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Arvind Kumar and Amruta Mishra, Phys. Rev. C 81,065204(2010),
Arvind Kumar and Amruta Mishra, arxiv:1010.0403 (nucl-th).

D mesons and charmonium states in hot asymmetric nuclear matter

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Outline :

1) Aim and motivation

2) Model used

3) D mesons in hot asymmetric nuclear matter

4) D mesons in strange hadronic matter

5) Charmonium states in hot asymmetric nuclear matter

6) J/psi suppression

7) Summary

Why study D-meson and charmonia mass modifications in asymmetric nuclear matter?

- Because of relevance in observables like

- Open charm-enhancement

- J/psi suppression

Asymmetric nuclear collisions in CBM experiment at future facility at GSI

- D mesons contain one light (u or d) quark (antiquark) and a heavy charm antiquark (charm quark).

- Within QCD sum rules the light quark or antiquark of D mesons interact with the light quark condensate of the nuclear medium and modify the properties of D mesons in the nuclear medium.

- Charmonium states are made up of a heavy charm quark and a charm antiquark and interact with the nuclear medium through the gluon condensates.

- The gluon condensates have small modifications in the nuclear medium.

A. Hayashigaki, Phys. Lett. B 487, 96 (2000)

A. Hayashigaki, Prog. Theor. Phys. 101,923 (1999) .

❖Different approaches to tackle the problem

- ❑QCD sum rules
- ❑Quark Meson Coupling (QMC) model
- ❑Coupled channel approach

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

- ❑Chiral models

We have used a chiral effective model to study masses of D mesons and charmonium states, due to their interactions with the light hadrons (nucleons and scalar mesons) and the scalar dilaton field (simulating the gluon condensates in the medium) respectively, in the hot asymmetric nuclear medium.

- *Model used*

- Chiral SU(3) model based on
- Chiral symmetry
- Broken scale invariance, leading to trace anomaly,

$$\theta_\mu^\mu = \langle \frac{\beta_{QCD}}{2g} G_{\mu\nu}^a G_a^{\mu\nu} \rangle$$

- Mean-field approximation

- Lagrangian density is given as,

$$\mathcal{L} = \mathcal{L}_{kin} + \sum_{W=X,Y,V,A,u} \mathcal{L}_{BW} + \mathcal{L}_{vec} + \mathcal{L}_0 + \mathcal{L}_{SB}$$

Kinetic term ($\mathcal{L}_{kin}$)

Baryon meson interactions ($\mathcal{L}_{BW}$)

Interaction of Vector mesons ($\mathcal{L}_{vec}$)

Meson-meson interactions ($\mathcal{L}_0$)

Explicit symmetry breaking ($\mathcal{L}_{SB}$)

1. *Weinberg–Tomozawa term*

$$\Gamma_\mu = -\frac{i}{4}\left[u^\dagger\partial_\mu u - \partial_\mu u^\dagger u + u\partial_\mu u^\dagger - \partial_\mu u u^\dagger\right]$$

$$i\mathrm{Tr}\bar{B}\gamma_\mu D^\mu B$$

$$D_\mu = \partial_\mu + i[\Gamma_\mu, \quad]$$

$$u_\mu = -\frac{i}{2}\left[u^\dagger\partial_\mu u - u\partial_\mu u^\dagger\right]$$

$$= -\frac{i}{8f_D^2}\Big[3\left(\bar{p}\gamma^\mu p + \bar{n}\gamma^\mu n\right)\Big(\Big(D^0(\partial_\mu\bar{D}^0) - (\partial_\mu D^0)\bar{D}^0\Big) + \Big(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^-\Big)$$
$$+ \left(\bar{p}\gamma^\mu p - \bar{n}\gamma^\mu n\right)\Big(\Big(D^0(\partial_\mu\bar{D}^0) - (\partial_\mu D^0)\bar{D}^0\Big) - \Big(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^-\Big)\Big]$$

2. *Explicitly symmetry breaking term*

❖ *Introduces mass term for pseudoscalar mesons*

$$\mathcal{L}_{SB} = \mathrm{Tr}A_p\left(u(X+iY)u + u^\dagger(X-iY)u^\dagger\right)$$
$$= \frac{m_D^2}{2f_D}\left[\left(\sigma + \sqrt{2\zeta_c}\right)\left(\bar{D}^0D^0 + D^-D^+\right) + \delta\left(\bar{D}^0D^0 - D^-D^+\right)\right]$$

$$A_p = 1/\sqrt{2}\mathrm{diag}(m_\pi^2 f_\pi, m_\pi^2 f_\pi, 2m_K^2 f_K - m_\pi^2 f_\pi)$$

Range terms

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3. Kinetic energy term for pseudoscalar mesons

$$\mathrm{Tr}(u_\mu X u^\mu X + X u_\mu u^\mu X)$$

$$= -\frac{1}{f_D}\Big[(\sigma + \sqrt{2}\zeta_c)\big((\partial_\mu \bar{D}^0)(\partial^\mu D^0) + (\partial_\mu D^-)(\partial^\mu D^+)\big) + \delta\big((\partial_\mu \bar{D}^0)(\partial^\mu D^0) - (\partial_\mu D^-)(\partial^\mu D^+)\big)\Big]$$

4. d_1 and d_2 terms

$$\mathcal{L}^{BM}_{d_1} = \frac{d_1}{2}\mathrm{Tr}(u_\mu u^\mu)\mathrm{Tr}(\bar{B}B)$$

$$= +\frac{d_1}{2f_D^2}(\bar{p}p + \bar{n}n)\left(\left(\partial_\mu \bar{D}^0\right)\left(\partial^\mu D^0\right) + \left(\partial_\mu D^-\right)\left(\partial^\mu D^+\right)\right)$$

$$\mathcal{L}^{BM}_{d_2} = d_2 Tr\left(\bar{B} u_\mu u^\mu B\right)$$

$$= \frac{d_2}{4f_D^2}\Big[(\bar{p}p + \bar{n}n))((\partial_\mu \bar{D}^0)(\partial^\mu D^0) + (\partial_\mu D^-)(\partial^\mu D^+)) + (\bar{p}p - \bar{n}n)((\partial_\mu \bar{D}^0)(\partial^\mu D^0)) - (\partial_\mu D^-)(\partial^\mu D^+))\Big]$$

Interaction Lagrangian density

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$$
\begin{aligned}
\mathcal{L}_{\mathcal{DN}} = & -\frac{i}{8f_D^2}\Big[3\big(\bar{p}\gamma^\mu p + \bar{n}\gamma^\mu n\big)\big(D^0(\partial_\mu \bar{D}^0) - (\partial_\mu D^0)\bar{D}^0\big) + \big(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^-\big) \\
& + \big(\bar{p}\gamma^\mu p - \bar{n}\gamma^\mu n\big)\big(D^0(\partial_\mu \bar{D}^0) - (\partial_\mu D^0)\bar{D}^0\big) - \big(D^+(\partial_\mu D^-) - (\partial_\mu D^+)D^-\big)\Big] \\
& + \frac{m_D^2}{2f_D}\Big[(\sigma + \sqrt{2}\zeta_c)\big(\bar{D}^0 D^0 + (D^- D^+)\big) + \delta\big(\bar{D}^0 D^0) - (D^- D^+)\big)\Big] \\
& - \frac{1}{f_D}\Big[(\sigma + \sqrt{2}\zeta_c)\Big((\partial_\mu \bar{D}^0)(\partial^\mu D^0) + (\partial_\mu D^-)(\partial^\mu D^+)\Big) \\
& + \delta\Big((\partial_\mu \bar{D}^0)(\partial^\mu D^0) - (\partial_\mu D^-)(\partial^\mu D^+)\Big)\Big] \\
& + \frac{d_1}{2f_D^2}(\bar{p}p + \bar{n}n)\big((\partial_\mu D^-)(\partial^\mu D^+) + (\partial_\mu \bar{D}^0)(\partial^\mu D^0)\big) \\
& + \frac{d_2}{4f_D^2}\Big[(\bar{p}p + \bar{n}n))\big((\partial_\mu \bar{D}^0)(\partial^\mu D^0) + (\partial_\mu D^-)(\partial^\mu D^+)\big) \\
& + (\bar{p}p - \bar{n}n)\big((\partial_\mu \bar{D}^0)(\partial^\mu D^0)) - (\partial_\mu D^-)(\partial^\mu D^+)\big)\Big]
\end{aligned}
$$

