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D mesons in asymmetric nuclear matter

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A.Mishra,E.Bratkovskaya,J.Schaffner-Bielich,
S.Schramm,H.Stoecker, Phys.Rev.C69,015202(2004);
L.Tolos,J.Schaffner-Bielich,A.Mishra,
Phys.Rev.C70,025203(2004);
A. Mishra, A.Mazumdar, Phys. Rev. C 79, 024908 (2009)

Outline

- Motivation

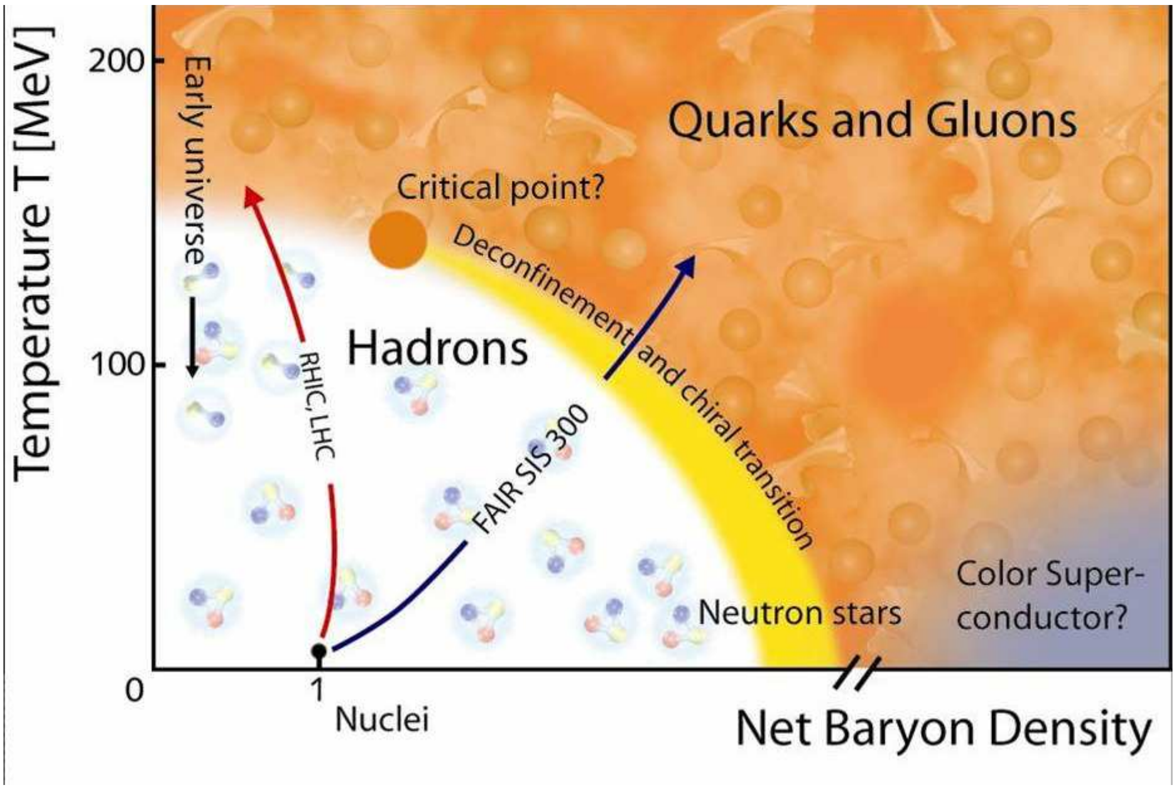
- In-medium Nucleons
(Chiral SU(3) model)

- D($\bar{D}$)-mesons ($c\bar{q}$($\bar{c}q$) bound states) in the medium
(generalize to SU(4) to include interaction of charmed mesons)

- Effects of isotopic asymmetry on D and $\bar{D}$ optical potentials
Important for isospin asymmetric heavy ion collisions!

- Summary and Outlook

QCD phase diagram (Schematic)



- **Hadron properties modified in Hot and Dense matter**

– modify observables in Relativistic Heavy Ion Collision experiments

(particle production, particle spectra, collective flow, $\cdots$)

Medium modification of nucleons

— modify the properties of D-mesons

–can modify dilepton spectra(M $>$ 1 GeV)

Prod. of D^+D^- pair

and $D^+ \rightarrow \bar{K}^0 e^+ \nu_e$, $D^- \rightarrow K^0 e^- \nu_e$

- Mass modification of $D\bar{D}$ pair can open up channels:

(J/Ψ, Ψ', χ_c) $\rightarrow D\bar{D}$

– can lead to J/Ψ suppression

— open charm enhancement!

- $J/\Psi N \rightarrow D\bar{D}N, D^*\bar{D}^*N, ...$ can lead to J/Ψ suppression!

Ref. W. Liu, C. M. Ko, Z. W. Lin, Phys. Rev. C 65, 015203 (2001)

- A mass drop in $D\bar{D}$ pair can lead to

–mass drop as well as shorter lifetimes ($\simeq$ few fm/c) of excited states of Charmonia (ψ(3686), ψ(3700))

(hence these excited charmonium states can decay inside the nucleus in $\bar{p}A$ annihilation experiments in the future accelerator expt. at GSI!)

– can modify the peaks for the excited charmonia (ψ(3686), ψ(3700)) in the dilepton spectra!

Ref. B. Friman, S. H. Lee, T. Song, Phys. Lett, B 548, 153 (2002); S. H. Lee and C. M. Ko, Phys. Rev. C 67, 038202 (2003).

