NUCLEAR-BOUND HEAVY-FLAVOR HADRONS

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INT Symposium
Symmetry in Subatomic Physic: In Memory of Ernest Henley
September 10-11, 2018
Subject too broad — decided to focus on a single heavy hadron

HEAVY QUARKONIA

Talk based on

GK, AW Thomas & K Tsushima
— Prog Part Nucl Phys 100, 161 (2018)

JT Castellà & GK
Ernie was a humble person
— thought it would be appropriate to talk on something nothing really ambitious
Ernie was a humble person

— thought it would be appropriate to talk on something nothing really ambitious

Understand matter that amounts to 5% of the mass of the universe
Ernie was a humble person — thought it would be appropriate to talk on something nothing really ambitious

Understand matter that amounts to 5% of the mass of the universe

- Atoms 4.9%
- Dark Matter 26.8%
- Dark Energy 68.3%
Actually, to make justice to his modesty
Actually, to make justice to his modesty

Focus on understanding the proton mass
Actually, to make justice to his modesty

Focus on understanding the proton mass
Starting point?

Seems to be

Q C D

Quantum Chromodynamics
Ab Initio Determination of Light Hadron Masses

Science 322 (5905), 1224-1227.
DOI: 10.1126/science.1163233
Ab initio calculation of the neutron-proton mass difference


Science 347 (6229), 1452-1455.
DOI: 10.1126/science.1257050
The proton mass gets closer to the neutron mass in medium.
Computation of the masses
Computation of the masses

\[ h(x) : \text{hadron interpolating field, e.g. } \pi^+(x) = \bar{u}(x)\gamma_5 d(x) \]

\[ \langle h(x)h(x + T) \rangle = \frac{\int [\mathcal{D}\psi\bar{\psi}A_\mu] \ h(x)h(x + T) \ e^{-\int d^4x \mathcal{L}_{QCD}}}{\int [\mathcal{D}\psi\bar{\psi}A_\mu] \ e^{-\int d^4x \mathcal{L}_{QCD}}} \]

\[ \lim_{T \to \infty} \langle h(x)h(x + T) \rangle \sim e^{-M_h T} \]
Great, Impressive …
Great, Impressive …

**BUT,** how precisely those numbers come out from the QCD Lagrangian?
Trace anomaly

Take \( m_q = 0 \) & \( m_Q = \infty \)

\[
q(x) \rightarrow q'(x) = \lambda^{3/2} q(\lambda x) \quad A_\mu(x) \rightarrow A'_\mu(x) = \lambda A_\mu(\lambda x)
\]

\[
S'_{\text{QCD}} = \int d^4x \lambda^4 \mathcal{L}_{\text{QCD}}(\lambda x) = \int d^4x' \mathcal{L}_{\text{QCD}}(x') = S_{\text{QCD}}
\]

Classical action is invariant
Hadron masses

\[ |h\rangle: \text{hadron state} \quad m_h = \langle h | T^\mu_\mu(x) | h \rangle \]

From classical Lagrangian:

\[
\frac{\delta S_{\text{QCD}}}{\delta \lambda} = - \int d^4x \ T^\mu_\mu(x) = 0
\]

\[
\langle h | T^\mu_\mu | h \rangle = m_h \rightarrow 0
\]
Quantum theory

$$\delta S_{\text{QCD}} = \delta \left( -\frac{1}{4\pi \alpha_s} \frac{1}{4} \int d^4x \, G_{\mu\nu}^a(x) G^{a\mu\nu}(x) \right) = -\frac{2\beta(\alpha_s)}{\alpha_s} S_{\text{QCD}} \delta \lambda$$

$$T^\mu_\mu(x) = \frac{2\beta(\alpha_s)}{\alpha_s} \frac{1}{4} G_{\mu\nu}^a(x) G^{a\mu\nu}(x) = -\frac{1}{2} b_0 \alpha_s \, G_{\mu\nu}^a(x) G^{a\mu\nu}(x)$$

$$= -\frac{9}{32\pi^2} g^2 G_{\mu\nu}^a(x) G^{a\mu\nu}(x)$$

— this is the trace anomaly
— no scale invariance
— trace of $T^{\mu\nu}$ is nonzero

$${m_h} = -\frac{9}{32\pi^2} \langle h | g^2 G_{\mu\nu}^a G^{a\mu\nu} | h \rangle$$

The entire mass comes from gluons
Contribution from quark masses

\[ m_h = \frac{\beta(\alpha_s)}{2\alpha_s} G_{\mu\nu}^a(x) G^{a\mu\nu}(x) + \langle h | \bar{q} m_q q | h \rangle \]

small
Why is this interesting?

