D mesons and charmonium states in hot isospin asymmetric strange hadronic matter

Amruta Mishra

Department of Physics,
Indian Institute of Technology, Delhi

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Plan of the talk

- D and $\bar{D}$ mesons in asymmetric hadronic matter
- Charmonium states in asymmetric hadronic matter
- Partial decay widths for Charmonium to $D\bar{D}$ pairs
- Results and Conclusions

Arvind Kumar and AM, Phys. Rev. C81,065204 (2010);
Arvind Kumar and AM, Phys. Rev. C82, 045207 (2010);
Arindam Mazumder and AM, Phys. Rev. C79,024908 (2009);
Arvind Kumar and AM, arxiv: 1102.4792 (nucl-th).

Why study D-mesons and charmonia in asymmetric medium?

Because of relevance in observables like:

- Open charm enhancement
- J/ψ suppression
- Dilepton spectra
- possibility of D-mesic nuclei

Asymmteric nuclear collisions at CBM experiment at FAIR project in the future facility at GSI!

D mesons and Charmonia in the hadronic medium

$D(\bar{D})$ mesons $(c\bar{q}(\bar{c}q))$ bound states.
Within QCD sum rule approach, the light quark/antiquark of the D-meson interacts with the light quark condensate of the nuclear medium and modifies the D mesons properties in the medium.

Charmonium states are $c\bar{c}$ bound states and interact with the medium through the gluon condensates.

A. Hayashigaki, Phys. Lett. B 487, 96 (2000);
A. Hayashigaki, Prog. Theo. Phys. 101,923 (1999).

Different methods to study the problem

- QCD sum rule approach
- Quark meson coupling model
- Coupled channel approach

$DN \to DN, \pi\Sigma_c, \pi\Lambda_c, ...$

- Chiral Effective model

The chiral effective model

Hadronic model constructed from symmetries of QCD at low energies:
Chiral symmetry is spontaneously broken in QCD ($\langle \bar{q}q \rangle \neq 0$)
- pions are Goldstone modes ($m_\pi^2 = -\left(\frac{m_u+m_d}{2}\right)\frac{\langle \bar{q}q \rangle}{f_\pi^2}$)
• Scale symmetry is also broken ($\langle G_{\mu\nu}G^{\mu\nu} \rangle \neq 0$)
Impose these constraints to construct low energy effective theory for hadrons
The scalar dilaton field, χ is related to scalar gluon condensate, $\langle G_{\mu\nu}G^{\mu\nu} \rangle$

Chiral Effective model

The general form of the Lagrangian density is

$$\mathcal{L} = \mathcal{L}_{kin} + \sum_W \mathcal{L}_{BW} + \mathcal{L}_{vec} + \mathcal{L}_0 + \mathcal{L}_{scalebreak} + \mathcal{L}_{SB}$$

The scale breaking part is

$$\mathcal{L}_{scalebreak} = -\frac{1}{4}\chi^4 \ln\frac{\chi^4}{\chi_0^4} + \frac{d}{3}\chi^4 \ln\left(\frac{\left(\sigma^2 - \delta^2\right)\zeta}{\sigma_0^2\zeta_0}\left(\frac{\chi}{\chi_0}\right)^3\right),$$

The trace of Energy momentum tensor in QCD in massless quark limit is

$$\theta_\mu^\mu = \langle\frac{\beta_{QCD}}{2g} G_{\mu\nu}^a G^{\mu\nu a}\rangle \equiv -(1-d)\chi^4,$$

Generalize to SU(4) to derive interactions of the charmed mesons in the hadronic medium.

Generalization to SU(4)

