Charmed hadrons in nuclear medium

Laura Tolos

Charm in nuclei

To study the properties of open and hidden charm embedded in a nuclear many-body system

Pions, kaons and light vectors have been a matter of intensive research for SIS energies at GSI. Including the charm degree of freedom FAIR project moves from the light quark sector to the heavy quark one
moves from the light to the heavy sector

in particular, it is an extension of the GSI program for in-medium modification of hadrons in the light quark sector, and provides first insight into charm-nucleus interaction
Some topics related to open charm ($D, D^*, D_s$):

- in-medium DN interaction at finite temperature
- DN and $D^* N$ interactions with heavy-quark symmetry
- hidden and charm scalar resonances in nuclear matter
- $D_s$ properties in nuclear matter
- ...
In-medium DN interaction at finite temperature

LT, Ramos, Mizutani, PRC 77 (2008) 015207

Experimental scenarios for open charm..

• $J/\Psi$ suppression
  
  *NA50 Collaboration, Gonin et al., NPA 610 (1996) 404c*
  
  initially predicted by color screening in QGP
  
  *Matsui and Satz, PLB 178 (1986) 416*
  
  but also due to comover scattering
  
  several authors: Capella, Vogt, Wang, Bratkovskaya, Cassing, Linnyk, Andronic..
  
  $J/\Psi + \pi, \rho \rightarrow \bar{D} + D$

• D-mesic nuclei
  
  predicted by QMC model for $D^-, \bar{D}^0 & D^0$ in $^{208}\text{Pb}$
  
  *Tsushima et al. PRC 59 (1999) 2824*
From the theoretical side..

- Predictions for the **mass shift** in mean-field models:
  \[ U_{D^+}(\rho_0) \sim -60 \text{ to } -200 \text{ MeV} \]  
  \[ U_{D^-}(\rho_0) \sim 20 \text{ to } -140 \text{ MeV} \]
  - **QMC model** Tsushima et al., PRC 59 (1999) 2824, Sibirtsev et al., EPJA 6 (1999) 351
  - **QCD sum-rule model** Hayashigaki, PLB 487 (2000) 96; Weise, Hirschegg’01, 249
  - **Chiral model** Mishra et al., PRC 69 (2004) 015202; Mishra et al, PRC 79 (2009) 024908

- **Spectral function** in self-consistent coupled-channel approach:
  - D meson self-energy with a SU(3) potential for u-, d- and c- quarks as bare interaction
    LT, Schaffner-Bielich and Mishra, PRC 70 (2004) 025203;
    LT, Schaffner-Bielich and Stoecker, PLB 635 (2006) 85 (finite T!)
  - D and D meson self-energy with a bare interaction saturated by a t-channel vector meson exchange between SU(4) multiplets
    Lutz and Korpa, PLB 633 (2006) 43
  - D meson self-energy using modified t--\(\rightarrow0\) limit (WT) + scalar-isoscalar attractive term (\(\Sigma_{DN}\))
    Mizutani and Ramos, PRC 74 (2006) 065201

**HERE:** we extend the model to \(\bar{D}\) mesons and implement finite T effects
DN interaction in hot nuclear matter: selfconsistent coupled-channel procedure

Free space

\[ T_{ij} = V_{ij} + V_{il} G_l T_{lj} \]

potential using broken SU(4) symmetry

Medium

\[ T_{ij}(\rho,T) = V_i + V_{il} G_l(\rho,T) T_{lj}(\rho,T) \]

Pauli blocking and baryon dressing

Dressed D meson:
\[ V_{ij} = -\kappa C_{ij} \frac{1}{4f_D^2} (2\sqrt{s} - M_i - M_j) \left( \frac{M_i + E}{2M_i} \right)^{1/2} \left( \frac{M_j + E'}{2M_j} \right)^{1/2} \]

SU(4) symmetry broken by the use of physical masses.

