Binding of Charmed Mesons (D, \( \bar{D} \)) and J/\( \Psi \) in Nuclei

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G. Krein, KT, A.W. Thomas (work in progress)

For other mesons and review of QMC:

Outline

• Introduction
• **QMC** model, *finite nuclei*
• \( D, \bar{D} \) in a nuclear medium
• \( J/\Psi \) in a nuclear medium
• Summary, outlook
Introduction

• (Large) nuclei, and nuclear matter in terms of quarks and gluons (or QCD) ???!!
• NN, NNN, NNNN... interactions \(\Rightarrow\) Nucleus ? \(\Leftarrow\) shell model, MF model,...
• Lattice QCD: still extracting NN and NY interactions, \([Y=\text{hyperons: } \Lambda, \Sigma, \Xi]\)
• Quark model based description of nucleus
• Hadron properties in a nuclear medium
Light (u,d) quarks interact self-consistently with mean $\sigma$ and $\omega$ fields.

$$m^*_q = m_q - g_\sigma \sigma = m_q - V_\sigma$$

$\downarrow$ nonlinear in $\sigma$

$$M^*_N \equiv M_N - g_\sigma^N \sigma + (d/2)(g_\sigma^N \sigma)^2$$

$$[i \partial \cdot \gamma - (m - V_\sigma^q) + \gamma_0 V_\omega^q] q = 0$$

1. Start

$$[i \partial \cdot \gamma - M^*_N + \gamma_0 V_\omega^N] N = 0$$

$V_\omega^N = 3V_\omega$

*Nuclear Binding !!*

$M^*_N = M_N - V_\sigma^N$

*Self-consistent !*

For a review, PPNP 58, 1 (2007)
At Nucleon Level Response to the Applied Scalar Field is the Scalar Polarizability

Nucleon response to a chiral invariant scalar field is then a nucleon property of great interest...

\[ M^*(\vec{R}) = M - g_\sigma \sigma(\vec{R}) + \frac{d}{2} \left( g_\sigma \sigma(\vec{R}) \right)^2 \]

Non-linear dependence of scalar polarizability

\[ d \approx 0.22 R \text{ in original QMC (MIT bag)} \]

Indeed, in nuclear matter at mean-field level (e.g. QMC), this is the ONLY place the response of the internal structure of the nucleon enters.
Bound quark Dirac spinor (1s\(_{1/2}\))

Quark Dirac spinor in a bound hadron:

\[
q_{1s}(r) = \begin{pmatrix} U(r) \\ i \sigma \cdot r L(r) \end{pmatrix} \chi
\]

Lower component is enhanced!

\[\Rightarrow g_A^* < g_A : \sim |U|^2 - (1/3) |L|^2,\]

\[\Rightarrow \text{Decrease of scalar density} \Rightarrow\]
Decrease in Scalar Density

Scalar density (quark): \( \sim |U|^2 - |L|^2 \),
\[
\Downarrow
\]
\( M_N^* \), N wave function, Nuclear scalar density etc., are **self-consistently** modified due to the N internal structure change!

\[ \Rightarrow \text{Novel Saturation mechanism!} \]
Nuclear (Neutron) matter, $E/A$

**Novel saturation mechanism!**

**Incompressibility**

QHD: $K \approx 500$ MeV  
QMC: $K \approx 280$ MeV  
(Exp. 200 ~ 300 MeV)

PLB 429, 239 (1998)
Finite nuclei ($^{208}$Pb energy levels)

NPA 609, 339 (1996)

Large mass nuclei

Nuclear matter

Based on quarks!