WT term

Explicit symmetry breaking

Kinetic term for pseudoscalar mesons

$d_1 term$

$d_2 term$

Range terms

Dispersion relations : Fourier transformations of equations of motion of the pseudoscalar meson fields give us the dispersion relations

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

Self-energy

(D^0, D^+)

D mesons

$$\begin{aligned}
\Pi(\omega, |\vec{k}|) &= \frac{1}{4f_D^2}\Big[3(\rho_p+\rho_n) \pm (\rho_p-\rho_n)\Big]\omega \\
&+ \frac{m_D^2}{2f_D}(\sigma' + \sqrt{2}\zeta_c{}' \pm \delta') \\
&+ \Big[-\frac{1}{f_D}(\sigma' + \sqrt{2}\zeta_c{}' \pm \delta') + \frac{d_1}{2f_D^2}(\rho_s^p + \rho_s^n) \\
&+ \frac{d_2}{4f_D^2}\Big(({\rho^s}_p + {\rho^s}_n) \pm ({\rho^s}_p - {\rho^s}_n)\Big)\Big](\omega^2 - \vec{k}^2)
\end{aligned}$$

$(\bar{D}^0, D^-)$

$\overline{D}$ mesons

$$\begin{aligned}
\Pi(\omega, |\vec{k}|) &= -\frac{1}{4f_D^2}\Big[3(\rho_p+\rho_n) \pm (\rho_p-\rho_n)\Big]\omega \\
&+ \frac{m_D^2}{2f_D}(\sigma' + \sqrt{2}\zeta_c{}' \pm \delta') \\
&+ \Big[-\frac{1}{f_D}(\sigma' + \sqrt{2}\zeta_c{}' \pm \delta') + \frac{d_1}{2f_D^2}(\rho_s^p + \rho_s^n) \\
&+ \frac{d_2}{4f_D^2}\Big(({\rho^s}_p + {\rho^s}_n) \pm ({\rho^s}_p - {\rho^s}_n)\Big)\Big](\omega^2 - \vec{k}^2)
\end{aligned}$$

How to find d_1 and d_2 ?

From low energy KN scattering lengths

$$a_{KN}(I=0) \approx -0.09\ \text{fm},$$

$$a_{KN}(I=1) \approx -0.31\ \text{fm}$$

$$a_{KN}(I=0) = \frac{m_K}{4\pi f_K{}^2(1+m_K/m_N)} \times \left[-\frac{m_K f_K}{2}\left(\frac{g_{\sigma N}}{m_\sigma{}^2} + \sqrt{2}\frac{g_{\zeta N}}{m_\zeta{}^2} - 3\frac{g_{\delta N}}{m_\delta{}^2}\right) + \frac{(d_1 - d_2)m_K}{2} \right]$$

$$a_{KN}(I=1) = \frac{m_K}{4\pi f_K{}^2(1+m_K/m_N)} \times \left[-1 - \frac{m_K f_K}{2}\left(\frac{g_{\sigma N}}{m_\sigma{}^2} + \sqrt{2}\frac{g_{\zeta N}}{m_\zeta{}^2} + \frac{g_{\delta N}}{m_\delta{}^2}\right) + \frac{(d_1 + d_2)m_K}{2} \right]$$

$$d_1 = \frac{2.56}{m_K}, d_2 = \frac{.73}{m_K}$$

Parameters used

- The values $g_{\sigma N} = 10.6$, $g_{\varsigma N} = 10.6$ are determined by fitting vacuum baryon masses and the parameters $g_{\omega N} = 13.3$, $g_{\rho N} = 5.5$, $g_4 = 79.7$, $g_{\delta N} = 2.5$, , $m_{\varsigma} = 1024.5 MeV$ $m_{\sigma} = 466.5 MeV$ $m_{\delta} = 899.5 MeV$ are fitted to the nuclear matter saturation properties in the mean field approximation.

Coupled equations of motion of scalar fields within chiral SU(3) model :

For sigma field :

$$k_0\chi^2\sigma - 4k_1(\sigma^2+\zeta^2+\delta^2)\sigma - 2k_2(\sigma^3+3\sigma\delta^2) - 2k_3\chi\sigma\zeta - \frac{d}{3}\chi^4\left(\frac{2\sigma}{\sigma^2-\delta^2}\right) + \left(\frac{\chi}{\chi_0}\right)^2 m_\pi^2 f_\pi - \sum g_{\sigma i}\rho_i^s = 0$$

For zeta field :

$$k_0\chi^2\zeta - 4k_1(\sigma^2+\zeta^2+\delta^2)\zeta - 4k_2\zeta^3 - k_3\chi(\sigma^2-\delta^2) - \frac{d}{3}\frac{\chi^4}{\zeta} + \left(\frac{\chi}{\chi_0}\right)^2\left[\sqrt{2}m_k^2 f_k - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right] - \sum g_{\zeta i}\rho_i^s = 0$$

For delta field :

$$k_0\chi^2\delta - 4k_1(\sigma^2+\zeta^2+\delta^2)\delta - 2k_2(\delta^3+3\sigma^2\delta) + k_3\chi\delta\zeta + \frac{2}{3}d\chi^4\left(\frac{\delta}{\sigma^2-\delta^2}\right) - \sum g_{\delta i}\rho_i^s = 0$$

For dilaton field :

$$k_0\chi(\sigma^2+\zeta^2+\delta^2) - k_3(\sigma^2-\delta^2)\zeta + \chi^3\left[1+\ln\left(\frac{\chi^4}{\chi_0^4}\right)\right] + (4k_4-d)\chi^3 - \frac{4}{3}d\chi^3\ln\left\{\left[\frac{(\sigma^2-\delta^2)\zeta}{\sigma_0^2\zeta_0}\right]\left(\frac{\chi}{\chi_0}\right)^3\right\} + \frac{2\chi}{\chi_0^2}\left[m_\pi^2 f_\pi\sigma + \left(\sqrt{2}m_k^2 f_k - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right)\zeta\right] = 0$$