\[ \kappa = 1 \quad (\text{non-charm exchange}) \quad DN \to DN, \ DsY \]
\[ = \left( \frac{m_p}{m_{D^*}} \right)^2 \sim 1/4 \quad (\text{charm exchange}) \quad DN \to \pi\Sigma_c, \ K\Xi_c \]

and supplemented by a scalar-isoscalar interaction (\( \Sigma_{DN} \) term)

\[ \mathcal{L}_\Sigma \equiv \frac{\Sigma_{DN}}{f_D^2} \bar{NNDD} \quad \rightarrow \quad V_\Sigma(\sqrt{s}) = -\frac{\Sigma_{DN}}{f_D^2} \left( \frac{M_N + E}{2M_N} \right) \sim -0.05 \text{ MeV}^{-1} \]

\[ f_D \sim 200 \text{ MeV} \quad \Sigma_{DN} \sim 2000 \text{ MeV} \quad (\text{from QCDSR}) \]
Loop function $G$ depends on $\rho$ and $T$

$$G(P_0, \vec{P}, T) = \int \frac{d^3q}{(2\pi)^3} \frac{M_N}{E_N(\vec{P} - \vec{q}, T)} \times \left[ \int_0^\infty d\omega S(\omega, \vec{q}, T) \frac{1 - n(\vec{P} - \vec{q}, T)}{P_0 - \omega - E_N(\vec{P} - \vec{q}, T) + i\epsilon} + \int_0^\infty d\omega S(\omega, \vec{q}, T) \frac{n(\vec{P} - \vec{q}, T)}{P_0 + \omega - E_N(\vec{P} - \vec{q}, T) - i\epsilon} \right]$$

Spectral density

$$S(q_0, \vec{q}, T) = -\frac{1}{\pi} \text{Im} D(q_0, \vec{q}, T) = -\frac{1}{\pi} \text{Im} \frac{\Pi(q_0, \vec{q}, T)}{|q_0^2 - \vec{q}^2 - m^2 - \Pi(q_0, \vec{q}, T)|^2}$$

Self-energy

$$\Pi(q_0, \vec{q}, T) = \int \frac{d^3p}{(2\pi)^3} n(\vec{p}, T) \times \left[ T^{(I=0)}(P_0, \vec{P}, T) + 3T^{(I=1)}(P_0, \vec{P}, T) \right]$$
The model generates the \( I=0 \) \( \Lambda_c(2595) \) and another resonance in \( I=1 \) around the nominal \( \Sigma_c(2800) \).

R. Mizuk et al. [Belle Collaboration]
PRL 94 (2005) 122002:
\( \Sigma_c(2800), \Gamma \sim 60 \text{ MeV} \)
D meson develops an important width

\[
U_D = \frac{\Pi_D(E_{qp}(q^\prime), q^\prime)}{2 \sqrt{m_D^2 + q^2}}
\]

Similar trend to previous finite temperature results

LT, Schaffner-Bielich, Stoecker, PLB 635 (2006) 85
$D$ meson

$$d_{DN}^{IJ} = -\frac{1}{4\pi} \frac{M_N}{\sqrt{s}} T_{DN\rightarrow DN}^{IJ}$$

<table>
<thead>
<tr>
<th>$I = 0$</th>
<th>WT+$\Sigma$</th>
<th>WT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Born approx.)</td>
<td>0.607</td>
<td>0</td>
</tr>
<tr>
<td>$I = 1$</td>
<td>-0.264</td>
<td>-0.289</td>
</tr>
<tr>
<td>(Born approx.)</td>
<td>-0.614</td>
<td>-0.876</td>
</tr>
</tbody>
</table>

Table 1: $\bar{D}N$ scattering lengths (fm)

close to

$Lutz and Korpa, PLB 633 (2006) 43$

$Haidenbauer et al., EPJA 33 (2007) 107$

$D$ and $\bar{D}$ mesons show an important width in hot nuclear matter

$J/\Psi$ suppression in a hot and dense environment?
DN and D*N interactions with HQS

