Charmed matter

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Happy Birthday Tony!
Motivation

Interaction of charm with ordinary matter is interesting for several reasons

• Quark-gluon plasma: $J/\Psi$ suppression

• D-mesons in medium: chiral-symmetry

• $J/\Psi$: possibly bound to ordinary matter

• Experiments underway: JLab @ 12 GeV, Panda, CBM @ Fair
Nuclear-Bound Quarkonium

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(Received 25 September 1989)

We show that the QCD van der Waals interaction due to multiple-gluon exchange provides a new kind of attractive nuclear force capable of binding heavy quarkonia to nuclei. The parameters of the potential are estimated by identifying multigluon exchange with the Pomeron contributions to elastic meson-nucleon scattering. The gluonic potential is then used to study the properties of $c\bar{c}$ nuclear-bound states. In particular, we predict bound states of the $\eta_c$ with $^3$He and heavier nuclei. Production modes and rates are also discussed.
Charmonium bound to nuclear matter
– an exotic nuclear bound state

• nucleons and charmonium have no quarks in common
• interaction has to proceed via gluons – QCD van der Waals
• no Pauli Principle – no short-range repulsion

\[ \text{BE (} \eta_c \text{ to } A = 9 \text{ nucleus)} \sim 180 \text{ MeV}^* \]

*Brodsky, Schmidt & de Téramond, PRL 64, 1011 (1990)
Is $J/\psi$-nucleon scattering dominated by the gluonic van der Waals interaction? 1

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Editor: M. Dine

Abstract

The gluon-exchange contribution to $J/\psi$-nucleon scattering is shown to yield a sizeable scattering length of about -0.25 fm, which is consistent with the sparse available data. Hadronic corrections to gluon exchange which are generated by $\rho\pi$ and $D\bar{D}$ intermediate states of the $J/\psi$ are shown to be negligible. We also propose a new method to study $J/\psi$-nucleon elastic scattering in the reaction $\pi^+d \rightarrow J/\psi pp$. © 1997 Elsevier Science B.V.
Here, possibility of J/ψ binding to nuclei*

Two (independent) mechanisms:

• second order stark effect – octet intermediate state

• D,D* meson-loop – color singlet intermediate state

D mesons feel
the nuclear medium

* GK, A.W. Thomas & K. Tsushima
Second-order Stark effect

\[ H = \frac{\alpha_s}{\pi} \vec{E}^a \cdot \vec{E}^a \]  
chromo-electric polarizability

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

\( \psi(k) \) : charmonium wavefunction

\( \rho_B \) : baryon density

\( m_c, m_N \) : masses charm quark and nucleon

\( \varepsilon = 2m_c - m_\psi \) : energy shift octet-charmonium
Numerical results:

\[ \left\langle \frac{\alpha_s}{\pi} E^2 \right\rangle_N = 0.5 \text{GeV}^2 \quad \alpha_s = 0.84 \quad \text{S.H. Lee & C.M. Ko, PRC 67, 038202 (2003)} \]

\[ \psi : \text{Gaussian - } \langle r^2 \rangle \text{ same as pot models} \]

\[ \Delta m_\psi (\rho_B) = -8 \text{MeV} \quad \text{at normal nuclear matter density} \]

\[ \text{J/Ψ N cross section > 17 mb} \]

\[ \Delta m_\psi (\rho_B) = -21 \text{MeV} \quad \text{Sibirtsev & Voloshin, PRD 71, 076005 (2005)} \]
D-meson loop

Calculate loop with effective Lagrangian

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

- need form factors
- need a model for medium dependence of D masses
Potential of J/Ψ in matter

\[ i\Sigma^{D\bar{D}}(k^2) = -\frac{8}{3} g_{\psi D\bar{D}}^2 \int \frac{d^4 q}{(2\pi)^4} F(q^2) \Delta_D(q) \Delta_{\bar{D}}(k - q) \]

\[ m^2 = (m^{(0)}_\psi)^2 + \Sigma^{D\bar{D}}(k^2 = m^2_\psi) \]

\[ m^*_2 = (m^{(0)}_\psi)^2 + \Sigma^{*D\bar{D}}(k^2 = m^*_\psi) \]

\[ U_{J/Ψ}(\rho_B) \equiv m^*_\psi - m^*_\psi \]
Structure of the mesons – form factors

Form factor for the loop calculation:

Quark model ($^3P_0$ pair creation):

$$F(q^2) = \gamma^2 \pi^{3/2} \frac{m_\psi^3}{\beta^3} \frac{2^6 r^3(1 + r^2)^2}{(1 + 2r^2)^5} e^{-q^2/2\beta_D^2(1+2r^2)}, \quad r = \frac{\beta_\psi}{\beta_D}$$

Phenomenological:

$$F(q^2) = \left[ \frac{\Lambda^2 + m_\psi^2}{\Lambda^2 + 4(q^2 + m_D^2)} \right]^2, \quad g_{\psi D\bar{D}} = 7.7$$
Model for D–mesons in matter
– Quark-Meson Coupling (QMC)*