Because

\[ \langle h | g^2 G_{\mu\nu} G^{\alpha\mu\nu} | h \rangle \]

contributes to threshold quarkonium-nucleon scattering

Bhanot & Peskin, Kaidalov & Volkovitsky, Voloshin et al, Kharzeev, Hoodbhoy, Brodsky et al., Luke et al, Swanson, …
Quarkonium-nucleon

Quarkonium: $\phi(s\bar{s})$, $\eta_c(c\bar{c})$, $J/\Psi(c\bar{c})$, $\eta_b(b\bar{b})$, $\Upsilon(b\bar{b})$
Quarkonium-nucleon scattering

\[ \varphi = \phi(s\bar{s}), \quad \eta_c(c\bar{c}), \quad J/\Psi(c\bar{c}), \quad \eta_b(b\bar{b}), \quad \Upsilon(b\bar{b}) \]

Forward amplitude

\[ A_{\varphi N} = \frac{1}{2} \alpha_{\varphi} \langle N | (gE)^2 | N \rangle \]

\( \alpha_{\varphi} : \text{color polarizability} \)

(property of the quarkonium)
\[ A_{\varphi N} = \frac{1}{2} \alpha_\varphi \langle N | (gE)^2 | N \rangle \]

Measure scattering length:

\[ a_{\varphi N} = -\left( \frac{\mu_{\varphi N}}{2\pi} \right) A_{\varphi N} = -\left( \frac{\mu_{\varphi N}}{4\pi} \right) \alpha_\varphi \langle N | (gE)^2 | N \rangle \]

Bound from trace anomaly:

\[ \langle N | \left[ (gE)^2 - (gB)^2 \right] | N \rangle = -\frac{1}{2} \langle N | g^2 G_{\mu\nu} G^{\alpha\mu\nu} | N \rangle = \frac{16\pi^2}{9} m_N \leq \langle N | (gE)^2 | N \rangle \]

\[ a_{\varphi N} \leq -\left( \frac{\mu_{\varphi N}}{4\pi} \right) \frac{16\pi^2}{9} m_N \alpha_\varphi = -\frac{4\pi m_N}{9} \mu_{\varphi N} \alpha_\varphi \]
Renewed interest in quarkonium-nucleon
Why quarkonium in nuclei?

— scattering amplitude is enhanced

— new exotic nuclear state

— adds a new flavor axis in the nuclear e.o.s.

Brodsky, Schmidt & de Teramond, Ko et al., Brodsky & Miller, Weise et al., Kharzeev, Sibirtsev & Voloshin. …
Low-momentum quarkonium in a nucleus

— Quarkonium interacts with light quarks in nucleons by exchanging gluons with wavelengths

\[ \lambda \sim r_N \]

— Size of quarkonium

\[ r_{J/\Psi} \sim 0.35 \text{ fm} \]

\[ \lambda \geq 2 r_{J/\Psi} \quad \Rightarrow \quad \text{Quarkonium behaves as a small color dipole immersed in a uniform gluon field} \]
Low-momentum quarkonium in a nucleus

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$$\langle T_N \rangle \sim \frac{3}{5} \frac{k_F^2}{2m_N} \sim 20 \text{ MeV} \ll \Lambda_{QCD}$$
Low-momentum quarkonium in a nucleus

