Charmed hadrons in nuclear matter and SU(4) flavor symmetry

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Outline

- Motivation
- $J/\Psi$ in matter
- DN interaction
- SU(4) flavor symmetry in couplings
- Conclusions & perspectives
Interaction of charm with ordinary matter

- Understanding of the nuclear force at QCD level; role of glue
  (origin of hadron masses & confinement)

- D-mesons in medium: chiral-symmetry restoration

- $J/\Psi, \eta_c, D \ldots$: possibly bound to ordinary matter

- Quark-gluon plasma

Experiments underway:
JLab @ 12 GeV, Panda & CBM @ Fair, JPARC, Nica
Charmonium binding in nuclear matter
- an exotic nuclear state

Brodsky, Schmidt & de Téramond, PRL 64, 1011 (1990)

- Nucleons and charmonium have no valence quarks in common

- Interaction has to proceed via gluons – QCD van der Waals

- No Pauli Principle – no short-range repulsion

- Also, binding via D,D* meson loop - interaction with nucleons

BE  ~ 10 - 20 MeV

D,D*-meson loops

Calculate loop with effective Lagrangians

– need coupling constants & form factors

– need a model for medium dependence of D masses
Effective Lagrangians

– SU(4) flavor symmetry

\[ \mathcal{L}_{\psi DD} = ig_{\psi DD} \psi^\mu \left[ \bar{D} (\partial_\mu D) - (\partial_\mu \bar{D}) D \right] \]

\[ \mathcal{L}_{\psi DD^*} = \frac{g_{\psi DD^*}}{m_\psi} \varepsilon_{\alpha\beta\mu\nu} (\partial^\alpha \psi^\beta) \left[ (\partial_\mu \bar{D}^{*\nu}) D + \bar{D} (\partial_\mu D^{*\nu}) \right] \]

\[ \mathcal{L}_{\psi D^* D^*} = ig_{\psi D^* D^*} \left\{ \psi^\mu \left[ (\partial_\mu \bar{D}^{*\nu}) D^*_\nu - \bar{D}^{*\nu} (\partial_\mu D^*_\nu) \right] \right. \\
+ \left. \left[ (\partial_\mu \psi^{\nu}) \bar{D}^*_\nu - \psi^{\nu} (\partial_\mu \bar{D}^*_\nu) \right] D^{*\mu} \right. \\
+ \left. \bar{D}^{*\mu} \left[ \psi^{\nu} (\partial_\mu D^*_\nu) - (\partial_\mu \psi^{\nu}) D^*_\nu \right] \right\} \]
J/Ψ single-particle energies in nuclei
– solve a Klein-Gordon equation, D, D* masses QMC model

<table>
<thead>
<tr>
<th></th>
<th>$\Lambda_{D,D^*} = 1500$ MeV</th>
<th>$\Lambda_{D,D^*} = 2000$ MeV</th>
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<tr>
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<tr>
<td></td>
<td>$1s$</td>
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<td>$1p$</td>
</tr>
<tr>
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<td>$-3.94$</td>
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<tr>
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<tr>
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<td>$-13.26$</td>
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<tr>
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<td>$^{40}_\psi$Ca</td>
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<td>$2s$</td>
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<td>$-12.22$</td>
</tr>
<tr>
<td>$^{208}_\psi$Pb</td>
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<tr>
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<td>$1s$</td>
<td>$1s$</td>
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<tr>
<td></td>
<td>$-16.83$</td>
<td>$-19.10$</td>
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<td>$1p$</td>
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<td>$-17.59$</td>
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<td></td>
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<td>$-13.61$</td>
<td>$-15.81$</td>
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<tr>
<td></td>
<td>$2s$</td>
<td>$2s$</td>
</tr>
<tr>
<td></td>
<td>$-13.07$</td>
<td>$-15.26$</td>
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</tbody>
</table>

Are those binding energies large enough to bind a $J/\Psi$ to a large nucleus?