• quarks are confined in a MIT bag
• in matter: non-overlapping bags,
  scalar ($\sigma$) and vector ($\omega$) mean fields couple to quarks

Single quark wavefunction in the bag

$$[i\gamma \cdot \partial - (m_q - g^q_\sigma \sigma) + g^q_\omega \gamma \cdot \omega] \psi_q = 0$$

*P.A.M. Guichon, PLB 200, 235 (1988)
Quarks and hadrons in matter

Single quark wave function in the bag

\[ [i \gamma \cdot \partial - (m_q - g^q_\sigma \sigma) + g^q_\omega \gamma \cdot \omega] \psi_q = 0 \]  

linear in \( \sigma \)

Single nucleon wave function in medium

\[ [i \gamma \cdot \partial - M_N^* + \gamma \cdot V^N_\omega] \psi_N \approx 0 \]

\[ M_N^* = M_N - g^N_\sigma \sigma + \frac{d}{2} \left( g^N_\sigma \sigma \right)^2 + \cdots \]  

nonlinear in \( \sigma \)
Gross properties of baryonic matter

nuclear matter

lead nucleus

K. Tsushima, ...
D mesons in matter

\[ \Delta = 164 \text{ MeV} \]
J/Ψ in matter

The graph shows the mass difference $m^*_Ψ - m_Ψ$ (in MeV) as a function of the baryon density $ρ_B/ρ_0$ for various cutoff energies. The density is set to $ρ_0 = 0.15 \text{ fm}^{-3}$. The legend indicates different cutoff energies: 1000 MeV, 1500 MeV, 2000 MeV, and 5000 MeV.
Can J/Ψ be bound to a large nucleus?

Condition for a bound state

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

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

\[ a = 5 \text{ fm} \rightarrow V_0 > 1 \text{ MeV} \]
Many issues:

- $J/\Psi$ moving, not at rest
- Finite nucleus
- Width of $D$ mesons
- Interactions with nucleons
- Production of charmed particles
Antiproton annihilation on the deuteron

\[ \bar{p} \rightarrow T_A \rightarrow D \]

\[ d \rightarrow p \]

\[ \bar{p} \rightarrow T_A \rightarrow D(\bar{D}) \]

\[ d \rightarrow T_M \rightarrow p \]

J. Haidenbauer, G. Krein, U.-G. Meissner, A. Sibirtseev


Meson exchange – effective Lagrangians

Couplings: SU(4) symmetry
The Model

Ingredients:
- meson & baryon exchanges (long distances)
- quark-gluon exchanges (short distances)

Important features:
- unitarization of amplitudes, solve Lipmann-Schwinger equation
- include higher partial waves, amplitudes are $s$ and $t$ dependent
Model Based on Previous K⁺N Model

Jülich model:
A. Müller-Groeling et al. NPA 513, 557 (1990)
M. Hoffmann et al. NPA 593, 341 (1995)

Contains a short-ranged
“repulsive sigma” \( m \sim 1.2 \text{ GeV} \)

Can be replaced by quark-gluon exchange
Model fits observables
and phase shifts
Influence of a $Z^+(1540)$ resonance on $K^+N$ scattering

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The impact of a $(f=0, J^P=\frac{1}{2}^+)$ resonance with a width of 5 MeV or more on the $K^+N(I=0)$ 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 $K^N$ 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.


and, if the pentaquark exists, it must be very narrow
### Scattering lengths

<table>
<thead>
<tr>
<th>a [fm]</th>
<th>Present work</th>
<th>Tólos et al.</th>
<th>Lutz</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$\bar{D}N$</td>
<td></td>
<td></td>
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<tr>
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<td>$D_N$</td>
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<table>
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<tr>
<th></th>
<th>$I = 0$</th>
<th>$I = 1$</th>
<th></th>
<th>$I = 0$</th>
<th>$I = 1$</th>
<th></th>
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<tr>
<td>$\bar{D}N$</td>
<td>+ 0.03</td>
<td>- 0.45</td>
<td>0.0</td>
<td>- 0.29</td>
<td>- 0.26</td>
<td></td>
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<tr>
<td>$D_N$</td>
<td>- 0.41 + i 0.04</td>
<td>- 2.07 + i 0.57</td>
<td>-</td>
<td>- 0.43 + i 0.0</td>
<td>- 0.41 + i 0.0</td>
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</tbody>
</table>

Tólos et al. PRC 77, 015207 (2006)

Lutz & Korpa PLB 633, 43 (2006)
Phase – shifts (s-wave): \textbf{MEx + OGE}

\textbf{Lessons:}
1) quark-gluon contributes with half of the interaction
2) rho and omega (scalars a little) dominant mesonic contributions
SU(4) symmetry breaking ???*

Need to know how good SU(4) is:  \( m_u < m_s \ll m_c \)

SU(4) symmetry:  \( g_{\overline{D}D\rho} = g_{\overline{D}D\omega} = g_{KK\rho} = \frac{1}{2} g_{\pi\pi\rho} \)

