 ± 12.5 |

1/2 resonances which leads to

\[
\begin{align*}
A(D^+\pi^+ \rightarrow D^+\pi^+) &= 0 \\
A(D^+\pi^0 \rightarrow D^+\pi^0) &= \frac{1}{3} A_{1/2} \\
A(D^+\pi^- \rightarrow D^+\pi^-) &= \frac{2}{3} A_{1/2}
\end{align*}
\]

and the sum of these amplitudes that enters the thermal average is equal to $A_{1/2}$. For the forward resonance amplitude $A_{1/2}$ we use the relativistic Breit-Wigner form

\[
A_{1/2} = \sum_{j=0,1,2} \frac{8\pi\sqrt{s}}{k} \frac{(2j+1)}{s-M_j^2+i\sqrt{s}\Gamma_j^{tot}},
\]

where $j = 0, 1, 2$ corresponds to the $s$-, $p$- and $d$- wave resonances $D_0^*$, $D^*$ and $D_2^*$ in the $D\pi$ system with masses $M_j$, partial and total widths $\Gamma_j^{D\pi}$ and $\Gamma_j^{tot}$, respectively; $j_1 = j_2 = 0$ are the spins of the $D$ and the pion, respectively, and $k$ is the c.m. momentum. The energy dependence of the widths is regulated by the specified partial wave

\[
\Gamma_j^{D\pi} = \frac{k}{\kappa_0}(2j+1)M_j^2 s\Gamma_j^{D\pi} + i\sqrt{s}\Gamma_j^{tot},
\]

where subscript '0' refers to on mass shell decay widths. When the same amplitude is evaluated for the $j_1 = 1 D^*$
the D* self-energy in a pion gas at rest is obtained by integration over the pion distribution which yields the corresponding modifications of the meson properties: the scattering width Γ and mass shift ReΣ/2M. The contribution of the narrow D* resonance with a width of about 100 KeV to the D meson medium modifications are of the order of the D* width and can be neglected (if one takes the in-medium modification of the D* into account, this is no more the case as will be seen later on). The contributions of the scalar and tensor D* mesons are, however, sizable and shown in Fig. 2 as a function of the temperature. Medium modifications of the vector D* mesons which are of similar magnitude arise from the coupling to axial and tensor mesons, see also Fig. 2.

For further applications to charmonium states the off-shell properties of D and D* mesons, namely the spectral functions will be important. Spectral function is defined by the off-shell self-energy Σ(m^2, |p|) as follows

$$\rho(m^2, |p|) = \frac{1}{\pi} \frac{-Im\Sigma}{(m^2 - M^2 - Re\Sigma)^2 + (Im\Sigma)^2}. \quad (8)$$

In medium spectral function depend not only on the invariant mass squared of the particle but also on its momentum. For D and D* mesons at rest in the hot pion medium with temperature $T = 200$ MeV the spectral functions are shown on Fig. 3 as the functions of the invariant mass. At other momenta typical for the decays of the charmonium states (see below) they don’t change significantly because the velocities of D and D* mesons are small compared to the thermal velocities of pions.

For D, D* mesons we calculated the spectral functions both, with vacuum (dashed lines) and in-medium (solid lines) spectral functions of D*, D mesons. In the latter case which is the first order self-consistent iteration, the vacuum propagators of D and D* in (6) are replaced by the corresponding in-medium propagators in order to obtain the iterated in-medium results

$$\frac{1}{s - M^2_{D(D*)} - \Sigma_{D(D*)}} \rightarrow \frac{1}{s - M^2_{D(D*)} - \Sigma_{D(D*)}}. \quad (9)$$

The medium modification of the D meson has thereby a feedback on the D* since it modifies the corresponding decay channel. The difference between the lowest
order and the first iteration is significant at small invariant masses of the $D, D^*$ mesons which is important for the charmonium decays.

![Graph of $\Gamma(J/\Psi \rightarrow D\bar{D})$ vs. $T$](image)

**FIG. 4:** (Color online) In-medium width of $J/\Psi$, $\chi_1$, $\chi_2$ and $\Psi'$ mesons.

With this information, one is able to evaluate the dissociation widths of the charmonium states $J/\Psi$, $\chi_1$, $\chi_2$, $\Psi'$ in the pion medium. Let us take into account the fact that in the medium $D, D^*$ mesons are not particles but resonances with finite collisional widths. Then the $J/\Psi \rightarrow D\bar{D}, D\bar{D}^*, D^*\bar{D}, D^*D^*$ decay can occur sub-threshold and thus account for the reactions $J/\Psi \rightarrow D\bar{D}, D\bar{D}^*, D^*\bar{D}, D^*D^*$ which are open in pion matter. The width $\Gamma(J/\Psi \rightarrow D\bar{D})$ can be easily found

\[
\Gamma(J/\Psi \rightarrow D\bar{D}) = \int \frac{g_{J/\Psi D\bar{D}}^2}{3\pi M_{J/\Psi}^2} p^3 \rho_D(m_1^2, p)\rho_{\bar{D}}(m_2^2, p) dm_1^2 dm_2^2,
\]