Condition for a bound state:

- spherical “square-well” radius $R$, depth $V_0$

\[
V_0 > \frac{\pi^2 \hbar^2}{8mR^2}
\]

$R = 5 \text{ fm} \rightarrow V_0 > 1 \text{ MeV}$
ATHENNA* collaboration JLab @ 12 GeV

Z.-E. Meziani (Co-spokesperson/Contact)
N. Sparveris (Co-spokesperson)
Z.W. Zhao (Co-spokesperson)

*A J/Ψ THreshold Electroproduction on the Nucleon and Nuclei Analysis
Issues:

1) Interaction of D mesons with nucleons
2) SU(4) flavor symmetry
3) Width of D mesons
4) $J/\Psi$ moving, not at rest
5) . . .

Next: 1) and 2)
Experiment
- antiproton annihilation on the deuteron*

* J. Haidenbauer, G. Krein, U.-G. Meissner, A. Sibirtsev

DN interaction
– meson + quark exchange

\[
\begin{array}{c}
\text{MEX: } \text{SU(4)-flavor symmetry for couplings, same cutoffs as KN} \\
\text{QEX: change quark masses (wave functions)}
\end{array}
\]
Meson-meson-meson vertices

\[ \mathcal{L}_{PPV} = g_{PPV} \Phi_P(x) \partial_\mu \Phi_P(x) \Phi^\mu_V(x) \]

\[ \mathcal{L}_{VV_P} = \frac{g_{VV_P}}{m_V} i \epsilon_{\mu \nu \tau \delta} \partial^\mu \Phi^\nu_V(x) \partial^\tau \Phi^\delta_V(x) \Phi_P(x) \]
Baryon-baryon-meson vertices

\[ \mathcal{L}_{NNP} = g_{NNP} \bar{\Psi}_N(x)i\gamma^5 \Psi_N(x)\Phi_P(x) \]

\[ \mathcal{L}_{NNV} = g_{NNV} \bar{\Psi}_N(x)\gamma_\mu \Psi_N(x)\Phi^\mu_V(x) + \frac{f_{NNV}}{4m_N} \bar{\Psi}_N(x)\sigma_{\mu\nu} \Psi_N(x)(\partial_\mu \Phi^\nu_V(x) - \partial^\nu \Phi^\mu_V(x)) \]

\[ \mathcal{L}_{N\Delta P} = \frac{f_{N\Delta P}}{m_P} \bar{\Psi}_{\Delta \mu}(x)\Psi_N(x)\partial_\mu \Phi_P(x) + \text{H.c.} \]

\[ \mathcal{L}_{N\Delta V} = \frac{f_{N\Delta V}}{m_V} i(\bar{\Psi}_{\Delta \mu}(x)\gamma^5 \gamma_\mu \Psi_N(x) - \bar{\Psi}_N(x)\gamma^5 \gamma_\mu \Psi_{\Delta \mu}(x))(\partial_\mu \Phi^\nu_V(x) - \partial^\nu \Phi^\mu_V(x)) \]

\[ \mathcal{L}_{NYP} = \frac{f_{NYP}}{m_P} (\bar{\Psi}_Y(x)\gamma^5 \gamma_\mu \Psi_N(x) + \bar{\Psi}_N(x)\gamma^5 \gamma_\mu \Psi_Y(x))\partial_\mu \phi_P(x) \]
Based on a previous KN Juelich model

- M. Hoffmann et al. NPA 593, 341 (1995)

Contains a short-ranged “repulsive scalar” $m \sim 1.2$ GeV

Can be replaced by quark-gluon exchange
Hadjimichef, Haidenbauer and GK, PRC 66, 055214 (2002)
Model fits available KN data
describes even phase shifts
... and helped to kill the pentaquark (1540)

PHYSICAL REVIEW C 68, 052201(R) (2003)

Influence of a $Z^+(1540)$ resonance on $K^+N$ scattering

J. Haidenbauer$^1$ and G. Krein$^2$

$^1$Forschungszentrum Jülich, Institut für Kernphysik, D-52425 Jülich, Germany
$^2$Instituto de Física Teórica, Universidade Estadual Paulista, Rua Pamplona, 145-01405-900 São Paulo, SP, Brazil