Garcia-Recio, Magas, Mizutani, Nieves, Ramos, Salcedo, LT, PRD 79 (2009) 054004;
LT, Garcia-Recio, Nieves, 0905.4859 [nucl-th]

• Heavy-quark symmetry (HQS)
Spin interactions vanish for infinitely massive quarks. Thus, heavy hadrons come in doublets (if the spin of the light quark is not zero), which are degenerated in the infinite quark-mass limit. Example: D and D* mesons

• Regularization of the in-medium loop function
Regularize the intermediate propagators in the nuclear medium beyond the cutoff method, by adding to the regularized loop in free space the medium corrections in the infinite cutoff limit
SU(8) extension of the SU(3) WT to incorporate HQS

The SU(3) WT lagrangian is

\[ \mathcal{L}_{\text{WT}} = \text{Tr}([M^\dagger, M][B^\dagger B]) = \left((M^\dagger \otimes M)_{8a} \otimes (B^\dagger \otimes B)_{8}\right)_1 \]

To ensure that SU(8) amplitudes will reduce to those of SU(3)

\[ \mathcal{L}^{\text{SU}(8)}_{\text{WT}} = \left((M^\dagger \otimes M)_{63a} \otimes (B^\dagger \otimes B)_{63}\right)_1 \]

But SU(8) symmetry is strongly broken:
1. adopt physical hadron masses for kernel and thresholds
2. consider different weak non-charmed and charmed, as well as pseudoscalar and vector meson decay constants

Then, the SU(8) WT matrix elements in IJSC sector are

\[ V_{ab}^{IJSC}(\sqrt{s}) = D_{ab}^{IJSC} \frac{2\sqrt{s - M_a - M_b}}{4f_a f_b} \sqrt{\frac{E_a + M_a}{2M_a}} \sqrt{\frac{E_b + M_b}{2M_b}} \]

with \( f \) the weak decay constant \& \( M(E) \) the baryon mass (energy)
Dynamically-generated baryonic resonances in nuclear matter

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$I(J^P)$</th>
<th>Status</th>
<th>Mass (MeV)</th>
<th>$\Gamma$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c(2595)$</td>
<td>0(1/2$^-$)</td>
<td>$\ast$</td>
<td>2595.4 ± 0.6</td>
<td>3.6 + 2.0 − 1.3</td>
</tr>
<tr>
<td>$\Lambda_c(2625)$</td>
<td>0(3/2$^-$)</td>
<td>$\ast$</td>
<td>2628.1 ± 0.6</td>
<td>&lt;1.9</td>
</tr>
<tr>
<td>$\Lambda_c(2765)$</td>
<td><em>(?)</em></td>
<td></td>
<td>2766.6 ± 2.4</td>
<td>50</td>
</tr>
<tr>
<td>or $\Sigma_c(2765)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c(2880)$</td>
<td>0(5/2$^+$)</td>
<td>$\ast$</td>
<td>2881.9 ± 0.5</td>
<td>5.8 ± 1.9</td>
</tr>
<tr>
<td>$\Lambda_c(2940)$</td>
<td><em>(?)</em></td>
<td></td>
<td>2939.8 ± 1.6</td>
<td>18 ± 8</td>
</tr>
<tr>
<td>$\Sigma_c(2800)^{++}$</td>
<td>1(?)</td>
<td>$\ast$</td>
<td>2801 + 4 − 6</td>
<td>75 + 22 − 17</td>
</tr>
<tr>
<td>$\Sigma_c(2800)^+$</td>
<td><em>(?)</em></td>
<td>$\ast$</td>
<td>2792 + 14 − 5</td>
<td>62 + 60 − 40</td>
</tr>
<tr>
<td>$\Sigma_c(2800)^0$</td>
<td><em>(?)</em></td>
<td>$\ast$</td>
<td>2802 + 4 − 7</td>
<td>61 + 28 − 18</td>
</tr>
</tbody>
</table>
Simultaneous self-consistent calculation of the D and D* meson self-energies and, hence, spectral functions