Isospin asymmetric nuclear matter:

Relevant for isospin asymmetric heavy ion collisions:
(Experiments with neutron rich beams)

Effects can show up in observables like:

π^-/π^+, **n/p**, Δ^-/Δ^{++} **ratios**
Production and flow pattern of K^+, K^0,
as well as K^-,$\bar{K}^0$

Isospin dependent energies for D **and** $\bar{D}$ **can be relevant in observables in asymmetric nuclear collisions**
Can show up in observables like D^+/D^0, $D^-/\bar{D}^0$, **collective flow of D-mesons...**

Look for signatures of D($\bar{D}$) potentials in CBM experiment at FAIR at GSI

- D-mesons are $\bar{c}q$ ($\bar{q}c$) bound states.

$$m_c \sim 1.3\text{GeV},\ m_q \sim 5-10\ \text{MeV}$$

- QCD sum rule calculations

Due to presence of light quark ($q \equiv u, d$),

D-mass shift can be appreciable ($\Delta m_D \sim \langle \bar{q}q \rangle$)

$\sim 50-100$ MeV at $\rho = \rho_0$

A.Hayashigaki, Phys. Lett.B487,96(2000); P. Morath, W.Weise, S.H. Lee in QCD:Perturbative or Nonperturbative?, World scientific, 425; H. Hilger, R. Thomas, B. Kaempfer, arxiv 0809.4996(nucl-th)

On the other hand, the mass shift of J/Ψ ($c\bar{c}$ bound state) in the leading order arises due to the medium modification of the $\langle G^{\mu\nu a} G^a_{\mu\nu} \rangle$ (seen to be small)

S. H. Lee and C. M. Ko, Phys. Rev. C 67, 038202 (2003)

- Quarkonium dissociation

Study of quarkonium dissociation using heavy quark potential from lattice QCD predicts similar drop for D meson mass at finite temperature.

S.Digal, P.Petreczky, H.Satz, Phys. Lett B514,57(2001)

However, the interpretation for the heavy quark effective potential in lattice QCD calculations is still an unresolved issue!

• Quark Meson coupling

D-meson mass modification in the Quark-meson coupling model (σ-ω model at the level of quarks confined inside the nucleon and D meson bags!)

$\Delta m_D \simeq 140 MeV$.

Attractive DN interaction can lead to D-mesic nuclei (D meson bound inside nucleus!)
— may be observed experimentally!

Ref. K. Tsushima, D. H. Lu, A. W. Thomas, K. Saito, R. H. Landau, Phys. Rev. C 59, 2824 (1999); A. Sibirtsev, K. Tsushima, A. W. Thomas, Eur. Phys. J. A 6, 351 (1999).

Coupled channel approach

Medium modification of nucleons due to coupling of DN to other channels
– leads to D-meson medium modifications

T matrix: $T_{ij} = V_{ij} + V_{il} G_l T_{lj}$

Channel i corresponds to Meson,baryon with masses m_i,M_i respectively.

V is a matrix whose elements are often chosen as Tomozawa-Weinberg type meson baryon interactions from the leading order chiral Lagrangian.

Next order contributions to meson-baryon interacions (scalar-isoscalar interaction and range terms), improve the data (elastic and inelastic K^- N scattering data)
– but they bring in new unknown parameters!

B.Borasoy, R. Nissler, W.Weise, PRL 94, 213401 (2005); J. A. Oller, J. Pardes and M. Verbeni, PRL 95, 172502 (2005); M.Lutz, PLB 426,12 (1998)

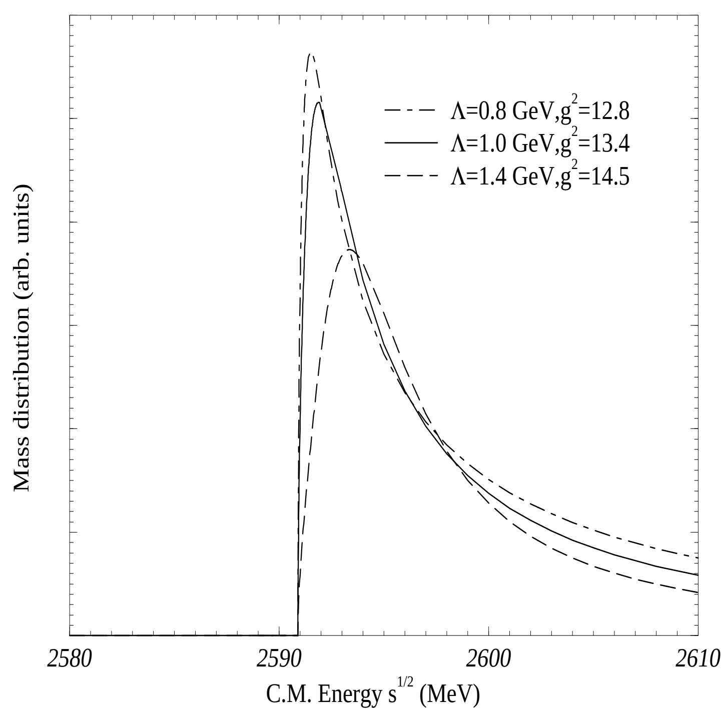
- DN system: $DN \rightarrow DN, \pi\Sigma_c, \eta\Sigma_c$ (I=0 channel)

(generates Λ_c (2593) resonance dynamically)
Similar to generation of Λ(1405) due to coupling of $\bar{K}N$ to $\pi\Sigma$ in the I=0 channel.

V is parametrised in terms of a coupling g and momentum cut off Λ, which are fitted to the mass and decay width of $\Lambda_c(2593)$.

$$V_{ij}(k,k') = g^2 C_{ij} v_i(k) v_j(k') \equiv \frac{g^2}{\Lambda^2} C_{ij} \theta(\Lambda - k)\theta(\Lambda - k')$$

For C_{ij}, the values used are as from SU(3) symmetry.



L. Tolos, J. Schaffner-Bielich, A.Mishra, Phys. Rev. C 70, 025203 (2005)

• Medium modification of D-meson mainly in strong increase in the decay width, with negligible modification in the mass!

L.Tolos, J. Schaffner-Bielich, H. Stoecker, Phys. Lett. B 635, 85 (2006)

However, ONLY I=0 channel contributions to the D-meson spectral function are considered!