The interaction Lagrangian density of the $D(\bar{D})$ meson is given as

$$
\begin{aligned}
\mathcal{L}_{int} = & -\frac{i}{8f_D^2}\Big[3\Big(\bar{p}\gamma^\mu p + \bar{n}\gamma^\mu n\Big)\Big(\Big(D^0(\partial_\mu \bar{D}^0) - (\partial_\mu D^0)\bar{D}^0\Big) \\
+ & \Big(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^-\Big)\Big) + \Big(\bar{p}\gamma^\mu p - \bar{n}\gamma^\mu n\Big) \\
& \Big(\Big(D^0(\partial_\mu \bar{D}^0) - (\partial_\mu D^0)\bar{D}^0\Big) - \Big(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^-\Big)\Big) \\
+ & 2\Big((\bar{\Lambda}^0\gamma^\mu\Lambda^0)\Big(\Big(D^0(\partial_\mu \bar{D}^0) - (\partial_\mu D^0)\bar{D}^0\Big) + \Big(D^+(\partial_\mu D^-) \\
- & (\partial_\mu D^+)D^-\Big)\Big) + 2\Big(\Big(\bar{\Sigma}^+\gamma^\mu\Sigma^+ + \bar{\Sigma}^-\gamma^\mu\Sigma^-\Big) \\
\times & \Big(\Big(D^0(\partial_\mu \bar{D}^0) - (\partial_\mu D^0)\bar{D}^0\Big) + \Big(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^-\Big)\Big) \\
+ & \Big(\bar{\Sigma}^+\gamma^\mu\Sigma^+ - \bar{\Sigma}^-\gamma^\mu\Sigma^-\Big)\Big(\Big(D^0(\partial_\mu \bar{D}^0) - (\partial_\mu D^0)\bar{D}^0\Big) \\
- & \Big(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^-\Big)\Big)\Big)
\end{aligned}
$$

$$
\begin{aligned}
+ \quad & 2\Big(\bar{\Sigma}^0\gamma^\mu\Sigma^0\Big)\Big(\Big(D^0(\partial_\mu\bar{D}^0) - (\partial_\mu D^0)\bar{D}^0\Big) \\
+ \quad & \Big(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^-\Big)\Big) + \Big(\bar{\Xi}^0\gamma^\mu\Xi^0 + \bar{\Xi}^-\gamma^\mu\Xi^-\Big) \\
& \Big(\Big(D^0(\partial_\mu\bar{D}^0) - (\partial_\mu D^0)\bar{D}^0\Big) + \Big(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^-\Big)\Big) \\
+ \quad & \Big(\bar{\Xi}^0\gamma^\mu\Xi^0 - \bar{\Xi}^-\gamma^\mu\Xi^-\Big)\Big(\Big(D^0(\partial_\mu\bar{D}^0) - (\partial_\mu D^0)\bar{D}^0\Big) \\
- \quad & \Big(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^-\Big)\Big)\Big] \\
+ \quad & \frac{m_D^2}{2f_D}\Big[(\sigma + \sqrt{2}\zeta_c)\big(\bar{D}^0D^0 + (D^-D^+)\big) + \delta\big(\bar{D}^0D^0) - (D^-D^+)\big)\Big] \\
- \quad & \frac{1}{f_D}\Big[(\sigma + \sqrt{2}\zeta_c)\Big((\partial_\mu\bar{D}^0)(\partial^\mu D^0) + (\partial_\mu D^-)(\partial^\mu D^+)\Big) \\
+ \quad & \delta\Big((\partial_\mu\bar{D}^0)(\partial^\mu D^0) - (\partial_\mu D^-)(\partial^\mu D^+)\Big)\Big]
\end{aligned}
$$

$$
\begin{aligned}
+ \quad & \frac{d_1}{2f_D^2}(\bar{p}p + \bar{n}n + \bar{\Lambda}^0\Lambda^0 + \bar{\Sigma}^+\Sigma^+ + \bar{\Sigma}^0\Sigma^0 + \bar{\Sigma}^-\Sigma^- \\
+ \quad & \bar{\Xi}^0\Xi^0 + \bar{\Xi}^-\Xi^-)\big((\partial_\mu D^-)(\partial^\mu D^+) + (\partial_\mu \bar{D}^0)(\partial^\mu D^0)\big) \\
+ \quad & \frac{d_2}{2f_D^2}\Big[\Big(\bar{p}p + \frac{1}{6}\bar{\Lambda}^0\Lambda^0 + \bar{\Sigma}^+\Sigma^+ + \frac{1}{2}\bar{\Sigma}^0\Sigma^0\Big)(\partial_\mu \bar{D}^0)(\partial^\mu D^0) \\
+ \quad & \Big(\bar{n}n + \frac{1}{6}\bar{\Lambda}^0\Lambda^0 + \bar{\Sigma}^-\Sigma^- + \frac{1}{2}\bar{\Sigma}^0\Sigma^0\Big)(\partial_\mu D^-)(\partial^\mu D^+)\Big]
\end{aligned}
$$

The interaction Lagrangian includes all terms upto leading (Weinberg-Tomazawa) and next to leading order terms (scalar exchange and range terms) in the chiral effective model!