Hadrons

Hypernuclei

(the latest QMC)
Summary: Scalar Polarizability

- Can always rewrite non-linear coupling as linear coupling plus non-linear scalar self-coupling – likely physical origin of non-linear versions of QHD

- In nuclear matter this is the only place the internal structure of the nucleon enters in MFA

- Consequence of polarizability in atomic physics is many-body forces:

\[ V = V_{12} + V_{23} + V_{13} + V_{123} \]
QMC $\iff$ QHD

- **QHD** shows importance of *relativity*: mean $\sigma$, $\omega$ and $\rho$ fields
- **QMC** goes far beyond **QHD** by incorporating effect of hadron *internal structure*

- Minimal model couples these mesons to *quarks* in relativistic quark model – e.g. MIT bag, or confining NJL... *any other quark models*

- $g_\sigma^q$, $g_\omega^q$, $g_\rho^q$ fitted to $\rho_0$, $E/A$ and *symmetry energy*

- **No additional parameters** predict change of structure and *binding in nuclear matter of all hadrons*:
  e.g. $\omega$, $\rho$, $\eta$, $J/\psi$, $N$, $\Lambda$, $\Sigma$, $\Xi$ $\iff$ see later!
Linking QMC to Familiar Nuclear Theory

Since early 70’s tremendous amount of work in nuclear theory is based upon **effective forces**

• Used for everything from nuclear astrophysics to collective excitations of nuclei

• **Skyrme Force**: Vautherin and Brink


  explicitly obtained effective force, 2- plus 3- body, of **Skyrme type**

  - equivalent to QMC model (required expansion around $\sigma = 0$)
Physical Origin of Density Dependent Force of the Skyrme Type within the QMC model

That is, apply new effective force directly to calculate nuclear properties using Hartree-Fock (as for usual well known force)

<table>
<thead>
<tr>
<th></th>
<th>$E_B$ (MeV, exp)</th>
<th>$E_B$ (MeV, QMC)</th>
<th>$r_c$ (fm, exp)</th>
<th>$r_c$ (fm, QMC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}O$</td>
<td>7.976</td>
<td>7.618</td>
<td>2.73</td>
<td>2.702</td>
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<tr>
<td>$^{40}Ca$</td>
<td>8.551</td>
<td>8.213</td>
<td>3.485</td>
<td>3.415</td>
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<tr>
<td>$^{48}Ca$</td>
<td>8.666</td>
<td>8.343</td>
<td>3.484</td>
<td>3.468</td>
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<tr>
<td>$^{208}Pb$</td>
<td>7.867</td>
<td>7.515</td>
<td>5.5</td>
<td>5.42</td>
</tr>
</tbody>
</table>

- Where analytic form of (e.g. $H_0 + H_3$) piece of energy functional derived from QMC is:

$$H_0 + H_3 = \rho^2 \left[ \frac{-3 G_\rho}{32} + \frac{G_\sigma}{8 (1 + \frac{d\rho}{d\rho} G_\sigma)^3} - \frac{G_\sigma}{2 (1 + \frac{d\rho}{d\rho} G_\sigma)} + \frac{3 G_\omega}{8} \right] +$$

$$\left(\rho_n - \rho_p\right)^2 \left[ \frac{5 G_\rho}{32} + \frac{G_\sigma}{8 (1 + \frac{d\rho}{d\rho} G_\sigma)^3} - \frac{G_\omega}{8} \right],$$

- highlights scalar polarizability
**Mesons in nuclear medium in QMC**

Light (u,d) quarks interact self-consistently with mean $\sigma$ and $\omega$ fields.

\[ m^*_q = m_q - g_\sigma \sigma = m_q - V^q_\sigma \]

↓ **nonlinear in $\sigma$**

\[ M^*_{MM} \cong M_M - g_\sigma^M \sigma + (d^M/2)(g_\sigma^M \sigma) \]

\[ [i \partial \cdot \gamma - (m_q - V^q_\sigma) + \gamma_0 V^q_\omega] \ q = 0 \]

$\sigma, \omega$ fields: **no couplings** with s,c,b quarks!!

Nuclear Binding !!