Variation of scalar fields with T and density

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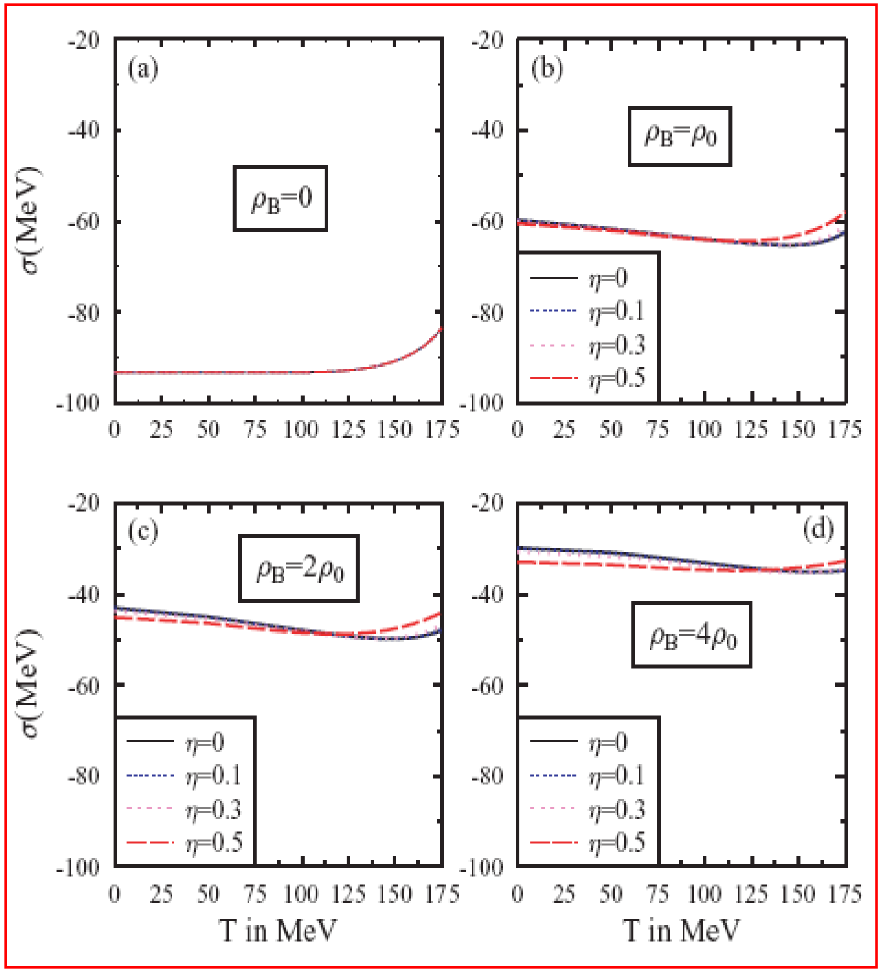
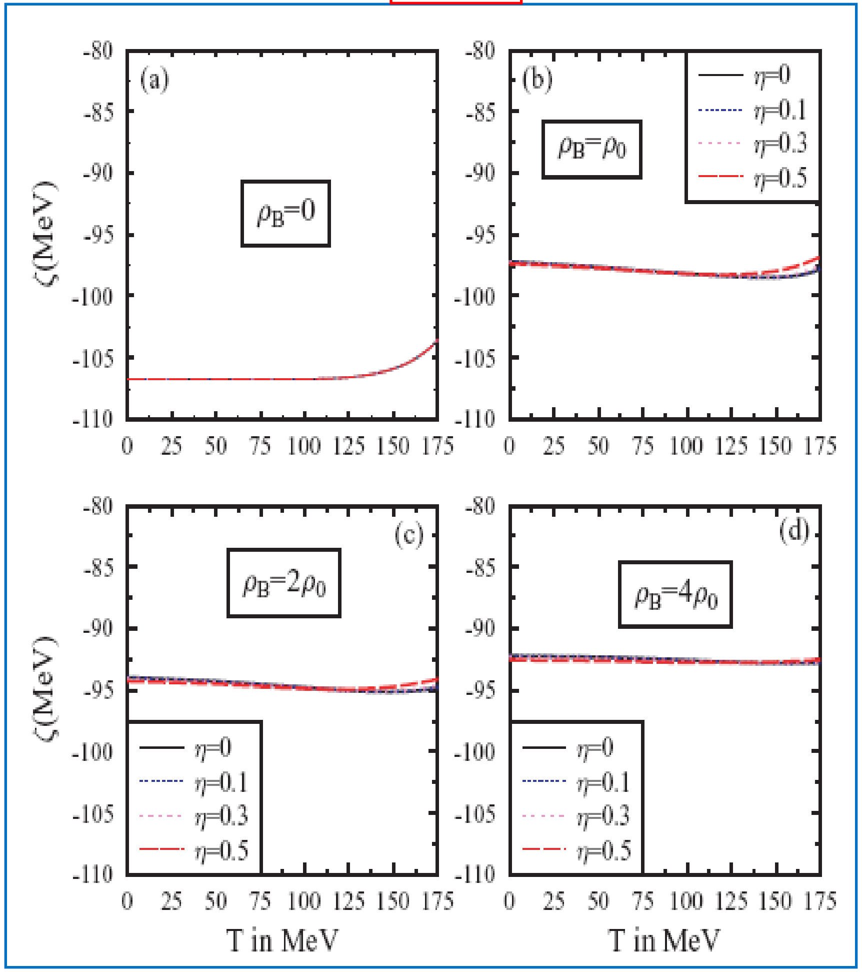
sigma



zeta



variation of scalar fields with T and density

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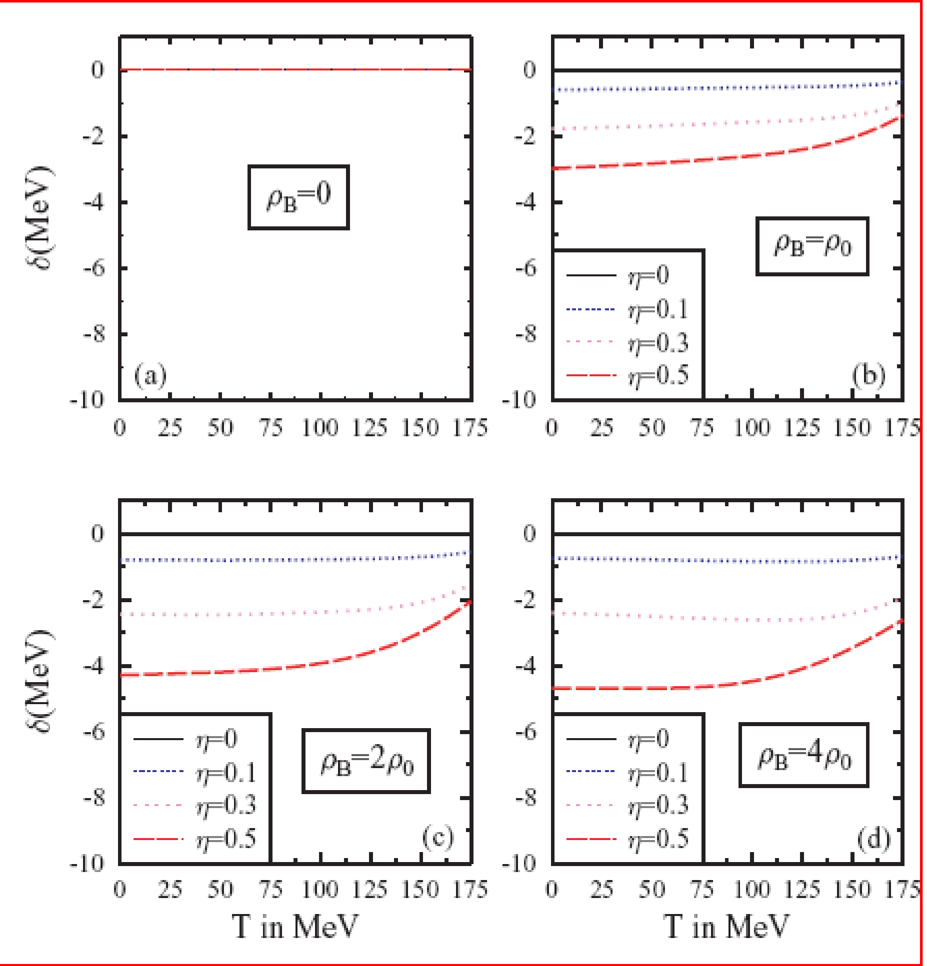
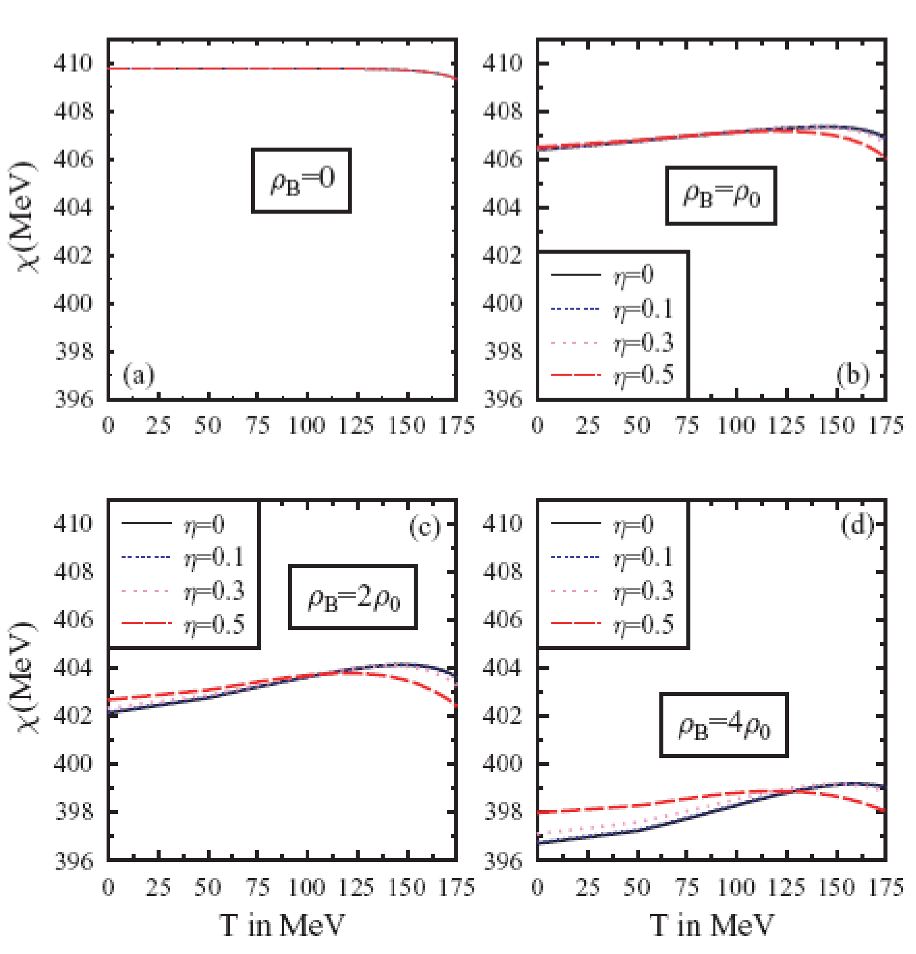
delta



dilaton



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D mesons in asymmetric hot nuclear matter