• Dynamic generation of Λ_c(2593) (I=0 channel) as well as a resonance Σ (2770) (I=1 channel)

With T=V, the mass drop of D-mesons are similar to calculations from QCD sum rule, QMC model or chiral effective theory calculations!

T.Mizutani and A. Ramos, Phys. Rev. C 74, 065201 (2006); L.Tolos, A. Ramos, T. Mizutani, Phys. Rev. C 77, 015207 (2008); J.Hofmann, M.F.M. Lutz, Nucl. Phys. A 763, 90 (2005); M.F.M. Lutz and C. L. Korpa, Phys. Lett. B 633, 43 (2006)

Chiral SU(3) 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

$$m_\pi^2 = -\left(\frac{m_u + m_d}{2}\right) \frac{\langle \bar{q}q \rangle}{f_\pi^2}$$

  Pions get mass from explicit breaking of chiral symmetry by small current quark masses.

- **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

Generalize to include strange quarks!

$\chi \quad \rightarrow$ dilaton field
$\rightarrow$ related to $< GG > \quad \rightarrow \langle G^a_{\mu\nu} G^{a\mu\nu} \rangle$.

Frozen χ approximation: $\chi = \chi_0$.

effective mass of baryon,i,: $m_i^* \simeq g_{\sigma i}\sigma + g_{\zeta i}\zeta$,
$\sigma \simeq \bar{u}u + \bar{d}d \quad , \quad \zeta \simeq \bar{s}s$

Two scalar fields coupling to the baryon field!

Generalization to SU(4)

$$\langle X\rangle = \begin{pmatrix} \sigma/\sqrt{2}+\delta & 0 & 0 & 0 \\ 0 & \sigma/\sqrt{2}-\delta & 0 & 0 \\ 0 & 0 & \zeta & 0 \\ 0 & 0 & 0 & \zeta_c \end{pmatrix},$$

$$P = \begin{pmatrix} \pi^0/\sqrt{2} & \pi^+ & \frac{2K^+}{1+w} & \frac{2\bar{D}^0}{1+w_c} \\ \pi^- & -\pi^0/\sqrt{2} & \frac{2K^0}{1+w} & \frac{2D^-}{1+w_c} \\ \frac{2K^-}{1+w} & \frac{2\bar{K}^0}{1+w} & 0 & 0 \\ \frac{2D^0}{1+w_c} & \frac{2D^+}{1+w_c} & 0 & 0 \end{pmatrix},$$

where $w=\sqrt{2}\zeta/\sigma$ **and** $w_c=\sqrt{2}\zeta_c/\sigma$**.**

PCAC: $\partial_\mu A^a_\mu = f_p m_p^2 p^a, \quad p=\pi, K, D$

$f_\pi = -\sigma$,
$f_K = -(\sigma+\sqrt{2}\zeta)/2$,
$f_D = -(\sigma+\sqrt{2}\zeta_c)/2$.

• The medium modifications of the light hadron sector, compatible with KN scattering data, are described by the effective chiral SU(3) model.

• Generalization of SU(3) to SU(4) gives the interaction of D - mesons to the light hadron sector, needed to study their mass modifications in the medium.

Interaction terms modifying energies of D($\bar{D}$):

$$\mathcal{L}_D = \mathcal{L}_{WT} + \mathcal{L}_{scalar} + \mathcal{L}_{range}$$

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

$$\begin{aligned}
\mathcal{L}_{scalar} &= \frac{m_D^2}{2f_D}\Big[(\sigma + \sqrt{2}\zeta_c)\big(\bar{D}^0 D^0 + (D^- D^+)\big) \\
&+ \delta\big(\bar{D}^0 D^0) - (D^- D^+)\big)\Big]
\end{aligned}$$

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

$$\mathcal{L}^{BM}_{(d_1)} = \frac{d_1}{2} Tr(u_\mu u^\mu)(\bar{B}B), \ ; \ \mathcal{L}^{BM}_{(d_2)} = d_2 Tr(\bar{B} u_\mu u^\mu B)$$

Low energy K-N scattering:

$$K(q)N(p) \rightarrow K(q')N(p')$$

$$T\langle f|(S-1)|i\rangle = i(2\pi)^4\delta^{(4)}(p'+q'-p-q)\bar{u}(p',s')\mathcal{T}u(p,s)$$

$$\text{Scattering length}: \quad a = \frac{\mathcal{T}}{4\pi\big(1+(m_K/m_N)\big)}$$

The K-N scattering lengths for I=0 and I=1

$$\begin{aligned} a_{KN}(I=0) &= \frac{m_K}{4\pi {f_K}^2\big(1+m_K/m_N\big)} \\ &\Bigg[- \frac{m_K f_K}{2}\bigg(\frac{g_{\sigma N}}{{m_\sigma}^2} + \sqrt{2}\frac{g_{\zeta N}}{{m_\zeta}^2} - 3\frac{g_{\delta N}}{{m_\delta}^2}\bigg) \\ &+ \frac{(d_1-d_2)m_K}{2}\Bigg], \end{aligned}$$

$$\begin{aligned} a_{KN}(I=1) &= \frac{m_K}{4\pi {f_K}^2\big(1+m_K/m_N\big)} \\ &\Bigg[-1 - \frac{m_K f_K}{2}\bigg(\frac{g_{\sigma N}}{{m_\sigma}^2} + \sqrt{2}\frac{g_{\zeta N}}{{m_\zeta}^2} + \frac{g_{\delta N}}{{m_\delta}^2}\bigg) \\ &+ \frac{(d_1+d_2)m_K}{2}\Bigg] \end{aligned}$$

$$a_{KN}(I=0) \approx -0.31 \text{ fm}, \quad \mathrm{a_{KN}(I=1)} \approx -0.09 \text{ fm}.$$

determine d_1 and d_2.