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\[ \langle T_N \rangle \sim \frac{3}{5} \frac{k_F^2}{2m_N} \sim 20 \text{ MeV} \ll \Lambda_{QCD} \]
Embedding quarkonium-nucleon into a Nonrelativistic nuclear many-body problem

\[ H = H_N + H_{\varphi N} \]

\[ H_{\varphi N} = \int d^3r \varphi^\dagger(t, \vec{r}) \left( -\frac{1}{2m_\varphi} \nabla^2 \right) \varphi(t, \vec{r}) \]

\[ + \int d^3r d^3r' N^\dagger(t, \vec{r}) \varphi^\dagger(t, \vec{r}') W_{\varphi N}(\vec{r} - \vec{r}') \varphi(t, \vec{r}') N(t, \vec{r}) \]

quarkonium-nucleon

G.K., A.W. Thomas & K. Tsushima, PPNP 100, 161 (2018)
Hartree-Fock equation
— for quarkonium in a nucleus

\[- \frac{1}{2m_\varphi} \nabla^2 \varphi_\alpha(\vec{r}) + W_{\varphi A}(\vec{r}) \varphi_\alpha(\vec{r}) = \epsilon_\alpha \varphi_\alpha(\vec{r}) \,\]

\[W_{\varphi A}(\vec{r}) = \int d^3 r' \, W_{\varphi N}(\vec{r} - \vec{r}') \, \rho_A(\vec{r}') \quad \text{quarkonium-nucleus potential}\]

\[\rho_A(\vec{r}) = \langle A | N^\dagger(\vec{r}) N(\vec{r}) | A \rangle = \sum_{n=1}^{A} N_n^*(\vec{r}) N_n(\vec{r}) \quad \text{nuclear density functional}\]

Neglecting back reaction of quarkonium on nucleons, take density from experiment, no need for a nuclear model
Need quarkonium-nucleon potential

\[ W_{\varphi A}(\vec{r}) = \int d^3r' W_{\varphi N}(\vec{r} - \vec{r}') \rho_A(\vec{r}') \]

From the forward amplitude:

\[ W_{\varphi N}^{\text{pol}}(\vec{r}) = \frac{4\pi}{2\mu_{\varphi N}} a_{\varphi N} \delta(\vec{r}) = -\frac{8\pi^2}{9} m_N \alpha_\varphi \delta(\vec{r}). \]

\[ W_{\varphi A}^{\text{pol}}(\vec{r}) = \frac{4\pi}{2\mu_{\varphi N}} a_{\varphi N} \rho_A(\vec{r}) = -\frac{8\pi^2}{9} m_N \alpha_\varphi \rho_A(\vec{r}). \]

\[ k \cotan \delta(k) = -\frac{1}{a} + \frac{1}{2} r_c k^2 + \cdots \]
J/Ψ in nuclei

--- nuclear potentials

Figure 8: J/Ψ nuclear potentials $W^{\text{pol}}_{J/Ψ A}(\vec{r})$ (solid line) for a polarizability $\alpha_{J/Ψ} = 1 \text{ GeV}^{-3}$ and $W^{\text{latt}}_{J/Ψ A}(\vec{r})$ (dashed line) from a fit to the lattice data with a cutoff $r_{vdW} = 0.5 \text{ fm}$.
**J/Ψ in nuclei**

— use scattering length only

Table 7: Predictions for J/Ψ single-particle energies in several nuclei obtained with the polarization potential $W_{J/Ψ}^{pol}(\vec{r})$, defined in Eq. (105).

<table>
<thead>
<tr>
<th></th>
<th>$^4\text{He}$</th>
<th>$^{12}\text{C}$</th>
<th>$^{16}\text{O}$</th>
<th>$^{40}\text{Ca}$</th>
<th>$^{48}\text{Ca}$</th>
<th>$^{90}\text{Zr}$</th>
<th>$^{208}\text{Pb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{J/Ψ} = 1 \text{ GeV}^{-3}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1s</td>
<td>n</td>
<td>-3.36</td>
<td>-4.41</td>
<td>-6.77</td>
<td>-6.84</td>
<td>-7.91</td>
<td>-8.38</td>
</tr>
<tr>
<td>1p</td>
<td>n</td>
<td>n</td>
<td>-0.39</td>
<td>-3.47</td>
<td>-3.95</td>
<td>-5.71</td>
<td>-7.05</td>
</tr>
<tr>
<td>2s</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>-0.26</td>
<td>-0.59</td>
<td>-2.70</td>
<td>-5.01</td>
</tr>
<tr>
<td>2p</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>-0.21</td>
<td>-2.94</td>
</tr>
<tr>
<td>3s</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>-0.70</td>
</tr>
</tbody>
</table>