Dispersion relations of $D(\bar{D})$ mesons

$$-\omega^2 + \vec{k}^2 + m_D^2 - \Pi\left(\omega, |\vec{k}|\right) = 0$$

Self-energy $\Pi\left(\omega, |\vec{k}|,\right)$ for the D meson doublet (D^0,D^+) is

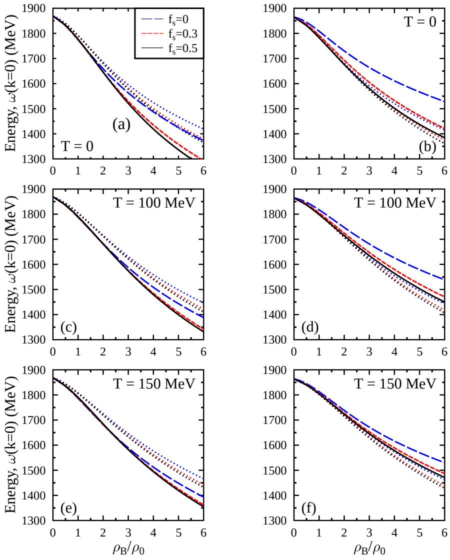
$$\begin{aligned}
\Pi(\omega, |\vec{k}|) &= \frac{1}{4f_D^2}\Big[3(\rho_p + \rho_n) \pm (\rho_p - \rho_n) \\
&+ 2\big((\rho_{\Sigma^+} + \rho_{\Sigma^-}) \pm (\rho_{\Sigma^+} - \rho_{\Sigma^-})\big) + 2(\rho_{\Lambda^0} + \rho_{\Sigma^0}) \\
&+ ((\rho_{\Xi^0} + \rho_{\Xi^-}) \pm (\rho_{\Xi^0} - \rho_{\Xi^-}))\Big]\omega + \frac{m_D^2}{2f_D}(\sigma' + \sqrt{2}\zeta_c{}' \pm \delta') \\
&+ \Big[-\frac{1}{f_D}(\sigma' + \sqrt{2}\zeta_c{}' \pm \delta') + \frac{d_1}{2f_D^2}(\rho^s_p + \rho^s_n + \rho^s_{\Lambda^0} + \rho^s_{\Sigma^+} + \rho^s_{\Sigma^0} \\
&+ \rho^s_{\Sigma^-} + \rho^s_{\Xi^0} + \rho^s_{\Xi^-}) + \frac{d_2}{4f_D^2}\Big((\rho^s_p + \rho^s_n) \pm (\rho^s_p - \rho^s_n) + \frac{1}{3}\rho^s_{\Lambda^0} \\
&+ (\rho^s_{\Sigma^+} + \rho^s_{\Sigma^-}) \pm (\rho^s_{\Sigma^+} - \rho^s_{\Sigma^-}) + \rho^s_{\Sigma^0}\Big)\Big](\omega^2 - \vec{k}^2).
\end{aligned}$$

Dispersion relations of $D(\bar{D})$ mesons

Self energy of $\bar{D} = (\bar{D^0}, D^-)$ is

$$
\begin{aligned}
\Pi(\omega, |\vec{k}|) &= -\frac{1}{4f_D^2}\Big[3(\rho_p+\rho_n) \pm (\rho_p - \rho_n) \\
&+ 2\big((\rho_{\Sigma^+}+\rho_{\Sigma^-}) \pm (\rho_{\Sigma^+}-\rho_{\Sigma^-})\big) \\
&+ 2(\rho_{\Lambda^0}+\rho_{\Sigma^0}) + ((\rho_{\Xi^0}+\rho_{\Xi^-}) \pm (\rho_{\Xi^0}-\rho_{\Xi^-}))\Big]\omega \\
&+ \frac{m_D^2}{2f_D}(\sigma' + \sqrt{2}\zeta_c{}' \pm \delta') \\
&+ \Big[-\frac{1}{f_D}(\sigma' + \sqrt{2}\zeta_c{}' \pm \delta') + \frac{d_1}{2f_D^2}(\rho_p^s + \rho_n^s \\
&+ \rho^s_{\Lambda^0} + \rho^s_{\Sigma^+} + \rho^s_{\Sigma^0} + \rho^s_{\Sigma^-} + \rho^s_{\Xi^0} + \rho^s_{\Xi^-}) \\
&+ \frac{d_2}{4f_D^2}\Big((\rho^s_p + \rho^s_n) \pm (\rho^s_p - \rho^s_n) + \frac{1}{3}\rho^s_{\Lambda^0} \\
&+ (\rho^s_{\Sigma^+} + \rho^s_{\Sigma^-}) \pm (\rho^s_{\Sigma^+} - \rho^s_{\Sigma^-}) + \rho^s_{\Sigma^0}\Big)\Big](\omega^2 - \vec{k}^2),
\end{aligned}
$$