* C.E. Fontoura
Couplings in the quark model: $^3P_0$ model

$qq$ creation with quantum numbers of the vacuum

$$H_{qq} = g \int d^3x \overline{\Psi}(x)\Psi(x)$$

Matrix element

$$\langle BC \mid H_{qq} \mid A \rangle = \delta(A - B - C) h_{fi}$$
Need meson wave functions:

Fig. from Ted Barnes
Wave functions:

\[ H = m_1 + \frac{p_1^2}{2m_1} + m_2 + \frac{p_2^2}{2m_2} + F_1 \cdot F_2 \left[ \frac{\alpha_c}{r} - \frac{3b}{4} r - \frac{8\pi\alpha_h}{3m_1m_2} \left( \frac{\sigma^3}{\pi^3} e^{-\sigma^2 r_2} \right) \right] S_1 \cdot S_2 - C \]

\[ H \mid \Phi \rangle = E \mid \Phi \rangle, \quad \mid \Phi \rangle = \sum_{n=1}^{N} \Phi_n \mid n \rangle \rightarrow H_{nn'} \mid \Phi_{n'} \rangle = E_N O_{nn'} \mid \Phi_n \rangle \]

\[ \langle \vec{r} \mid n \rangle = e^{-n\beta^2 r^2 / 2}, \quad \beta : \text{variational parameter} \]

\[ O_{nn'} = \frac{1}{\beta^3} \left( \frac{2\pi}{n + n'} \right)^{3/2} \]

\[ H_{nn'} = \frac{1}{\beta^3} \left( \frac{2\pi}{n + n'} \right)^{3/2} \left[ m_1 + m_2 + \frac{3\beta^2}{2\mu} \frac{nn'}{n + n'} + \frac{4}{3} \alpha_c\beta \sqrt{\frac{2(n + n')}{\pi}} + \frac{b}{8\beta} \sqrt{\frac{8}{\pi(n + n')}} \right. \]

\[ + \frac{32\sigma^3\alpha_h}{9m_1m_2\sqrt{\pi}} \left( \frac{n + n'}{n + n' + 2\sigma^2 / \beta^2} \right)^{3/2} \langle \vec{S}_1 \cdot \vec{S}_2 \rangle + \frac{4}{3} C \]
Results for masses:

<table>
<thead>
<tr>
<th></th>
<th>β</th>
<th>( M_{cal} )</th>
<th>( M_{exp} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi )</td>
<td>347</td>
<td>139.7</td>
<td>137</td>
</tr>
<tr>
<td>( \rho )</td>
<td>272</td>
<td>770</td>
<td>770</td>
</tr>
<tr>
<td>K</td>
<td>362</td>
<td>492.5</td>
<td>495</td>
</tr>
<tr>
<td>D</td>
<td>499</td>
<td>1863.3</td>
<td>1867</td>
</tr>
</tbody>
</table>

All values in MeV
SU(4) breaking in the couplings \((at \ q^2 = 0\)

\[ h_{f_i}(q^2) = g \ F(q^2) \]

<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>1.31</td>
<td>1.25</td>
</tr>
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</table>

SU(4) symmetry breaking: at the level of 25% – 30%
SU(4) breaking in baryon-meson couplings

<table>
<thead>
<tr>
<th>SU(4) broken</th>
<th>$g_{N\Lambda_sK}/g_{N\Lambda_cD}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.05</td>
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</table>

SU(4) symmetry breaking: very small
DN Experiment: antiproton annihilation on the deuteron – Panda @ FAIR

Fig. 6. Predictions for the $\bar{p}p \rightarrow \bar{D}D$ annihilation cross section taken from Refs. [54] (solid line) and [55] (dashed and dash-dotted lines).

J. Haidenbauer, G. Krein, U.-G. Meissner, A. Sibirtseev
Production of $\Lambda_c \bar{\Lambda}_c$ *

- extension of Juelich model for $\Lambda\bar{\Lambda}$:
  - ISI (OPE + optical potential)
  - FSI (optical potentials)
  - transition potential ($D, D^*$)

- quark-model transition potential (Kohno & Weise)

\[
V_{pp\to\Lambda\bar{\Lambda}}(r) = \frac{4}{3} \frac{4\pi \alpha}{m_G^2} \delta_{S1} \delta_{T0} \left( \frac{3}{4\pi \langle r^2 \rangle} \right)^{3/2} \exp\left(-3r^2/(4\langle r^2 \rangle)\right)
\]

*Haidenbauer & GK 0912.2663 [hep-ph]
Fig. 4. Total reaction cross sections for $\bar{p}p \rightarrow \bar{\Lambda}_c^- \Lambda_c^+$ as a function of the excess energy $p_{lab}$. The dark (red) shaded band (blue grid) is the prediction of our meson-exchange (quark-gluon) transition potential. The dotted curve is the result from Ref. [4] while the dash-dotted curve and the corresponding (green) band is from Ref. [2].

- production of $\Lambda_c \bar{\Lambda}_c \sim 0.1$ production of $\Lambda \bar{\Lambda}$

- our results factor 100 – 1000 larger than existing predictions