| $\alpha_{J/Ψ} = 2 \text{ GeV}^{-3}$ |               |                 |                 |                 |                 |                 |                 |
| 1s     | -4.49         | -10.76          | -12.62          | -16.41          | -16.16          | -17.70          | -17.27          |
| 1p     | n             | -3.98           | -6.54           | -11.95          | -12.44          | -14.95          | -16.30          |
| 2s     | n             | n               | -0.54           | -6.74           | -7.50           | -11.07          | -13.95          |
| 2p     | n             | n               | n               | -1.62           | -2.52           | -7.33           | -11.41          |
| 3s     | n             | n               | n               | n               | n               | -2.71           | -8.28           |

$\alpha_{J/Ψ} = 1 \text{ GeV}^{-3} \leftarrow a_{J/ΨN} = -0.18 \text{ fm}$

$\alpha_{J/Ψ} = 2 \text{ GeV}^{-3} \leftarrow a_{J/ΨN} = -0.36 \text{ fm}$
Quarkonium-nucleus bound states from lattice QCD


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Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
Department of Physics, College of William and Mary, Williamsburg, Virginia 23187-8795, USA
Jefferson Laboratory, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA
Departament d’Estructura i Constituents de la Matèria and Institut de Ciències del Cosmos, Universitat de Barcelona, Martí i Franquès 1, Barcelona, 08028, Spain

Quarkonium-nucleus systems are composed of two interacting hadronic states without common valence quarks, which interact primarily through multigluon exchanges, realizing a color van der Waals force. We present lattice QCD calculations of the interactions of strange and charm quarkonia with light nuclei. Both the strangeonium-nucleus and charmonium-nucleus systems are found to be relatively deeply bound when the masses of the three light quarks are set equal to that of the physical strange quark. Extrapolation of these results to the physical light-quark masses suggests that the binding energy of charmonium to nuclear matter is $B_{\text{NM}}^{\text{phys}} \lesssim 40 \text{ MeV}$.

DOI: 10.1103/PhysRevD.91.114503

PACS numbers: 11.15.Ha, 12.38.Gc, 13.40.Gp
### TABLE I. Estimates for the binding energies of charmonium to light nuclei and nuclear matter (in MeV) from selected models. A “∗” indicates the system is predicted to be unbound, while entries with center dots indicate that the system was not addressed.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>$^3\text{He} \eta_c$</th>
<th>$^4\text{He} \eta_c$</th>
<th>NM $\eta_c$</th>
<th>$^4\text{He} J/\psi$</th>
<th>NM $J/\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>19</td>
<td>140</td>
<td>*</td>
<td>27</td>
<td>*</td>
</tr>
<tr>
<td>[2]</td>
<td>0.8</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>[5]</td>
<td>*</td>
<td>*</td>
<td>9</td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td>[7]</td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td>[8]</td>
<td></td>
<td></td>
<td></td>
<td>15.7</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE V. The binding energies (in MeV) of charmonium-nucleus systems calculated on the $L = 24$ and $32$ ensembles. The rightmost column shows the infinite-volume estimate, which, without results on the $L = 48$ ensemble, is taken to be the binding calculated on the $L = 32$ ensemble. The first and second sets of parentheses shows the statistical and quadrature-combined statistical plus systematic uncertainties, respectively.