(Received 22 September 2003; published 18 November 2003)

The impact of a ($J=0, I^P = \frac{1}{2}^+$) $Z^+(1540)$ resonance with a width of 5 MeV or more on the $K^+N(J=0)$ elastic cross section and on the $P_{01}$ phase shift is examined within the $KN$ meson-exchange model of the Jülich group. It is shown that the rather strong enhancement of the cross section caused by the presence of a $Z'$ with the above properties is not compatible with the existing empirical information on $KN$ scattering. Only a much narrower $Z'$ state could be reconciled with the existing data—or, alternatively, the $Z'$ state must lie at an energy much closer to the $KN$ threshold.

Predictions for the PANDA measurement

Use SU(4) symmetry for couplings:

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* J. Haidenbauer, G. Krein, U.-G. Meissner, A. Sibirtsev
DN interaction
– in a color confining chiral quark model*

Inspired in the QCD Hamiltonian in Coulomb gauge

Derive from the same underlying Hamiltonian:
– constituent quark masses (mass generation)
– hadron wave-functions, hadron masses (confinement)
– effective meson-baryon interaction (nuclear force)
– X-sections, etc (observables)
– density & temperature dependence on hadron masses (not here)

Hamiltonian

\[ H = H_0 + H_{\text{int}} \]

\[ H_0 = \int dx \, \Psi^\dagger(x)(-i\alpha \cdot \nabla + \beta m)\Psi(x) \]

\[ H_{\text{int}} = -\frac{1}{2} \int dx \, dy \, \rho^a(x) \, V_C(|x - y|) \, \rho^a(y) \]
\[ + \frac{1}{2} \int dx \, dy \, \rho^a_i(x) \, D^{ij}(|x - y|) \, \rho^a_j(y) \]

\[ \rho^a(x) = \Psi^\dagger(x) \, T^a \, \Psi(x) \]
\[ J^a_i(x) = \Psi^\dagger(x) \, T^a \, \alpha_i \, \Psi(x) \]
Input from the lattice

- Coulomb kernel – potential

\[ V_{Coul}(\mathbf{k}) = \frac{1}{8L_s^3} \left( \sum_{a,\tilde{x},\tilde{y}} e^{i\mathbf{k} \cdot (\tilde{x} - \tilde{y})} [M^{-1}(-\Delta)M^{-1}]^{aa}_{\tilde{x}\tilde{y}} \right) \]

\[ V_{Coul}(q) = \frac{6}{\beta} a^2 V_{Coul}^L(k, \beta), \quad q_i(k_i) = \frac{2}{a} \sin \left( \frac{\pi k_i}{L_i} \right) \]

- Fit from simulations*

\[ V_{Coul}(q) = \frac{8\pi \sigma_{Coul}}{q^4} + \frac{4\pi C}{q^2} \]

\( \begin{cases} 
\sigma_{Coul} = (552 \text{ MeV})^2 \\
C = 6 
\end{cases} \)

Transverse-gluon propagator

\[ D_{ij}^{ab}(\vec{k}) = \langle \tilde{A}_i^a(\vec{k})\tilde{A}_j^b(-\vec{k}) \rangle = \delta^{ab}\left( \delta_{ij} - \frac{p_i(\vec{k})p_j(\vec{k})}{p^2} \right) D_{tr}(p) \]

\[ p_i(\vec{k}) = \frac{2}{a} \sin\left( \frac{\pi k_i}{L} \right) \]

finite in the infrared
From the same Hamiltonian:

- dynamically generated quark masses
- hadron wavefunctions (color singlets only)
- hadron-hadron interactions
- X-sections, phase-shifts, ...
Quark mass function

- dynamical chiral symmetry breaking

(Dyson-Schwinger equation)
Cross-sections

- short-distance: quark interchange
- long-distance: meson-exchange (mainly rho, omega sigma)
Phase shifts

\( \delta \) [degrees]

\( E_{\text{c.m.}} - m_N - m_K \) [MeV]

\( E_{\text{c.m.}} - m_N - m_D \) [MeV]