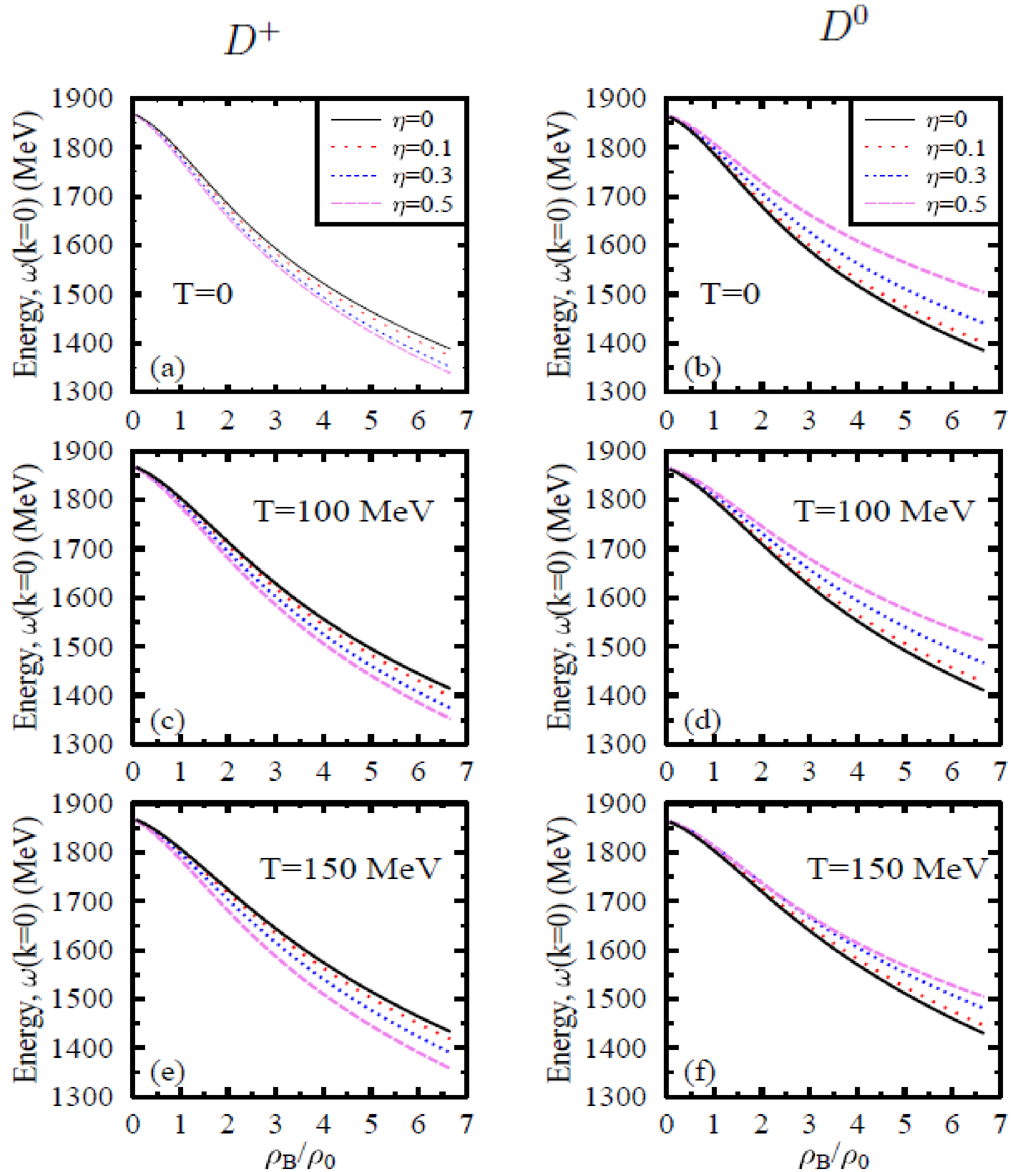
- Energy of D meson decreases with increase in density

- D^+ energy decreases with isospin asymmetry , D^0 mesons energy increases

- The mass of D mesons observed at finite T is observed to be more than the T = 0 case at a given baryon density.

  - T = 0, D^+ drop is 78 MeV
    At T = 100 MeV, drop is 65 MeV.

$$d_1 = \frac{2.56}{m_K}, d_2 = \frac{0.73}{m_K}$$



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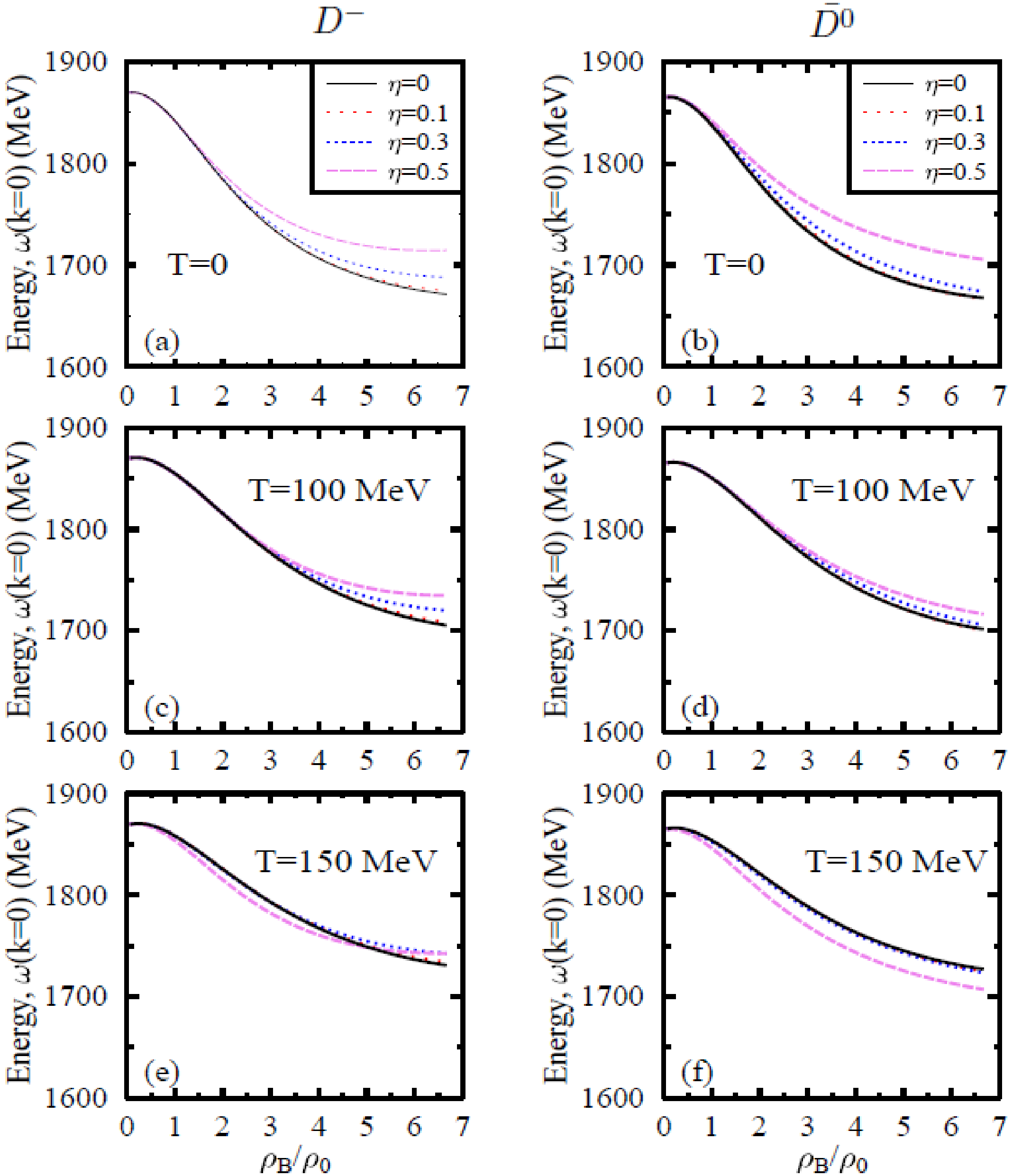
$\bar{D}$ mesons $(D^-, \bar{D}^0)$ mass modifications in asymmetric nuclear matter:

- Mass of $\bar{D}$ meson decreases with increase in the density because attractive scalar exchange and range terms dominate over repulsive Weinberg-Tomozawa term
- Drop in the mass of $\bar{D}$ mesons is smaller at high temperatures
- Upto $\rho_B = \rho_0$ masses have little isospin dependence but at higher densities masses are quite sensitive to isospin asymmetry of the medium
- In symmetric medium
  T = 0 D^- drop is 27.2 MeV
  T = 100 MeV drop is 21.4 MeV.