Isospin averaged KN scattering length:

$$\bar{a}_{KN} = \frac{1}{4}a_{KN}(I=0) + \frac{3}{4}a_{KN}(I=1) \approx -0.255 \text{ fm}$$

Pion nucleon scattering lengths:

$$a_{\pi N}\Big(I=\frac{3}{2}\Big) = \frac{m_\pi}{4\pi {f_\pi}^2\big(1+m_\pi/m_N\big)} \left[-\frac{1}{2}-\frac{g_{\sigma N}}{{m_\sigma}^2}m_\pi f_\pi+\frac{(d_1+d_2)m_\pi}{2}\right]$$

$$a_{\pi N}\Big(I=\frac{1}{2}\Big) = \frac{m_\pi}{4\pi {f_\pi}^2\big(1+m_\pi/m_N\big)} \left[1-\frac{g_{\sigma N}}{{m_\sigma}^2}m_\pi f_\pi+\frac{(d_1+d_2)m_\pi}{2}\right]$$

Iso-vector and isoscalar scattering lengths:

$$a_- = \Big(a_{\pi N}(I=1/2)-a_{\pi N}(I=3/2)\Big)/3,$$
$$a_+ = \Big(a_{\pi N}(I=1/2)+2a_{\pi N}(I=3/2)\Big)/3$$

$a_-=0.078/m_\pi, a_+=-0.0266/m_\pi$
(present calculation)

$a_-=0.0936/m_\pi, a_+=-0.0029/m_\pi$
extracted from pionic atoms
(S.R.Beane et al, Nucl.Phys.A720,399(2003))

Dispersion relations for $D(\bar{D})$:

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

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

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

$\pm$ **refer to D^0 and D^+.**

$\sigma'(= \sigma - \sigma_0)$, $\zeta_c{}'(= \zeta_c - \zeta_{c0})$ **and** $\delta'(= \delta - \delta_0)$ **are the fluctuations from vacuum expectation values.**

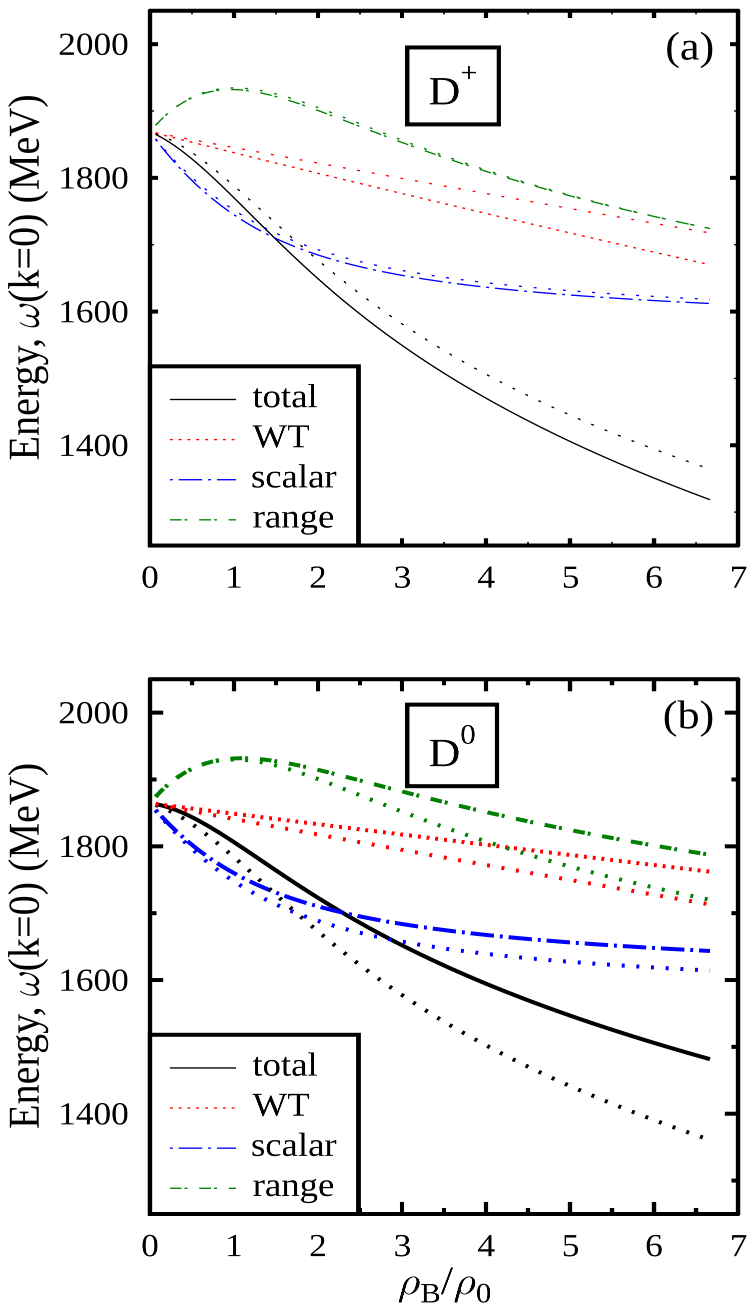
Self energy for $\bar{D}$ meson doublet, ($\bar{D}^0$,D^-):