PSA GWDAC

Model 1

Model 2

I = 1

(b)
How good is SU(4) flavor symmetry for couplings?

\[ m_u < m_s \ll m_c \]

SU(4) symmetry:

\[ g_{\bar{D}\rho\bar{D}} = g_{K\rho K} = \frac{1}{2} g_{\pi\rho\pi} \]

\[ g_{N\Lambda_c\bar{D}} = g_{N\Lambda\bar{K}} = g_{NN\pi} \]
Coupling constants & Form factors

Dyson-Schwinger & Bethe-Salpeter equations:
- rainbow ladder, no free parameters (heavily constrained spectrum and e.w. decay constants)

\[ \frac{g_{K\rho K}}{g_{D\rho D}} \sim \frac{1}{4} \rightarrow 400\% \text{ violation} \]

\[ \frac{g_{K\rho K}}{g_{\pi\rho\pi}} \sim \frac{1}{2} \rightarrow \text{SU}(4) \text{ OK} \]

COUPLING LARGE, BUT FORM FACTORS ARE SOFT
- DN X-SECTION ONLY 5 TIMES LARGER THAN SU(4)

On the other hand:
- nonrelativistic quark model + $^3P_0$ decay

<table>
<thead>
<tr>
<th></th>
<th>$g_{\rho\pi\pi}/2g_{\rho KK}$</th>
<th>$g_{\rho\pi\pi}/2g_{\rho DD}$</th>
<th>$g_{\rho KK}/g_{\rho DD}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU(4) symmetric</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SU(4) broken</td>
<td>1.05</td>
<td>1.28</td>
<td>1.22</td>
</tr>
</tbody>
</table>

SU(4) BREAKING: AT THE LEVEL OF 20% – 30%

C. E. Fontoura, GK, J. Haidenbauer (2013)
Nonrelativistic quark model + $^3P_0$ decay

<table>
<thead>
<tr>
<th></th>
<th>$\frac{g_{NN\pi}}{g_{N\Lambda_s K}}$</th>
<th>$\frac{g_{NN\pi}}{g_{N\Lambda_c \bar{D}}}$</th>
<th>$\frac{g_{N\Lambda_s K}}{g_{N\Lambda_c \bar{D}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU(4) symmetric</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SU(4) broken</td>
<td>1.07</td>
<td>1.20</td>
<td>1.12</td>
</tr>
</tbody>
</table>

SU(4) BREAKING: AT THE LEVEL OF 10% – 15%
QCD sum rules\(^1\) & Lattice\(^2\)

– looked at SU(4) symmetry breaking within the charm sector only

\[ g_\rho DD = g_\rho D^* D^* = g_\pi D^* D \]

**QCD sum rules**

<table>
<thead>
<tr>
<th>SU(4) relation</th>
<th>Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{\psi DD} = g_{\bar{\psi} D^* D^*}$</td>
<td>(7%)</td>
</tr>
<tr>
<td>$g_{\rho DD^<em>} = \frac{\sqrt{6}}{2} g_{\bar{\psi} D^</em> D^*}$</td>
<td>(12%)</td>
</tr>
<tr>
<td>$g_{\rho DD} = \frac{\sqrt{6}}{4} g_{\bar{\psi} DD}$</td>
<td>(17%)</td>
</tr>
<tr>
<td>$g_{\pi D^* D^<em>} = \frac{\sqrt{6}}{2} g_{\bar{\psi} DD^</em>}$</td>
<td>(20%)</td>
</tr>
<tr>
<td>$g_{D^* D^* \rho} = \frac{\sqrt{6}}{4} g_{\bar{\psi} D^* D^*}$</td>
<td>(20%)</td>
</tr>
<tr>
<td>$g_{DD^* \rho} = \frac{\sqrt{6}}{4} g_{\bar{\psi} D^* D^*}$</td>
<td>(21%)</td>
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<td>$g_{\rho D^* D^*} = \frac{\sqrt{6}}{4} g_{\bar{\psi} DD}$</td>
<td>(25%)</td>
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<td>$g_{\pi D^* D^<em>} = g_{\rho DD^</em>}$</td>
<td>(29%)</td>
</tr>
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<td>$g_{\rho DD} = g_{\rho D^* D^*}$</td>
<td>(36%)</td>
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<td>$g_{D^* D^* \rho} = g_{D^* D^* \rho}$</td>
<td>(52%)</td>
</tr>
<tr>
<td>$g_{D^* D^<em>} = \frac{\sqrt{6}}{4} g_{\bar{\psi} D^</em> D^*}$</td>
<td>(62%)</td>
</tr>
<tr>
<td>$g_{D^* D^*} = \frac{\sqrt{6}}{4} g_{\bar{\psi} DD}$</td>
<td>(64%)</td>
</tr>
<tr>
<td>$g_{D^* D^<em>} = g_{DD^</em> \rho}$</td>
<td>(70%)</td>
</tr>
</tbody>
</table>