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D mesons in strange hadronic matter

❖In this strange hadronic matter we have nucleons, hyperons, scalar mesons.

❖In interaction Lagrangian density we have interactions of D meson with nucleons and scalar mesons.

❖But here nucleons are modified in the medium which has scalar mesons and hyperons.

❖So the nucleons modified in presence of scalar mesons and hyperons are interacting with D mesons.

D mseons in strange hadronic matter

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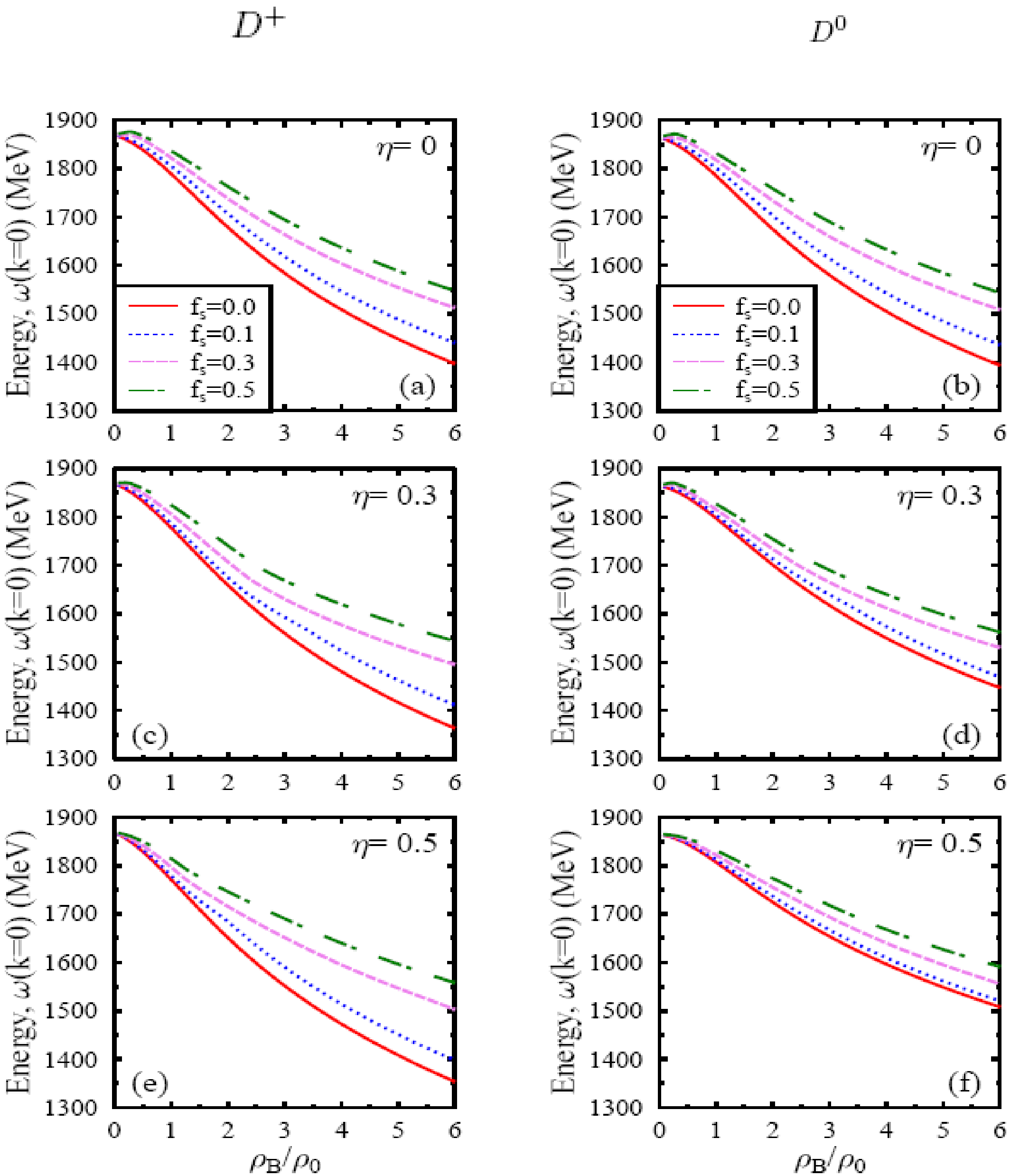
arxiv:1010.0403 (nucl-th)

❖Energy of D mesons increases as a function of strangeness fraction

❖In symmetric medium, at $\rho_B = \rho_0$ about 47 MeV increase

in energy of D meson
in moving from fs = 0 to 0.5

❖At $\eta = 0.5$, $\rho_B = \rho_0$
energy of D^+
increases by 43 MeV
and that of D^0 by 25
MeV



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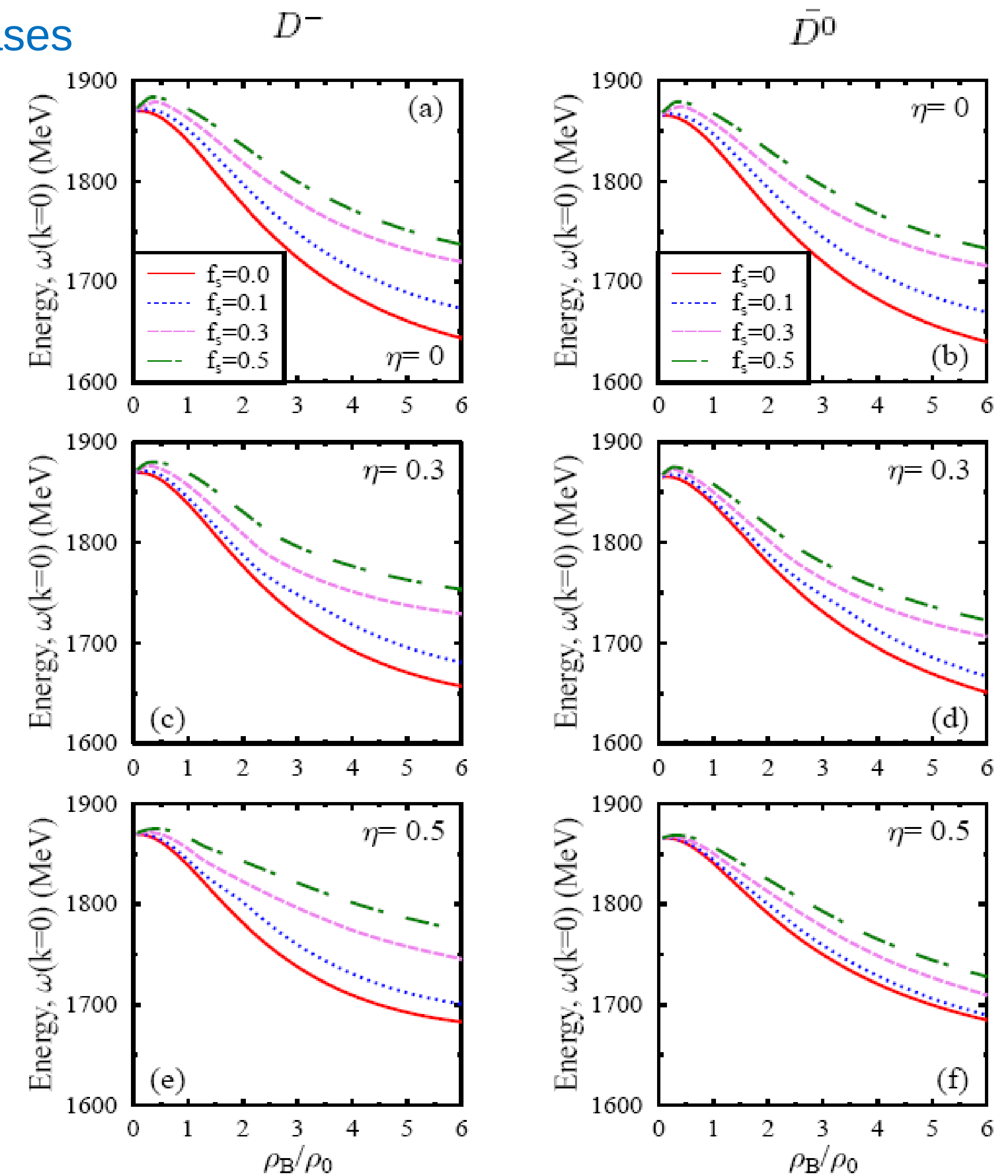
❖Energy of $\bar{D}$ mesons also increases as a function of strangeness fraction