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

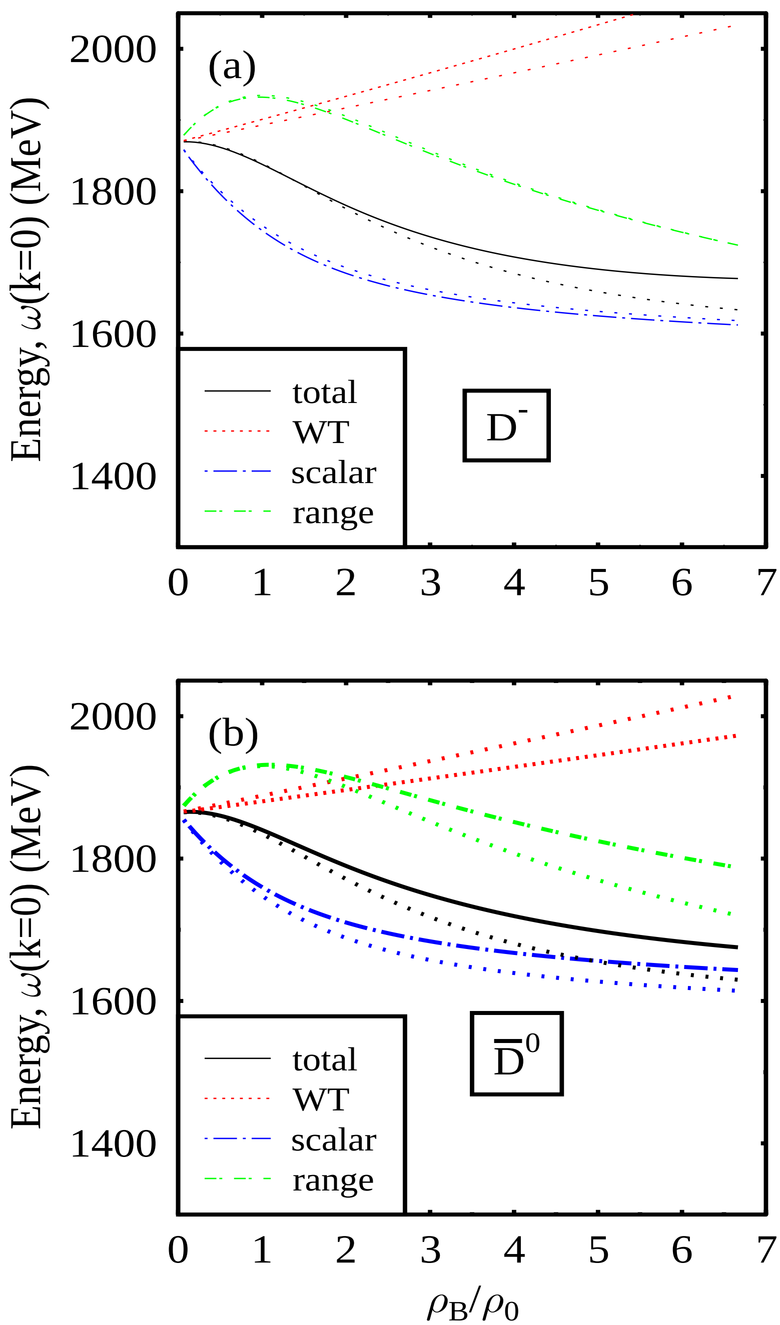
$\pm$ signs refer to $\bar{D}^0$ and D^-.

Optical potentials of D and $\bar{D}$ mesons:

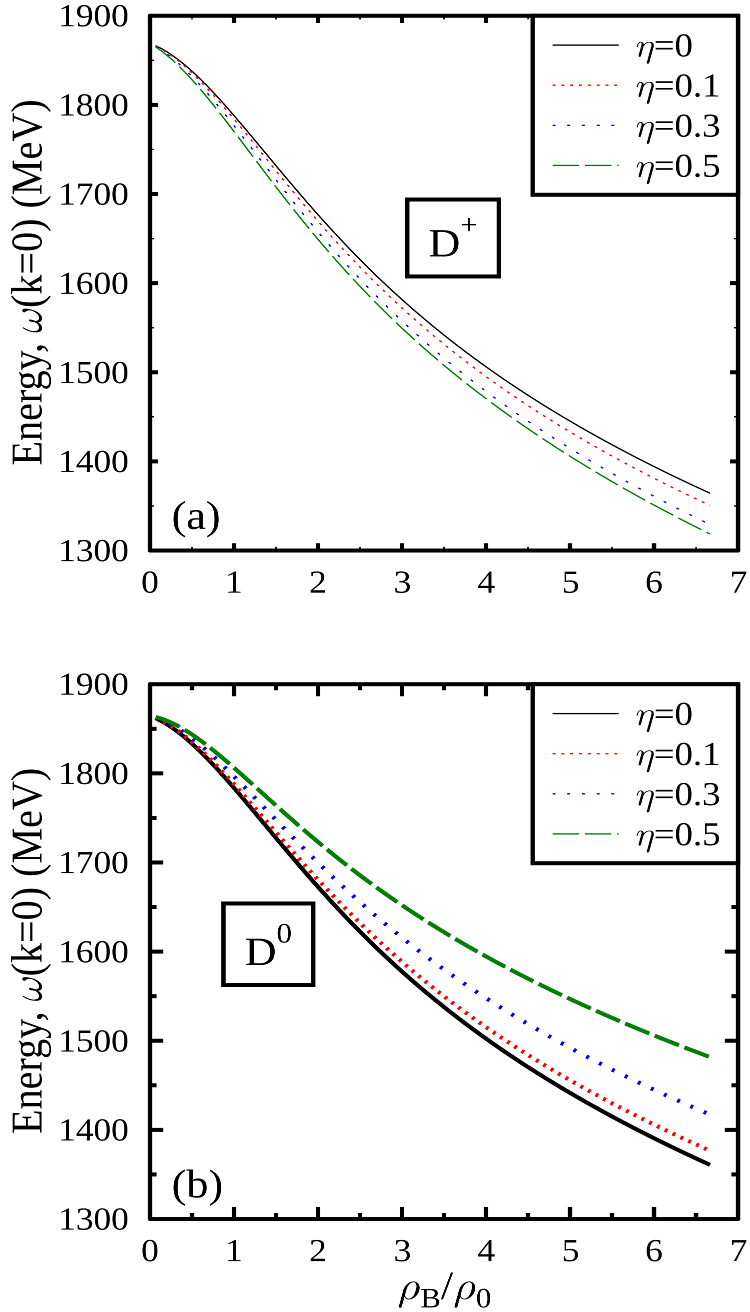
$$U(\omega,k)=\omega(k)-\sqrt{k^2+m_D^2},$$