Lattice

\[ g_{D^* D \pi} = 16.23(1.71) \]

\[ g_{DD \rho} = 4.84(34) \]

\[ g_{D^* D^* \rho} = 5.94(56) \]

Perspectives
- supernuclei (or charm hypernuclei)

A: primary vertex
B: vertex decay of a supernucleus decay
C: decay of $\bar{D}^0$ (signal of $c\bar{c}$ pair)

Yu. A. Batusov et al., JETP Lett. 33, 56 (1981)
Theory, QMC model:

TABLE I. Single-particle energies (in MeV) for $^{17}$O, $^{41}$Ca, and $^{49}$Ca ($j = \Lambda_c^+, \Lambda_b$). Single-particle energy levels are calculated up to the same highest states as that of the core neutrons. Results for the hypernuclei are taken from Ref. [10]. Experimental data for $\Lambda$ hypernuclei are taken from Ref. [28], where spin-orbit splittings for $\Lambda$ hypernuclei are not well determined by the experiments.

<table>
<thead>
<tr>
<th></th>
<th>$^{16}$O (Expt.)</th>
<th>$^{17}$O $\Lambda_c^+$</th>
<th>$^{17}$O $\Lambda_b$</th>
<th>$^{40}$Ca (Expt.)</th>
<th>$^{41}$Ca $\Lambda_c^+$</th>
<th>$^{41}$Ca $\Lambda_b$</th>
<th>$^{49}$Ca $\Lambda_c^+$</th>
<th>$^{49}$Ca $\Lambda_b$</th>
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</thead>
<tbody>
<tr>
<td>1s1/2</td>
<td>12.5</td>
<td>14.1</td>
<td>12.8</td>
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<td>20.0</td>
<td>19.5</td>
<td>12.8</td>
<td>23.0</td>
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<td>1p3/2</td>
<td>2.5</td>
<td>5.1</td>
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<td>12.0</td>
<td>12.3</td>
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<tr>
<td>1p1/2</td>
<td>(1p3/2)</td>
<td>5.0</td>
<td>7.3</td>
<td>16.5</td>
<td>12.3</td>
<td>12.3</td>
<td>9.1</td>
<td>20.9</td>
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<tr>
<td>1d5/2</td>
<td>-4.7</td>
<td>-4.8</td>
<td>-18.4</td>
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<td>-6.5</td>
<td>-19.5</td>
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</tr>
<tr>
<td>2s1/2</td>
<td>-3.5</td>
<td>-3.4</td>
<td>-17.4</td>
<td>-5.4</td>
<td>-5.3</td>
<td>-18.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1d3/2</td>
<td>-4.6</td>
<td>-4.8</td>
<td>-18.4</td>
<td>-6.4</td>
<td>-6.4</td>
<td>-19.5</td>
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<tr>
<td>1f7/2</td>
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</tbody>
</table>
Nonmesonic decays of charm hypernuclei*

\[ \Lambda_c + N \rightarrow N + N \]
\[ \Lambda_c + N \rightarrow N + \Lambda \]

\(L: \) weak vertex

\(R: \) strong vertex

\(V = H_W \otimes H_S\)

*A.P. Galeão, GK, F. Krmpotic