where $p$ is c.m. momentum for the decay of $J/\Psi$ meson to $D$ and $D^*$ mesons with masses $m_1$ and $m_2$, respectively and $g_{J/\Psi D\bar{D}}$ is the $J/\Psi D\bar{D}$ coupling constant. Taking the value of $g_{J/\Psi D\bar{D}} = 7.8$ from ref. one obtains a dissociation width of $\Gamma(J/\Psi \rightarrow D\bar{D}) = 0.54$ MeV at a temperature of $T = 200$ MeV. The other decay channels ($D\bar{D}^*, D^*\bar{D}, D^*D^*$) can be treated analogously. To do so, we use the coupling constants

\[
g_{J/\Psi D^*D^*} = g_{J/\Psi D\bar{D}}, \quad g_{J/\Psi D\bar{D}} = \frac{g_{J/\Psi D\bar{D}}}{M_D}
\]

in combination with appropriate phenomenological vertices $\chi$. In total one obtains thus at a temperature of $T = 200$ MeV a $J/\Psi$ collisional width of $1.15$ MeV (see Fig.4).

These values can now be compared to the collisional width $\Gamma(J/\Psi \pi \rightarrow DD, DD^*, D^*D, D^*D^*) = 5 \div 14$ MeV. The later one was obtained by multiplying the average cross section for the $J/\Psi$ dissociation through pions evaluated at the same temperature and equal to $<\sigma^{\pi J/\Psi} v> \approx 0.75 \div 2$ mb ($v$ being the relative velocity) with the corresponding pion density. The order of magnitude agreement between the $J/\Psi$ subthreshold decay width to $D$ mesons and the $J/\Psi\pi$ dissociation width is not surprising because both effects are of common nature. In fact, the $J/\Psi$ dissociation through pion capture by one of the $D$ mesons is connected to the $D$ mesons collision widths. In the calculation of the $J/\Psi$ decay rate the $D$ mesons collision width appears in the denominator of the Breit-Wigner amplitude which, due to the sub-threshold character of the $J/\Psi$ decay, can be expanded in powers of the pion density entering the $D$-meson collision width. To lowest order the result coincides with the $J/\Psi$ dissociation rate through one-pion capture by one of the $D$ mesons. However, the inclusion of realistic spectral functions turns out to reduce the $J/\Psi$ dissociation. So, the results of previous calculations differ from the present ones because some contribution (contact 4-particle interaction) is not considered in our approach (see diagram 1c in Fig. 1 in ) and because our amplitude is closer to the unitarity constraint. In this context it should be mentioned that there appear additional dissociation mechanisms at the quark level , e.g. $s$-channel box diagrams, which cannot be expressed in terms of effective meson degrees of freedom and may lead to an additional increase of the width.

The in-medium width of the excited $\Psi'$ is estimated analogously assuming the same $g_{\Psi' D\bar{D}}$ coupling constant as for the $J/\Psi$. Since the $\Psi'$ lies only $52$ MeV below the $DD$ threshold in free space its in-medium width is about $50$ times larger than that of the $J/\Psi$. Finally, the in-medium widths of the $\chi_1, \chi_2$ states were estimated using the phenomenological vertices $g_{MD\chi_1}(D\bar{D})$ and $g_{M\chi_2}(D\bar{D})$ with $g = g_{J/\Psi D\bar{D}}$, respectively. As seen from Fig.4 $\chi_1, \chi_2$ mesons also receive a substantial width in pion matter.

In conclusion, the $D$ meson self-energies in pion matter have been determined to leading order in density taking thereby resonances in the $D\pi$ amplitude into account. The resonances in $s, p$ and $d$ waves of $D$ meson-pion system were represented by low lying scalar, vector and tensor $D^*$ mesons which have been observed experimentally. This allows to determine the $D$ self-energy in a model independent way. At a temperature around $200$ MeV the $D$-meson mass is reduced by about $30$ MeV and the scattering width is about $60$ MeV. Similar medium modifications were found for $D^*$ vector mesons. Consequently, the widths of the decay and dissociation channels of the charmonium states $\Psi', \chi_c$.
and $J/\Psi$ to $D\bar{D}$, $D^*\bar{D}$, $DD^*$, $D^*\bar{D}^*$ pairs are enhanced (from $\Gamma_{J/\Psi} \simeq 1.15$ MeV to $\Gamma_{\Psi'} \simeq 62$ MeV at $T \simeq 200$ MeV). As a consequence, feeding of $J/\Psi$ states from excited charmonium states ceases in a hot pion gas which characterizes the hadronic final state in high energetic heavy ion reactions in good approximation.

Hence, $D$ mesons modifications in hot pion medium are important for the production of $J/\Psi$ during the fireball expansion in heavy ion reactions. The back reactions of $J/\Psi$ formation in $D$ mesons collisions from charmed meson rich medium become important for corresponding transport simulations.

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