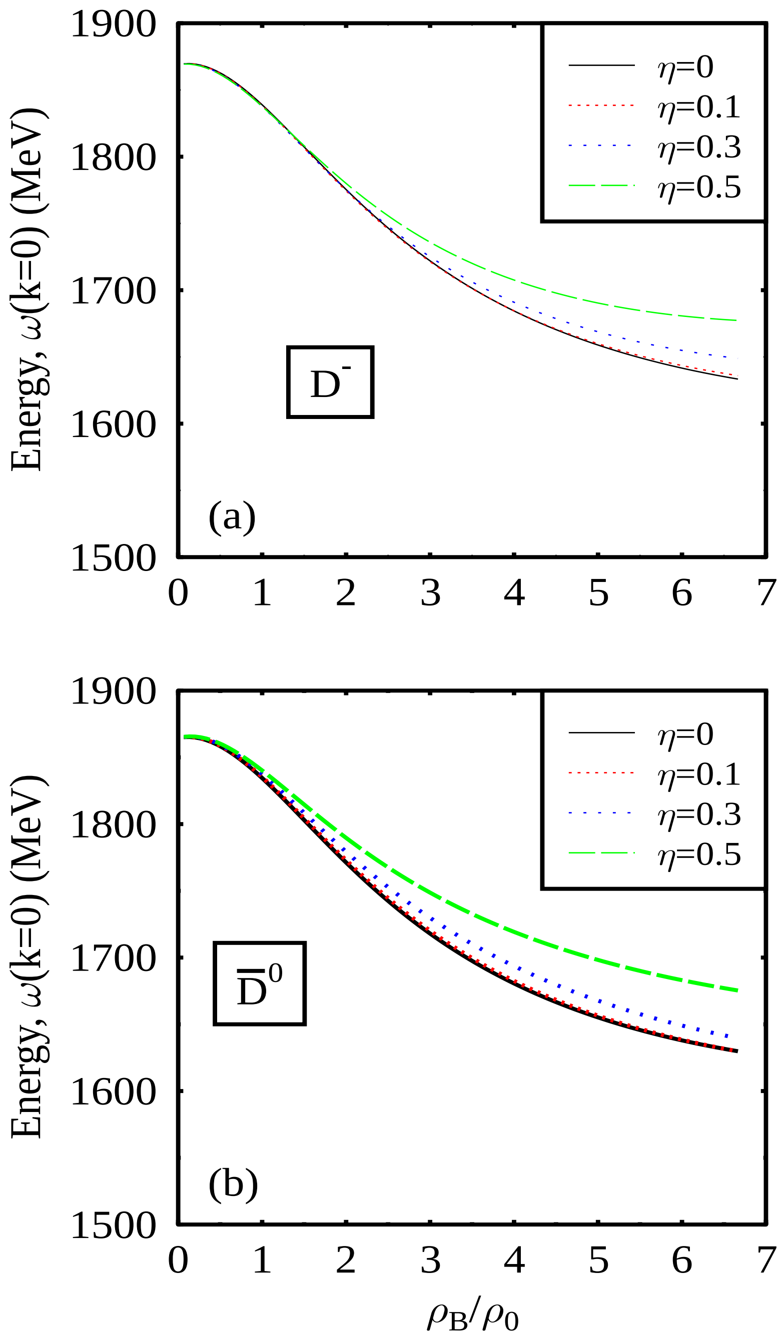
(a)
D+
total
WT
scalar
range
Energy, ω(k=0) (MeV)
(b)
D0
ρB/ρ0



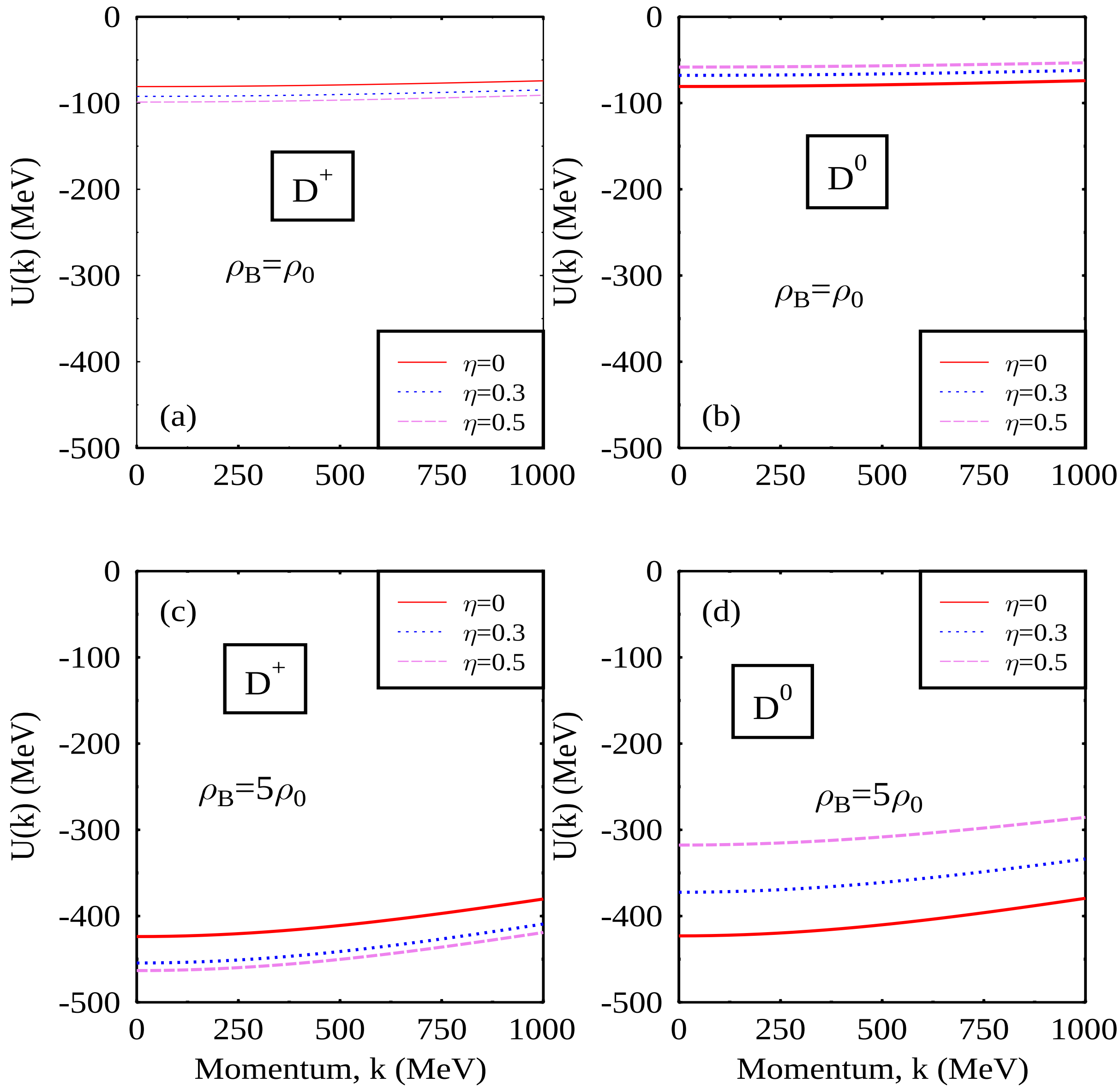
(a)
Energy, ω(k=0) (MeV)
total
WT
scalar
range
D-
(b)
Energy, ω(k=0) (MeV)
total
WT
scalar
range
D̄0
ρB/ρ0