❖In symmetric medium, at $\rho_B = \rho_0$ about 32 MeV increase

in energy of $\bar{D}$ meson in moving from fs = 0 to 0.5

❖At $\eta = 0.5$, $\rho_B = \rho_0$ energy of D^- increases by 28 MeV and that of $\bar{D}^0$ by 17 MeV



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Charmonia in hot asymmetric nuclear matter

- Mass modification of charmonium states in nuclear medium due to interaction with the gluon condensate of QCD

- Gluon condensate simulated by a scalar dilaton field introduced to incorporate the broken scale invariance of QCD within the effective chiral model

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

$$\theta_\mu^\mu = \chi\frac{\partial\mathcal{L}}{\partial\chi} - 4\mathcal{L} = -(1-d)\chi^4.$$

$$\theta_\mu^\mu = -\frac{9}{8}\frac{\alpha_s}{\pi}G_{\mu\nu}^a G^{\mu\nu a}$$

$$\left\langle \frac{\alpha_s}{\pi}G_{\mu\nu}^a G^{a\mu\nu}\right\rangle = \frac{8}{9}(1-d)\chi^4$$

Dilaton field and medium modifications of charmonia

In terms of color electric and magnetic field

$$\left\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{a\mu\nu} \right\rangle = \frac{8}{9}(1-d)\chi^4$$

$$\left\langle \frac{\alpha_s}{\pi}(E^2 - B^2) \right\rangle_{\rho_B} = -\frac{1}{2}\left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle_{\rho_B}$$

In QCD 2nd order stark effect, mass shift of charmonium states

in linear density approx. is

Phys. Rev. C **67**, 038202 (2003)

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

QCD 2nd order stark effect + chiral SU(3) model leads to mass shift :

$$\Delta m_\psi(\epsilon) = \frac{4}{81}(1-d)\int dk^2 \left|\frac{\partial\psi(k)}{\partial k}\right|^2 \frac{k}{k^2/m_c + \epsilon}\left((\chi^4)_{\rho_B} - (\chi^4)_{vac}\right)$$

$J/\psi(3097)$

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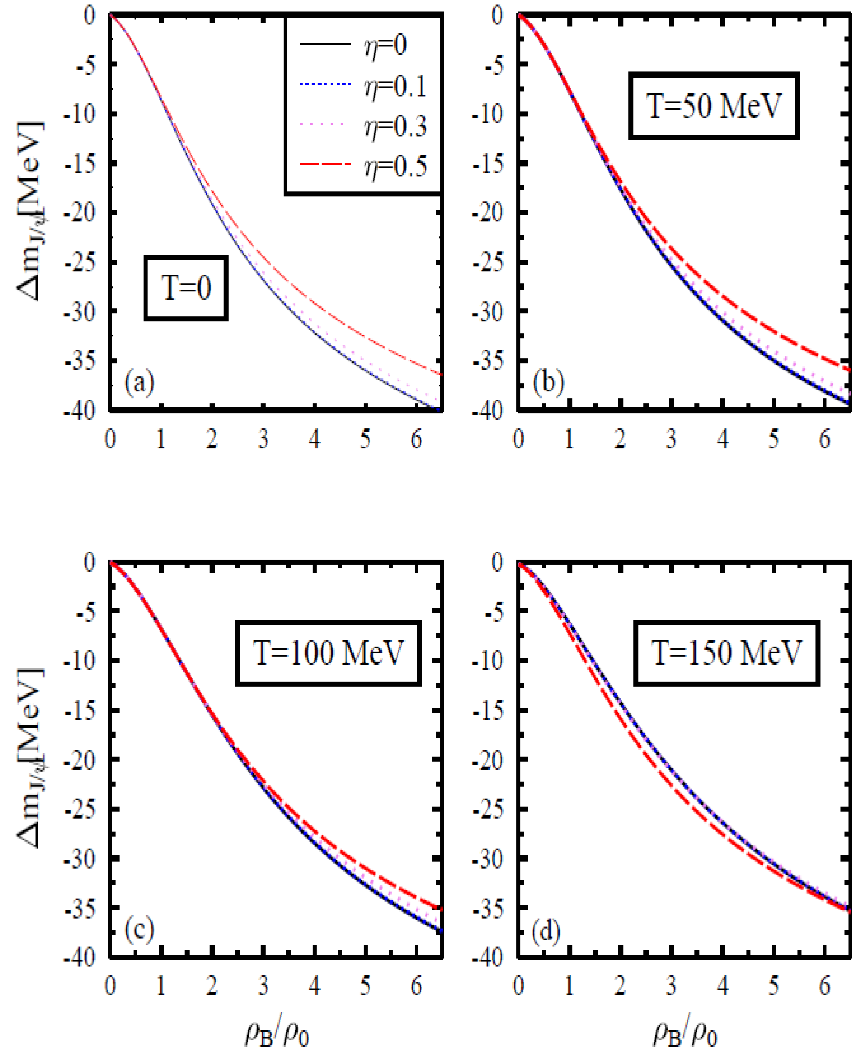
Undergoes small modifications in the medium

- Mass of J/ψ drops with increase in density.

For $\eta = 0$,T =0 and $\rho_B = \rho_0$ mass shift is -8.6 MeV and at $\rho_B = 4\rho_0$ mass shift is -32.2 MeV

- *Mass shift is smaller in asymmetric medium because of less drop in field but effect is small.*
  At T =0, $\rho_B = \rho_0$, $\eta = 0.5$ mass shift is is = -8.4 MeV

- Mass shift is smaller at finite T as compared to T = 0 , because of less drop in dilaton field at finite T. At T = 100 MeV, $\rho_B = \rho_0$, $\eta = 0$ mass shift is -6.77 MeV . At $\rho_B = 4\rho_0$ mass shift is -28.4 MeV .



$\psi(3686)$

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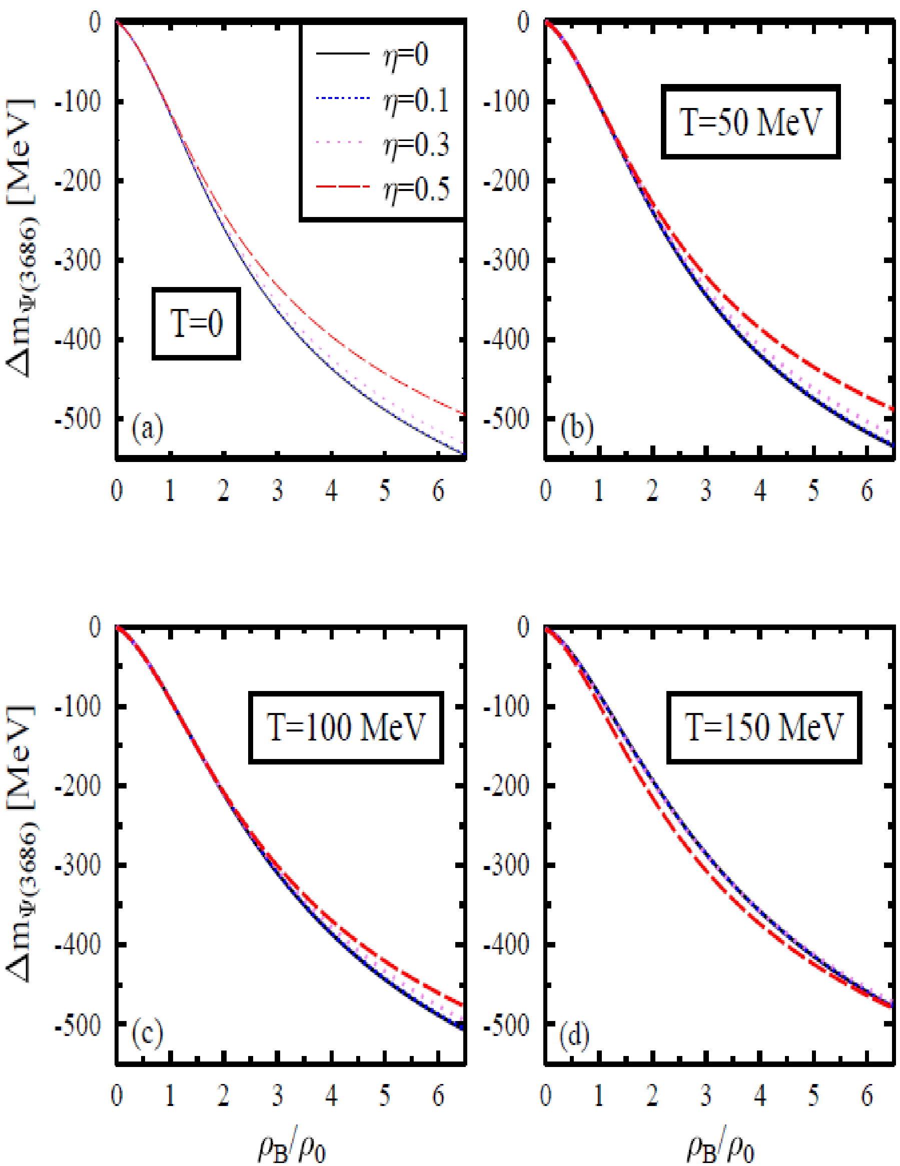
- Mass shift for $\psi(3686)$ is -117 MeV at $\rho_B = \rho_0$, T = 0 and $\eta = 0$
  At $\eta = 0.5$. it is -114 MeV.