D meson masses in the medium

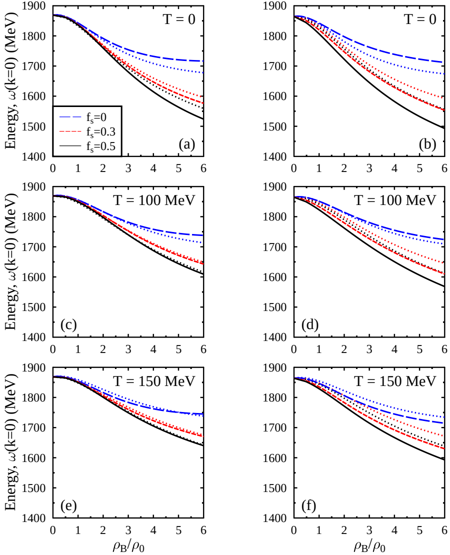


D meson masses in the medium

For given isospin asymmetry, strangeness and temperature, the masses of both D^+ and D^- are observed to drop with density. Δm_D=77 (345) MeV for ρ_B/ρ_0=1 (4) for T=0,η=0, f_s=0.

The introduction of hyperons into the medium is observed to lead to a larger drop in the D mesons masses as compared to the case of nuclear matter.
The isospin asymmetry leads to a smaller (larger) drop of $D^+(D^0)$ meson, as compared to the isospin symmetric case.

$\bar{D}$ meson masses in the medium



$\bar{D}$ meson masses in the medium

There is seen to be decrease in the $\bar{D}$ meson masses with density. $\Delta m_{\bar{D}}$=27 (161) MeV for ρ_B/ρ_0=1 (4) for η=0, f_s=0 and T=0. Effect of strangeness is to decrease the masses of the $\bar{D}$ mesons, similar to as for the D mesons.
The D mesons are more sensitive to isospin asymmetry as compared to $\bar{D}$ mesons, whereas the $\bar{D}$ mesons are seen to be more sensitive to strangeness of the medium as compared to the D mesons.

Masses of Charmomium states in the medium

Mass modifications of the charmonium states in hadronic medium due to interaction with the gluon condensates of QCD.
Gluon condensate simulated by scalar dilaton field introduced to incorporate the broken scale invariance within the chiral effective model.
Mass shift of the charmonium state can be written as

$$\Delta m_\psi = -\frac{1}{9}\int dk^2 \left|\frac{\partial\psi(k)}{\partial k}\right|^2 \frac{k}{k^2/m_c+\epsilon} \times \left(\left\langle\frac{\alpha_s}{\pi}E^2\right\rangle - \left\langle\frac{\alpha_s}{\pi}E^2\right\rangle_0\right).$$

m_c is the mass of the charm quark, m_ψ is the vacuum mass of the charmonium state and $\epsilon = 2m_c - m_\psi$ is the binding energy. $\psi(k)$ is the wave function of the charmonium state in the momentum space.

S.H. Lee and C.M.Ko, Phys. Rev. C 67, 038202 (2003);
B. Friman,S. H. Lee and T. Song, Phys. Lett. B 548, 153 (2002);
Arvind Kumar and AM, arxiv:1102.4792 (nucl-th).