<table>
<thead>
<tr>
<th>System</th>
<th>$24^3 \times 64$</th>
<th>$32^3 \times 64$</th>
<th>$L = \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N \eta_c$</td>
<td>17.9(0.4)(1.5)</td>
<td>19.8(0.7)(2.6)</td>
<td>19.8(2.6)</td>
</tr>
<tr>
<td>$d \eta_c$</td>
<td>39.3(1.3)(4.8)</td>
<td>42.4(1.1)(7.9)</td>
<td>42.4(7.9)</td>
</tr>
<tr>
<td>$p \eta_c$</td>
<td>37.8(1.1)(4.5)</td>
<td>41.5(1.0)(7.5)</td>
<td>41.5(7.6)</td>
</tr>
<tr>
<td>$^3\text{He} \eta_c$</td>
<td>57.2(1.3)(8.3)</td>
<td>56.7(2.0)(9.4)</td>
<td>56.7(9.6)</td>
</tr>
<tr>
<td>$^4\text{He} \eta_c$</td>
<td>70(02)(13)</td>
<td>56(06)(17)</td>
<td>56(18)</td>
</tr>
<tr>
<td>$^4\text{He} J/\psi$</td>
<td>75.7(1.9)(9.4)</td>
<td>53(07)(18)</td>
<td>53(19)</td>
</tr>
</tbody>
</table>
Can one do better?
Quarkonium-nucleon

Lattice

Chiral EFT

J.T. Castellà, GK
PRD (2018), arXiv: 1803.05412
Degrees of freedom & Scales & Power counting

DOF: nucleons, quarkonia, pions

Scales: $E_N, E_\phi \sim m_\pi \ll \Lambda_\chi \sim 1\text{GeV}$

Power counting: terms of the effective Lagrangian organized in powers of $\frac{m_\pi}{\Lambda_\chi}$

Loops: dimensional regularization
Quarkonium

\[ \mathcal{L}^\Phi = \phi^\dagger \left( i\partial_0 + \frac{\nabla^2}{2\hat{m}_\phi} \right) \phi \]

Nucleon-pion

\[ u^2 = U = e^{i\Phi/F}, \quad \Phi = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix} \]

\[ \mathcal{L}^N = N^\dagger \left( iD_0 + \frac{D^2}{2\hat{m}_N} \right) N - \frac{g_A}{2} N^\dagger u \cdot \sigma N \]

\[ u_\mu = i \{ u^\dagger, \partial_\mu u \} \quad D_\mu N = \partial_\mu N + \Gamma_\mu N \] \quad \Gamma_\mu = \frac{1}{2} [u^\dagger, \partial_\mu u] \]
Quarkonium-Pion

\[ \mathcal{L}^{\phi^+ - \pi^-} = \frac{F^2}{4} \phi^\dagger \phi \left( c_{d0} \langle u_0 u_0 \rangle + c_{di} \langle u_i u^i \rangle + c_m \langle \chi_+ \rangle \right) \]

\[ c_{d0} = -\frac{4\pi^2 \alpha_\phi}{b} \kappa_1 \]

\[ c_{di} = -\frac{4\pi^2 \alpha_\phi}{b} \kappa_2 \]

\[ c_m = -\frac{12\pi^2 \alpha_\phi}{b} \]

Chromopolarizability

\[ g^2 \langle \pi^+(p_1) \pi^-(p_2) | E_a^2 | 0 \rangle = \frac{8\pi^2}{3b} \left( (p_1 + p_2)^2 \kappa_1 + m_\pi^2 \kappa_2 \right) \]

\[ \kappa_1 = 1 - \frac{9\kappa}{4}, \quad \kappa_2 = 1 - \frac{9\kappa}{2} \quad b = \frac{11}{3} N_c - \frac{2}{3} N_f \]

\[ \kappa = 0.186 \pm 0.003 \pm 0.006 \]

\[ \alpha_\varphi = -\frac{2V_A^2 T_F}{3N_c} \langle \varphi | r^i \frac{1}{E_\varphi - h_0} r^i | \varphi \rangle \]
Quarkonium-Nucleon

\[ \mathcal{L}^{\phi-N} = -c_0 N^\dagger N \phi^\dagger \phi - d_m \langle \chi_+ \rangle N^\dagger N \phi^\dagger \phi - d_1 \nabla (N^\dagger N) \cdot \nabla (\phi^\dagger \phi) \]
\[ - d_2 \left( N^\dagger \vec{D} N \right) \cdot \left( \phi^\dagger \vec{\nabla} \phi \right) - d_3 D N^\dagger \cdot D N \phi^\dagger \phi \]
\[ - d_4 N^\dagger N \nabla \phi^\dagger \cdot \nabla \phi \]

\[ \chi_\pm = u^\dagger \chi u^\dagger \pm u \chi^\dagger u \quad \chi = 2B\hat{m} \mathbb{1} \quad m_u = m_d \equiv \hat{m} \]
Low-energy quarkonium-nucleon dynamics