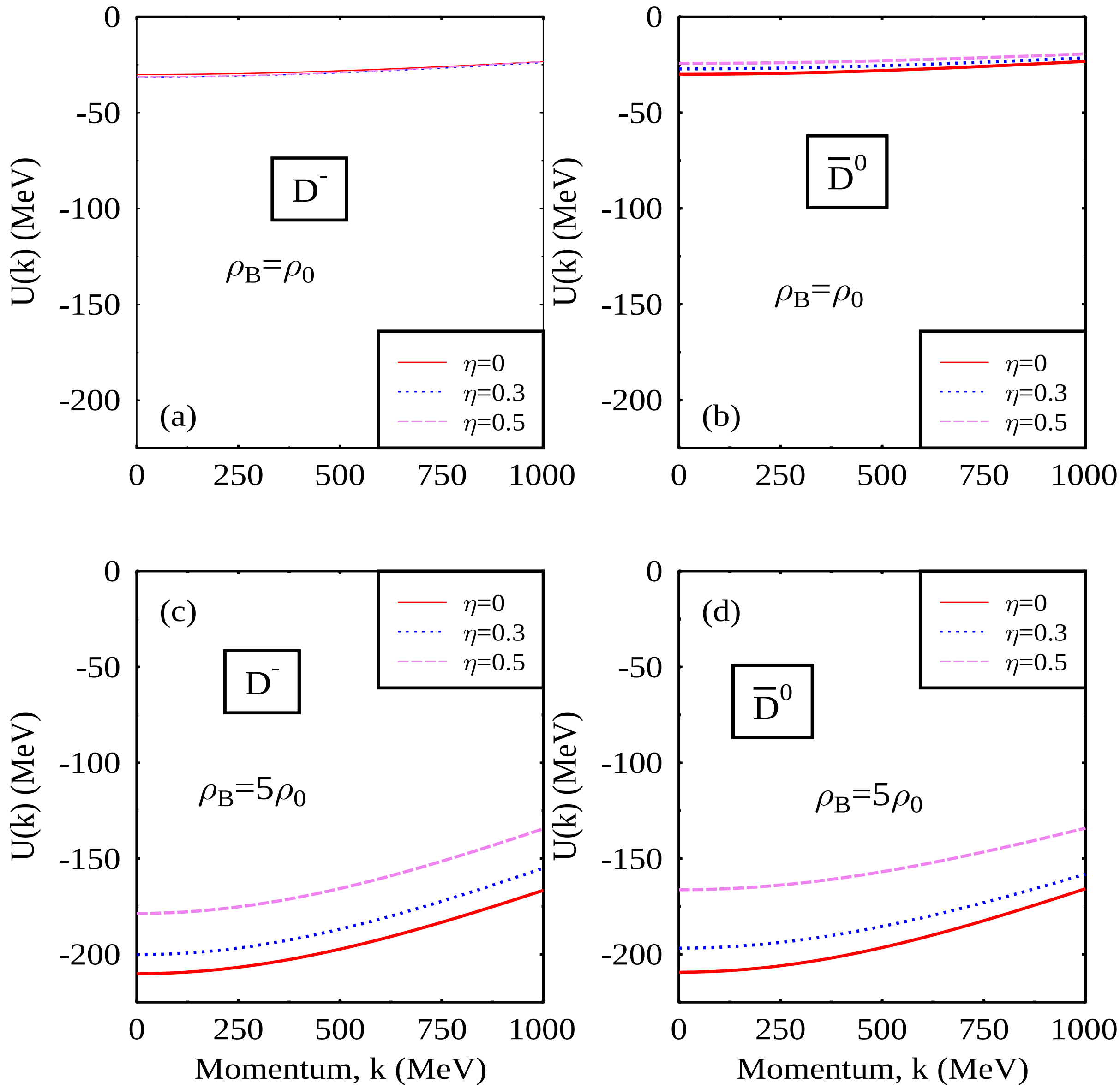
Energy, ω(k=0) (MeV)
η=0
η=0.1
η=0.3
η=0.5
D^+
(a)
D^0
(b)
ρ_B/ρ_0