Masses of Charmomium states in the medium

In the non-relativistic limit the color electric field part can be written in terms of the scalar gluon condensate as

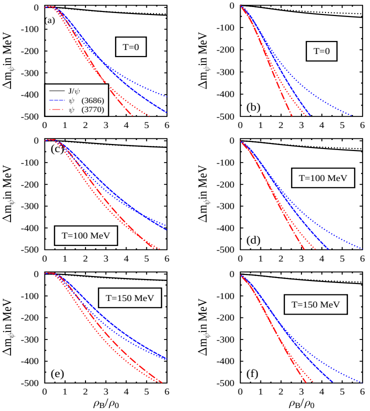
$$\left\langle \frac{\alpha_s}{\pi} E^2 \right\rangle = -\frac{1}{2} \left\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{\mu\nu a} \right\rangle ,$$

The wave functions for the charmonium states are taken to be Gaussian and are given as

$$\psi_{N,l}(r) = \mathrm{N} \times Y_l^m(\theta, \phi)(\beta^2 r^2)^{\frac{1}{2}l} exp^{-\frac{1}{2}\beta^2 r^2} L_{N-1}^{l+\frac{1}{2}} \left(\beta^2 r^2\right)$$

$\beta = \sqrt{M\omega/\hbar}$ is the strength of the harmonic potential, $M = m_c/2$ is the reduced mass of the $c\bar{c}$ system. $L_p^k(z)$ is the associated Laguerre Polynomial. β determined from the rms radii of J/ψ, $\psi(3686)$ and $\psi(3770)$ states as 0.47,0.96 and 1 fm respectively. Modification of β due to shift in the mass of ψ is used to calculate the radii of the charmonia in the medium.

Masses of Charmomium states in the medium



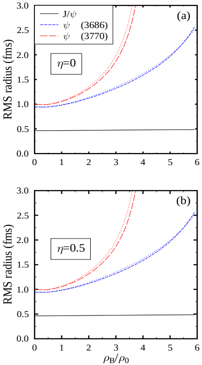
Charmomium states in the medium

Mass shifts of J/ψ, $\psi(3686)$ and $\psi(3770)$ at $\rho_B = \rho_0$ observed to be -9.32, -126 and -167 MeV, when the masses of the quarks are neglected in the energy momentum tensor and -4.35, -59 and -78.5 MeV when the finite quark masses are taken into account.

The dominant medium modifications to the charmonium masses are due to the density effects. The effects of the temperature, isospin asymmetry and strangeness are seen to be small.

The modifications of the strengths of the harmonic oscillator wave functions of the charmonium states can be obtained from their mass shifts, e.g., $\delta M_{J/\psi} = \frac{3}{2M}\delta\beta^2$ and $\delta M_\psi = \frac{7}{2M}\delta\beta^2$ for $\psi(3686)$ and $(\psi(3770)$. These, in turn, can be used to compute the rms radii of the charmonium states in the hadronic medium. The modifications are seen to be large for $\psi(3686)$ and $\psi(3770)$ and negligible for J/ψ.

Radii of Charmomium states in the medium



Partial Decay widths of the charmonium states to $D\bar{D}$ pairs

$$\Gamma_{\psi \to D\bar{D}} = 2\pi \frac{p_D E_D E_{\bar{D}}}{M_\psi} |M|^2,$$

where, M is the matrix element for the decay of the parent charmonium state to the $D\bar{D}$ pairs, p_D is the magnitude of the 3-momentum of the D ($\bar{D}$) meson when the charmonium state ψ decays at rest and is given by

$$p_D = \left(\frac{{M_\psi}^2}{4} - \frac{{m_D}^2 + {m_{\bar{D}}}^2}{2} + \frac{({m_D}^2 - {m_{\bar{D}}}^2)^2}{4{M_\psi}^2} \right)^{1/2},$$

T. Barnes et al, Phys. Rev. D 55, 4157 (1997),
A. Le Yaouanc et al, Phys. Lett. B 71, 397 (1977);
B. Friman,S. H. Lee and T. Song, Phys. Lett. B 548, 153 (2002)

Partial Decay widths of the charmonium states to $D\bar{D}$ pairs

The decay widths for the charmonium states J/ψ, $\psi(3686)$ and $\psi(3770)$ decaying to $D\bar{D}$ (D^+D^- and $D^0\bar{D}^0$), are given as

$$\Gamma(J/\psi \to D\bar{D}) = \pi^{1/2}\frac{E_D E_{\bar{D}}\gamma^2}{2M_{J/\psi}}\frac{2^8 r^3(1+r^2)^2}{3(1+2r^2)^5}x^3 \times \exp\Big(-\frac{x^2}{2(1+2r^2)}\Big),$$