Quarkonium-nucleon dynamics, e.g. bound to nucleus occurs at energies

\[ E_{\phi N} \sim \frac{k_{\phi N}^2}{2\mu_{\phi N}} < \frac{m_{\pi}^2}{\Lambda_{\chi}} \ll m_{\pi} \]

Integrate out the pion
Quarkonium-nucleon potential
— pQNEFT

Integrate out the pion

\[
\mathcal{L}^\text{pQNEFT} = N^\dagger \left( i\partial_0 + \frac{\nabla^2}{2m_N} \right) N + \phi^\dagger \left( i\partial_0 + \frac{\nabla^2}{2m_\phi} \right) \phi
\]

\[
- C_0 N^\dagger N \phi^\dagger \phi - D_1 \nabla \left( N^\dagger N \right) \cdot \nabla \left( \phi^\dagger \phi \right)
\]

\[
- D_2 \left( N^\dagger \nabla N \right) \cdot \left( \phi^\dagger \nabla \phi \right) - D_3 \nabla N^\dagger \cdot \nabla N \phi^\dagger \phi - D_4 N^\dagger N \nabla \phi^\dagger \cdot \nabla \phi
\]

\[
- \int d^3r N^\dagger N(t, \mathbf{x}_1) V(\mathbf{x}_1 - \mathbf{x}_2) \phi^\dagger \phi(t, \mathbf{x}_2)
\]
Matching

Renormalization of couplings + van der Waals

\[ C_0 = c_0 + 4m_\pi^2 d_m + \frac{9g_A^2 m_\pi^2 c_0}{64\pi^2 F^2} \left( \log \frac{m_\pi}{\nu} + \frac{2}{3} \right) + \frac{3g_A^2 m_\pi^3}{64\pi F^2} (5c_{di} - 3c_m) \]

\[ D_1 = d_1 + \frac{g_A^2 m_\pi}{256\pi F^2} (23c_{di} - 5c_m) \]

\[ D_j = d_j \quad \text{for} \quad j = 2, 3 \text{ and } 4 \]
Long-distance part of QN potential
— vdW force

\[ V(r) = \frac{3g_A^2 m_\pi^3}{128\pi^2 F^2 r^6} e^{-2m_\pi r} \left\{ c_{di} [6 + m_\pi r (2 + m_\pi r) (6 + m_\pi r (2 + m_\pi r))] \right. \]

\[ + c_m m_\pi^2 r^2 (1 + m_\pi r)^2 \} \]

No free parameters here:
— trace anomaly
— chiral physics

First, model-independent derivation of a quarkonium-nucleon van der Waals force
For \( r \gg \frac{1}{2m_\pi} \):

\[
V(r) = \frac{3g_A^2 m_\pi^4 (c_{di} + c_m)}{128\pi^2 F^2} \frac{e^{-2m_\pi r}}{r^2}
\]

To extrapolate lattice data to physical quark masses, need:

\[
m_N = \hat{m}_N - 4c_1 m_\pi^2 - \frac{3g_A^2 m_\pi^3}{32\pi F^2}
\]

\[
m_\phi = \hat{m}_\phi - F^2 c_m m_\pi^2
\]
Unknown contact couplings
— get them from lattice QCD