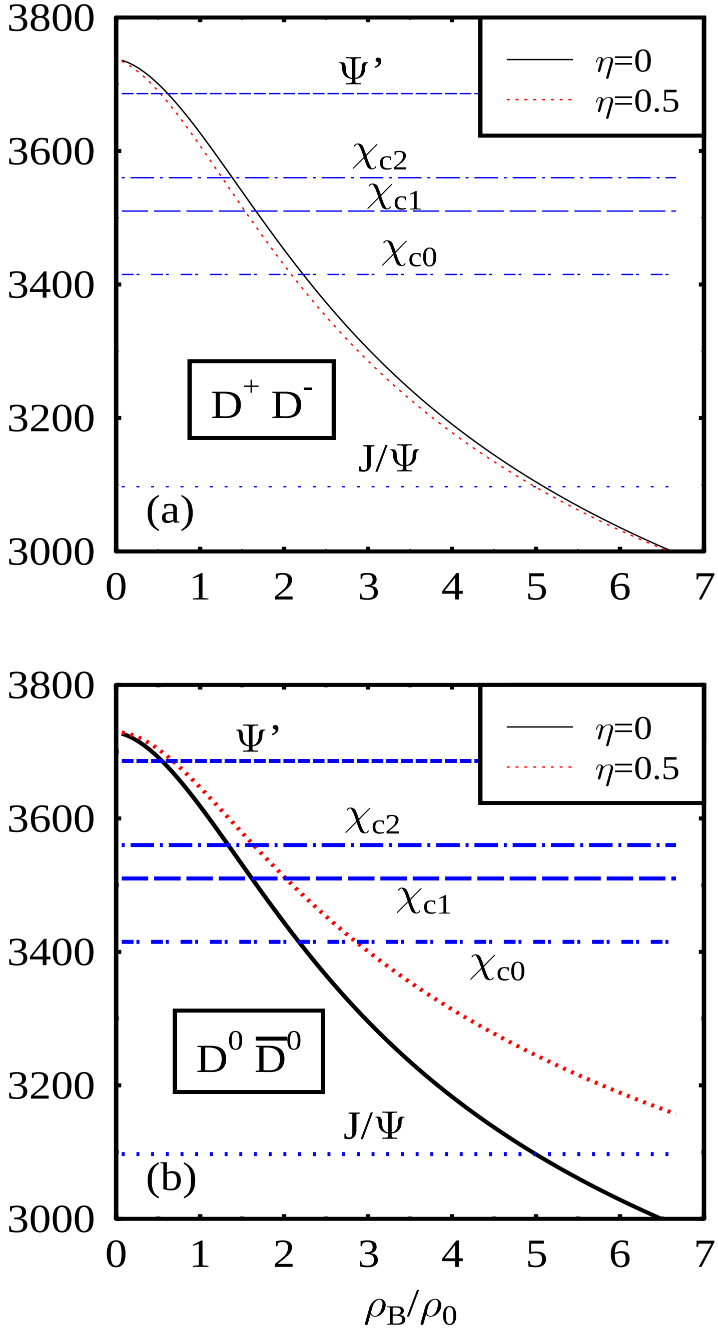
1900
1800
1700
1600
1500
Energy, ω(k=0) (MeV)
η=0
η=0.1
η=0.3
η=0.5
D$^-$
(a)
0 1 2 3 4 5 6 7
$\bar{D}^0$
(b)
ρ_B/ρ_0



U(k) (MeV)
Momentum, k (MeV)
D+
D0
ρB=ρ0
ρB=5ρ0
η=0
η=0.3
η=0.5
(a)
(b)
(c)
(d)



U(k) (MeV)
D-
ρB=ρ0
(a)
(b)
η=0
η=0.3
η=0.5
D̄0
(c)
(d)
ρB=5ρ0
Momentum, k (MeV)
0
-50
-100
-150
-200
250
500
750
1000


3800
3600
3400
3200
3000
0
1
2
3
4
5
6
7
Ψ'
χ_{c2}
χ_{c1}
χ_{c0}
J/Ψ
η=0
η=0.5
D+ D-
(a)
(b)
D0 $\overline{D}$0
ρ_B/ρ_0

Summary and Outlook

• Chiral SU(4) model is used to calculate the D meson properties in the dense hadronic matter with leading and next to leading contributions (Weinberg-Tomozawa + scalar-isoscalar+range terms)

• In-medium $D(\bar{D})$ optical potentials calculated in asymmetric nuclear matter consistent with KN and π N scattering lengths

– Strong isospin asymmetry effects observed on $D(\bar{D})$ potentials at high densities!

–Effects on $D(\bar{D})$ production and propagation

• Mass modification of $D\bar{D}$ pair can open up channels:

(J/Ψ, Ψ', χ_c) $\rightarrow D\bar{D}$

– can lead to J/Ψ suppression
— open charm enhancement!

Mass modification of D^+D^- seen to be insensitive to isospin asymmetry, but $D^0\bar{D}^0$ mass has strong isospin dependence!

Threshold densities for the decay of charmonia to $D\bar{D}$ seen to shift to higher values in presence of isospin asymmetry!

• Optical potentials for D^+ and D^0 are seen to be very different in the asymmetric nuclear matter at high densities! This should show up in observables like D^+/D^0 in asymmetric nuclear collisions.

Explore at GSI future facility

– Compressed baryonic matter (CBM) experiment of the proposed project FAIR (Facility for Antiproton and Ion Research) at GSI, Germany
(Experiments with neutron rich beams are planned to be used!)

• Mass shift of J/Ψ can be calculated from the modification of the dilation field, χ in the dense matter
(χ within the chiral effective model simulates the scale symmetry breaking,
$\langle GG \rangle \simeq \chi^4$)

• Effects of the mass shift of $D(\bar{D})$ mesons on the mass of the charmonia (J/Ψ, χ_c, ψ') in the asymmetric nuclear matter

• Coupling to other channels $DN \rightarrow \pi\Sigma_c, \eta\Sigma_c, \eta\Lambda_c$ can modify the $D(\bar{D})$ optical potentials