T=0

\[ \Sigma_c(2823)N^{-1} \]

\[ \Sigma_c(2868)N^{-1} \]

\[ \Lambda_c(2902)N^{-1} \]

\[ \Lambda_c(2941)N^{-1} \]

\[ \Lambda_c(2595)N^{-1} \]

\[ \Lambda_c(2595)N^{-1} \]
Compared to SU(4) calculation, we obtain for D meson similar mass shift but much smaller width, while first results for D* meson scattering lengths for DN and D*N different to Lutz and Korpa, PLB 633 (2006) 43 Haidenbauer et al., EPJA 33 (2007) 107 for D meson because of different resonant-hole contributions close to threshold, and first results for D* meson

\[ \begin{array}{c|cc}
 J = 1/2 I = 0 & 0.001 + i 0.002 & -0.44 + i 0.19 \\
 J = 1/2 I = 1 & 0.33 + i 0.05 & -0.36 + i 0.18 \\
 J = 3/2 I = 0 & -1.93 + i 0.19 & -0.57 + i 0.15 \\
 J = 3/2 I = 1 & & \\
\end{array} \]

Compared to SU(4) calculation, we obtain for D meson similar mass shift but much smaller width, while first results for D* meson

D\(^0\)-nucleus bound states? Garcia-Recio, Nieves and LT (in preparation)
Scalar resonances in nuclear matter


The modification of the properties of elementary particles in nuclei give us information about the excitation mechanisms in the nucleus as well as the nature of those particles

ex. $\Lambda(1520)$ resonance:
width at nuclear matter density is five times bigger than the free one

$\Lambda^*(1520) + p \rightarrow \Sigma^*(1385) + n$

Kaskulov and Oset, PRC 73 (2006) 045213
$D_{s0}(2317)^1$ and $X(3700)^2$

Charm and hidden charm scalar resonances are generated dynamically

Close to a pole:

$T_{ij} \approx \frac{g_i g_j}{z - z_R}$

$D_{s0}(2317)$

| Channel | $|g_i|$ (GeV) |
|---------|-------------|
| $\pi\pi$ | 0.21        |
| $K\bar{K}$ | 0.03       |
| $\eta\eta$ | 0.00       |
| $D\bar{D}$ | 10.41      |
| $D_s\bar{D}_s$ | 6.73     |
| $\eta\eta_c$ | 0.29       |

$X(3700)$

$T_{ij} = V_{ij} + V_{il} G_l T_{ij}$

broken SU(4) symmetry

Resonances in nuclear matter

\[ T_{ij}(\rho) = V_{ij} + V_{il} G_l(\rho) T_{lj}(\rho) \]

\[ D_{s0}(2317) : \]
\[ D^0 K^+ \rightarrow D^0 K^+ \]

\[ X(3700) : \]
\[ D^0 \bar{D}^0 \rightarrow D^0 D^0 \]

Experimental analysis of the resonances in nuclear medium (transparency ratio) : test of the D meson interaction in nuclei and the nature of those charm scalar resonances
Conclusions

We perform a self-consistent coupled-channel calculation of the D and D̄ self-energies in symmetric nuclear matter and study the effect on charm and hidden charm scalar resonances

✓ SU(8) scheme that incorporates heavy-quark symmetry generates a wider spectrum of resonances than SU(4) model
✓ As a consequence, D meson spectral function has a complicated $Y_c N^{-1}$ structure in SU(8) model
✓ D meson spectral function dilutes with density and temperature, while D and D̄ potentials follow this behavior
✓ D meson develops a small width in SU(8) model: D⁰-nucleus bound states??
✓ First results for D* meson properties in nuclear matter within SU(8) scheme
✓ Transparency ratios are a useful tool to investigate $D_{s0}(2317)$ and $X(3700)$ resonances in matter as those states develop important in-medium widths