- At T = 100 MeV, $\rho_B = 4\rho_0$ and $\eta = 0$ mass shift is -386 MeV .
  At $\eta = 0.5$. mass shift is -369 MeV.

- Mass shift is small in symmetric medium as compared to asymmetric case at high temperature . Dilaton field has large drop in asymmetric medium. This is due to drop in magnitude of field δ at high temperature.

- Mass shift is small at finite T as compared to T = 0 case.



$\psi(3770)$

- Mass shift for $\psi(3770)$ is -155 MeV at $\rho_B = \rho_0,$ T = 0 and $\eta = 0$

At $\eta = 0.5.$ it is -150 MeV.

- At $\rho_B = 4\rho_0$, T=0, $\eta = 0$

mass shift is -577 MeV.

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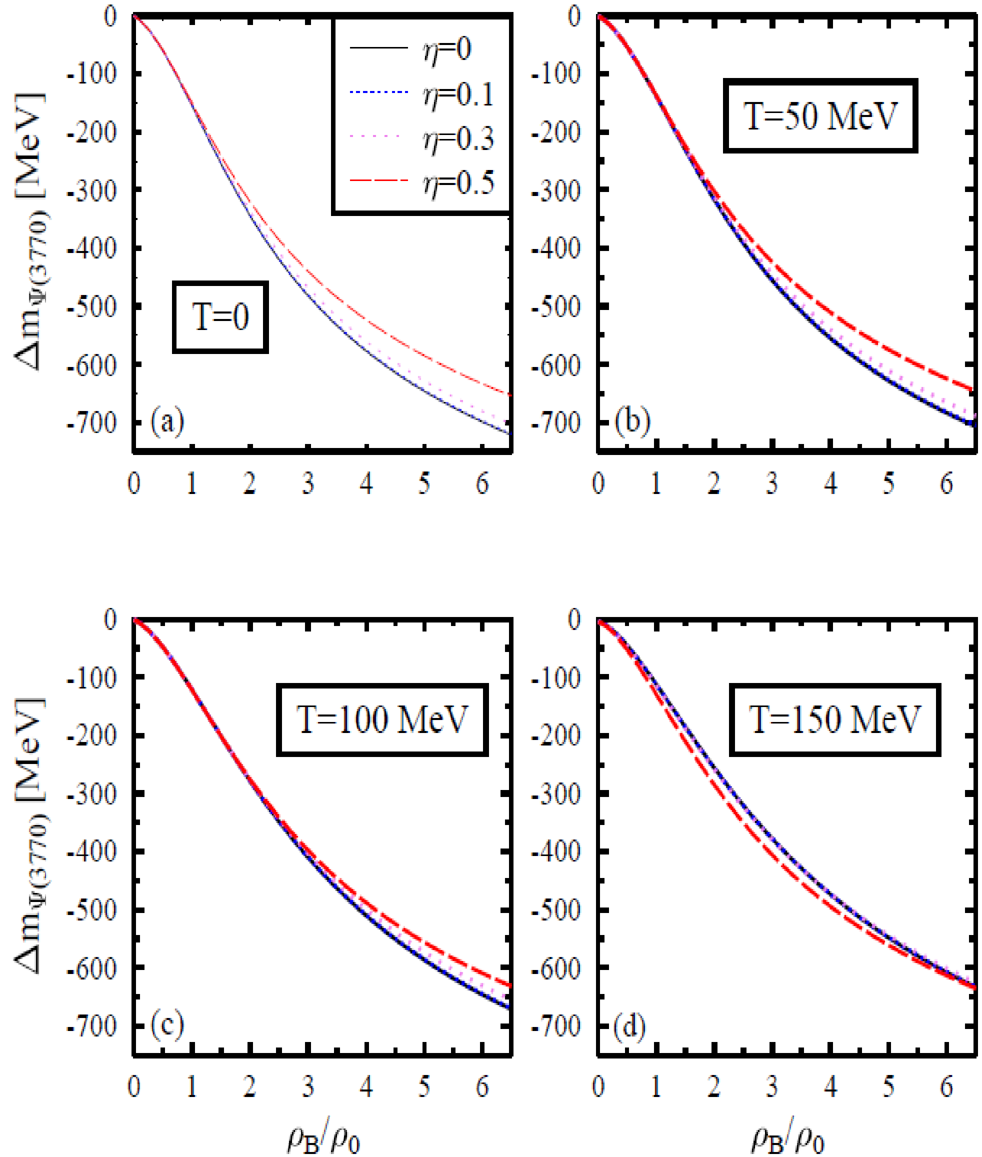


- The observed values of the mass shift are in agreement with results from QCD 2nd order stark effect calculations and QCD sum rules.

Charmonium masses in asymmetric medium at high baryon densities which will be of relevance for CBM experiment, FAIR at GSI