(For a review, PPNP 58, 1 (2007))

**Applied quark model (lattice) mass formula**
Scalar potentials in QMC respects SU(3) (light quark # !)
D meson scalar potential

\[ m_u = 5 \text{ MeV}, \quad m_c = 1300 \text{ MeV} \]

\[ R_N = 0.8 \text{ fm} \]
$D$ and $D^*$ potentials in nuclear matter

$D^+ = c \bar{d}$

$D^0 = c \bar{u}$
D^- (d) total potential in Pb

\( V^q \)

\( r \) (fm)

\( \rho_B \) (fm\(^{-3}\))

\( 208\text{Pb} \)

1.96\( \times V^q_\omega \)
$D^- (\bar{c}d)$ bound state wave functions in Pb
### Bound State Energy in Pb

<table>
<thead>
<tr>
<th>state</th>
<th>$\bar{D}^{-} \times Vq\omega$</th>
<th>D$^{-}$ Vq$\omega$</th>
<th>D$^{-}$ Vq$\omega$ No Coulomb</th>
<th>$\bar{D}^{0}$ 1.96*Vq$\omega$</th>
<th>$\bar{D}^{0}$ Vq$\omega$</th>
<th>$\bar{D}^{0}$ Vq$\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1s</td>
<td>-10.6</td>
<td>-35.2</td>
<td>-11.2</td>
<td>unbound</td>
<td>-25.4</td>
<td>-96.2</td>
</tr>
<tr>
<td>1p</td>
<td>-10.2</td>
<td>-32.1</td>
<td>-10.0</td>
<td>unbound</td>
<td>-23.1</td>
<td>-93.0</td>
</tr>
<tr>
<td>2s</td>
<td>-7.7</td>
<td>-30.0</td>
<td>-6.6</td>
<td>unbound</td>
<td>-19.7</td>
<td>-88.5</td>
</tr>
</tbody>
</table>
**$J/\psi$** pot. in matter (**color octet**)

\[ H = \frac{\alpha_{\psi}}{2} \langle N | \mathbf{E}_a \cdot \mathbf{E}_a | N \rangle \]

**M.B. Voloshin**: chromo-polarizability

at \( \rho_0 \), \( V < -21 \ (\alpha_{\psi}/2 \ \text{GeV}^{-3}) \ [\text{MeV}] \),
PPNP 61, 455 (2008)

**S.H. Lee, C.M. Ko**: QCD Stark effect

\( V = -8 + 3 \ (\text{D-loop}) \ [\text{MeV}] \),


\( V = -11 \sim -8 \ [\text{MeV}] \),
PLB 288, 355 (1992)
$J/\Psi(\Upsilon, \phi)$ mass in medium (loop!)

$J/\Psi(\Upsilon, \phi)$ bound in large nuclei?

D, B, K (in medium!)

Color singlet!

$J/\Psi(\Upsilon, \phi)$, $J/\Psi(\Upsilon, \phi)$

D, B, K (in medium!)

K. Tsushima
D–D loop: $J/\Psi$ potential in matter
Summary, outlook

1. $D^-$ will form nuclear (atomic) bound state
2. $J/\Psi$ potential in nuclear matter
   - Color octet, QCD Stark $\Rightarrow$ attraction!
   - Color singlet, $D-\bar{D}$ loop $\Rightarrow$ attraction!
     (Loops with $D^*$ $\Rightarrow$ additional attraction!)
3. $J/\Psi$ will be bound in (large mass) nuclei
4. Loops involve $D^*$ must be added
5. $\Upsilon$, $\Phi$?
## Spin-Orbit Splitting

<table>
<thead>
<tr>
<th></th>
<th>Neutrons (Expt)</th>
<th>Neutrons (QMC)</th>
<th>Protons (Expt)</th>
<th>Protons (QMC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}$O</td>
<td>6.10</td>
<td>6.01</td>
<td>6.3</td>
<td>5.9</td>
</tr>
<tr>
<td>$1p_{1/2}-1p_{3/2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{40}$Ca</td>
<td>6.15</td>
<td>6.41</td>
<td>6.0</td>
<td>6.2</td>
</tr>
<tr>
<td>$1d_{3/2}-1d_{5/2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>6.05 (Sly4)</td>
<td>5.64</td>
<td>6.06 (Sly4)</td>
<td>5.59</td>
</tr>
<tr>
<td>$1d_{3/2}-1d_{5/2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>2.15 (Sly4)</td>
<td>2.04</td>
<td>1.87 (Sly4)</td>
<td>1.74</td>
</tr>
<tr>
<td>$2d_{3/2}-2d_{5/2}$</td>
<td></td>
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</tbody>
</table>

Agreement generally very satisfactory – NO parameter adjusted to fit