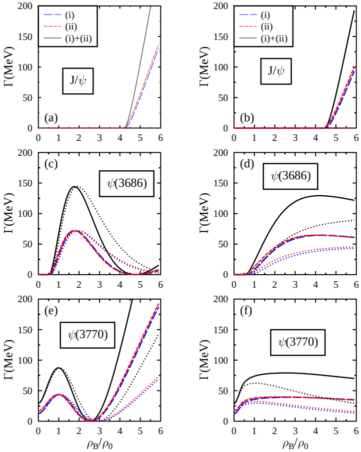
$$\Gamma(\psi(3686) \to D\bar{D}) = \pi^{1/2}\frac{E_D E_{\bar{D}}\gamma^2}{2M_{\psi(3686)}} \times \frac{2^7(3+2r^2)^2(1-3r^2)^2}{3^2(1+2r^2)^7}x^3 \left(1+\frac{2r^2(1+r^2)}{(1+2r^2)(3+2r^2)(1-3r^2)}x^2\right)^2 \times \exp\Big(-\frac{x^2}{2(1+2r^2)}\Big),$$

Partial Decay widths of the charmonium states to $D\bar{D}$ pairs

$$\Gamma(\psi(3770) \to D\bar{D}) = \pi^{1/2} \frac{E_D E_{\bar{D}} \gamma^2}{2M_{\psi(3770)}} \frac{2^{11} 5}{3^2} \left(\frac{r}{1+2r^2}\right)^7$$
$$\times \quad x^3 \left(1 - \frac{1+r^2}{5(1+2r^2)} x^2\right)^2 \exp\left(-\frac{x^2}{2(1+2r^2)}\right),$$

In the above, $r = \frac{\beta}{\beta_D}$ is the ratio of the harmonic oscillator strengths of the decaying charmonium state and the produced $D(\bar{D})$-mesons, $x = p_D/\beta_D$ and γ is a measure of the strength of the 3P0 vertex.

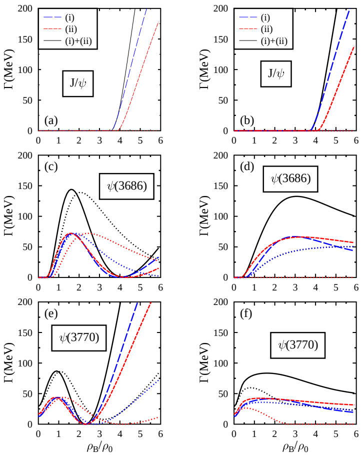
Partial Decay widths of the charmonium states to $D\bar{D}$ pairs for symmetric hadronic matter



Partial Decay widths of the charmonium states to $D\bar{D}$ pairs

The dependence of the partial decay widths on $p_D = x\beta_D$, is through the polynomial as well as the gaussian parts. Due to the vanishing of the polynomial term, the decay widths vanish at certain densities, leading to nodes.
For the case of η=0, there are nodes observed at densities of about 4.5 ρ_0 and 2.8 ρ_0, for $\psi(3686)$ and $\psi(3770)$, when the mass modifications of the $D(\bar{D})$ mesons are taken into account.
However, there are important modifications when the charmonium masses are also taken into account.

Partial Decay widths of the charmonium states to $D\bar{D}$ pairs for asymmetric hadronic matter



Results and Conclusions

• The masses of the $D(\bar{D})$ mesons are computed in the hot asymmetric strange hadronic matter within a chiral effective model.

• The mass modifications are seen to be dominant at high densities and should be of direct relevance in the observables in the asymmetric heavy ion collisions at the CBM experiment at the future facility at GSI.

• Charmonium masses have been computed within the model, from the medium modifications of a scalar dilaton field, which is incorporated into the effective hadronic model to simulate the gluon condensates in QCD.

• The results at small densities are similar to the existing results in the literature carried in the linear density approximation.

Results and Conclusions-continued

• The possibility of decay of the charmonium states to the $D\bar{D}$ pairs depend on the medium modifications on these mesons. However, there are seen to be nodes in the partial decay widths when the internal structures of these mesons are considered, with the in-medium $D(\bar{D})$ mesons, but no mass modifications for the charmonium states.
These have been observed in the Ref. B. Friman,S. H. Lee and T. Song, Phys. Lett. B 548, 153 (2002).

• The partial decay widths have been studied When the modifications of the charmonium as well as $D(\bar{D})$ mesons are considered, as have been computed within the effective hadronic model.