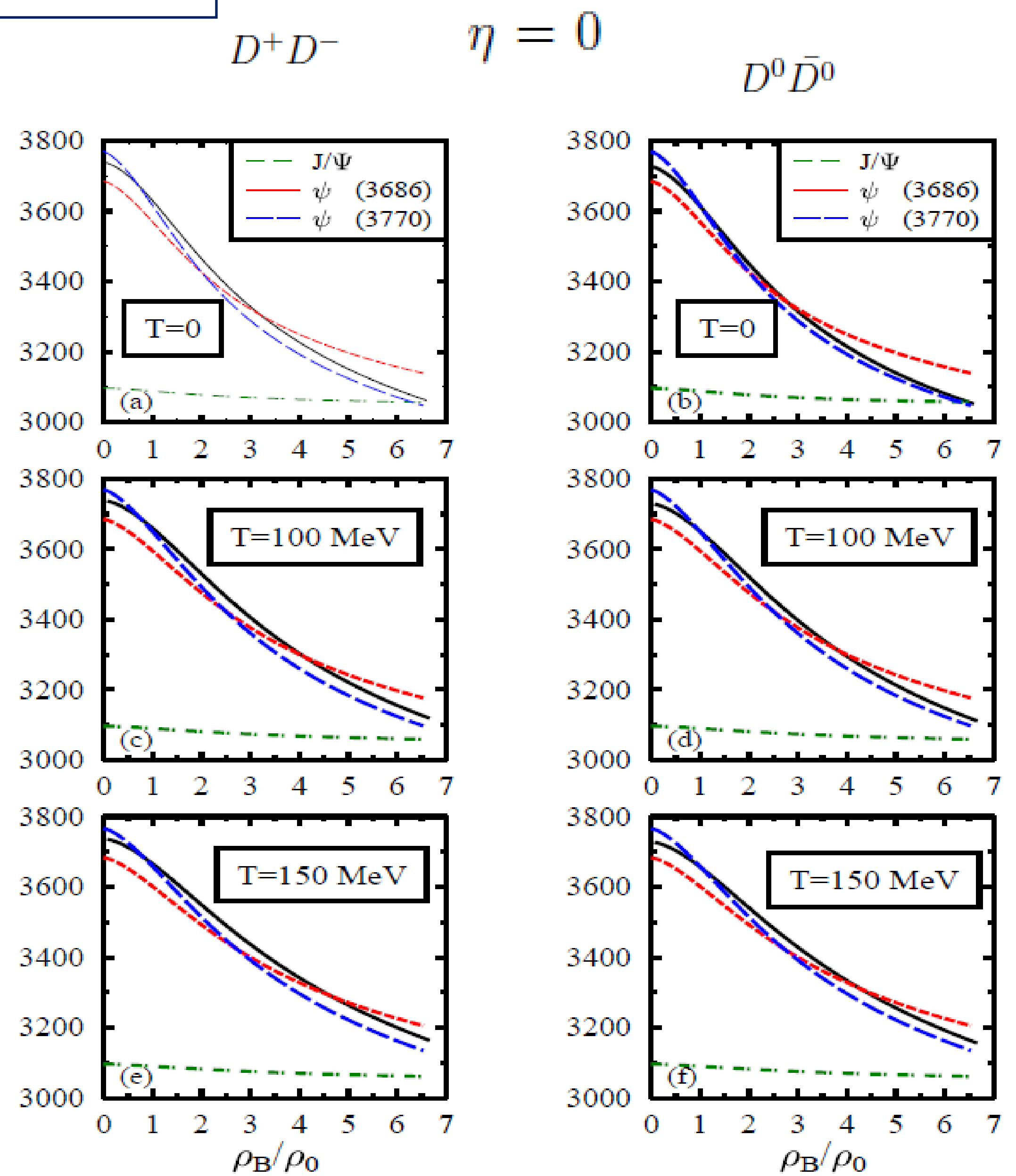
J/ψ suppression

- Excited charmonium states decay to J/ψ

- But due to drop in the masses of D mesons in the medium, it can become a possibility that charmonium decays to $D\bar{D}$ pairs instead of J/ψ

- Can lead to drop in J/ψ yield and hence suppression can take place.

- Can be an explanation of J/ψ suppression observed by NA50 collaboration at 158 GeV/nucleon in Pb-Pb collisions



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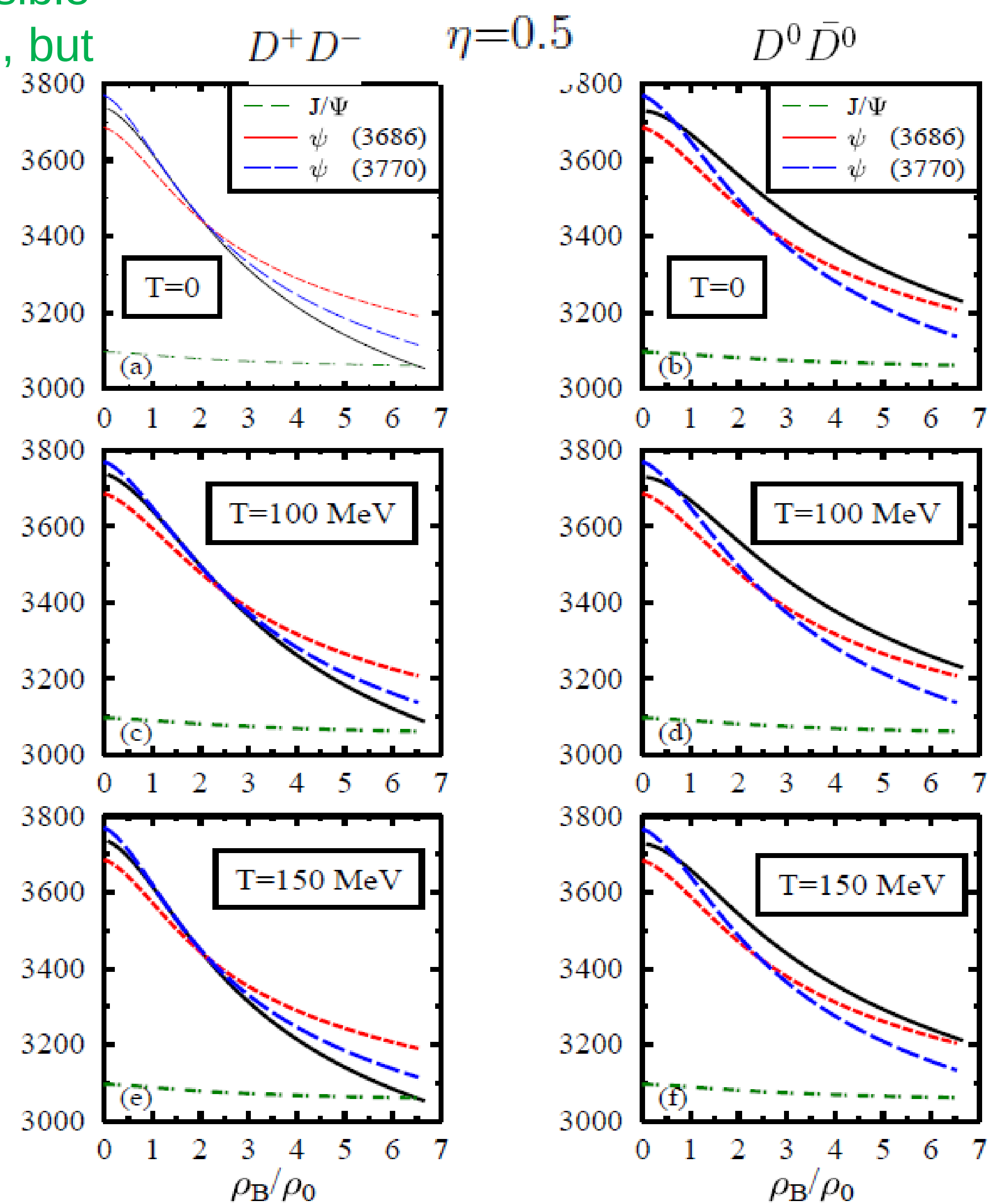
- ❑Decay of $\psi(3770)$ to D^+D^- possible above $2\rho_0$ in asymmetric medium, but Decay to $D^0\bar{D}^0$ is not possible

- ❑Decay of $\psi(3686)$ to D^+D^- and $D^0\bar{D}^0$ possible in symmetric medium but in isospin asymmetric medium decay is not possible to $D^0\bar{D}^0$ pairs.

- ❑ Effect of temperature on the decay Of charmonium is marginal.



Summary :

- Studied properties of D mesons in hot and dense asymmetric nuclear matter within a chiral SU(4) model .

- Masses of D mesons are strongly isospin dependent and the masses of D-mesons observed at finite temperatures are larger as compared to T =0 case at a given baryon density.

- Observed small attractive potentials for $\bar{D}$ mesons are in favor of $\bar{D}$ mesic nuclei .

- Ratio D^+/D^0 is seen to be strongly isospin dependent and should be observed in the asymmetric nuclear collisions.

- As a function of strangeness fraction of the medium the masses of D and $\bar{D}$ mesons increases

- Ratios D^+/D^0 and $D^-/\bar{D}^0$ could be promising observables to study the effect of strangeness fraction of the medium on the properties of D and $\bar{D}$ mesons.

- Studied charmonia mass modifications in hot and dense asymmetric nuclear matter using QCD 2nd order stark effect.

- Observed mass-shift for J/ψ is small whereas $\psi(3686)$ and $\psi(3770)$ have appreciable mass-shift at nuclear saturation density . At finite densities, mass-shifts for charmonia are smaller at finite T as compared to T = 0 case.

- Experimentally, measurement of dilepton spectra may provide clue about modifications of properties of these excited charmonium states in $\bar{p}$-A annihilation in future facility at GSI, provided they decay inside the nucleus.

S. H. Lee and C. M. Ko, Phys. Rev C 67, 038203 (2003)

B. Friman, S. H. Lee, and T. Song, Phys. Lett. B 548, 153 (2002).

Thank You

Wave functions for the charmonium states :

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

B. Friman, S. H. Lee, and T. Song, Phys. Lett. B 548, 153 (2002).

S. H. Lee and C. M. Ko, Phys. Rev C 67, 038203 (2003)

Mean square radii

Harmonic oscillator constant

Charmonium	$N\,^{2S+1}L_J$	$\langle r^2 \rangle$ in fm^2	β in GeV
$J/\psi(3097)$	$1\,^3S_1$	0.46^2	0.51
$\psi(3686)$	$2\,^3S_1$	0.96^2	0.38
$\psi(3770)$	$1\,^3D_1$	1	0.37