<table>
<thead>
<tr>
<th>Reference</th>
<th>Channel</th>
<th>$a_0$ [fm]</th>
<th>$c_0$ [GeV$^{-2}$]</th>
<th>$d_m$ [GeV$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSF</td>
<td>$\eta_c$</td>
<td>$-0.70(66)$</td>
<td>$-31(29)$</td>
<td>Quenched</td>
</tr>
<tr>
<td></td>
<td>$J/\psi$</td>
<td>$-0.71(48)$</td>
<td>$-31(21)$</td>
<td></td>
</tr>
<tr>
<td>LLE</td>
<td>$\eta_c$</td>
<td>$-0.39(14)$</td>
<td>$-17(6)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$J/\psi$</td>
<td>$-0.39(14)$</td>
<td>$-17(6)$</td>
<td></td>
</tr>
<tr>
<td>[29]</td>
<td>$\eta_c$</td>
<td>$-0.25(5)$</td>
<td>$-8(2)$</td>
<td>Quenched</td>
</tr>
<tr>
<td></td>
<td>$J/\psi$</td>
<td>$-0.35(6)$</td>
<td>$-12(3)$</td>
<td></td>
</tr>
<tr>
<td>[28]</td>
<td>$\eta_c$</td>
<td>$-0.18(9)$</td>
<td>$9.7(1.2)$</td>
<td>$14.7(4.8)$</td>
</tr>
<tr>
<td></td>
<td>$J/\psi$</td>
<td>$-0.40(80)$</td>
<td>$-12(18)$</td>
<td>$-100(80)$</td>
</tr>
<tr>
<td>[12]</td>
<td>$\alpha J/\psi$</td>
<td>[GeV$^{-3}$]</td>
<td>$-0.37$</td>
<td>$-16.5$</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.24</td>
<td></td>
<td>$-0.05$</td>
<td>$-2.0$</td>
</tr>
</tbody>
</table>

Lattice:
Comparing long distance part with HAL lattice potential

Kanaway & Sasaki, PRD 82, 091501 (2010)
vdW force

\[ \eta_c - N \]

Lattice:
T. Kawanay & S. Sasaki, Pos (Lattice) 2010, 156 (2010)
vdW force

\[ J/\Psi - N \]

Lattice:

T. Kawanay & S. Sasaki, Pos (Lattice) 2010, 156 (2010)
# Fits of the polarizabilities

<table>
<thead>
<tr>
<th>$\beta_{\eta_c} = 0.17 \text{ GeV}^{-3}$</th>
<th>$c_{d0} \text{ [GeV}^{-3}\text{]}$</th>
<th>$c_{di} \text{ [GeV}^{-3}\text{]}$</th>
<th>$c_m \text{ [GeV}^{-3}\text{]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{J/\psi} = 0.24 \text{ GeV}^{-3}$</td>
<td>-0.83</td>
<td>-1.71</td>
<td>-2.24</td>
</tr>
<tr>
<td></td>
<td>-1.17</td>
<td>-2.42</td>
<td>-3.16</td>
</tr>
</tbody>
</table>

Table II. Values of the pion-quarkonium couplings according to the expressions in Eq. (5) for the values of the polarizabilities, in Eq. (29), obtained from the fit of the potential to the lattice data of Ref. Kawanai:2010ev.

**Change of notation**

$\alpha_\varphi \rightarrow \beta_\varphi$
Are there quarkonium-nucleon bound states at this order in pQNEFT?

Scattering amplitude (s-wave)

\[ A = \frac{2\pi}{\mu_N} \frac{1}{p \cot \delta - ip} = \frac{2\pi}{\mu_N} \frac{1}{-\frac{1}{a_0} + \frac{1}{2} r_0 p^2 + \ldots} \]

\[ a_0 = \frac{\mu_N}{2\pi} \left[ c_0 + 4d_m m_\pi^2 + \frac{9g_A^2 m_\pi^2 c_0}{64\pi^2 F^2} \left( \log \frac{m_\pi^2}{\nu^2} + \frac{2}{3} \right) + \frac{3g_A^2}{64\pi F^2 m_\pi} (5c_{di} - 3c_m) \right] \]

\[ r_0 = \frac{8\pi}{\mu_N c_0^2} \left[ (d_1 + d_2) + \frac{g_A^2}{256\pi F^2} m_\pi (23c_{di} - 5c_m) \right] \]

No quarkonium-nucleon bound states within the applicability of the present calculation:

\[ |p_{\phi N}| \leq m_\pi \]
Are there quarkonium-nucleus bound states at this order in pQNEFT?

YES, for sufficiently large nuclei
Experiments
— JLab

J/ψ photoproduction at GlueX

Preliminary 2016 + 2017 (20%)

No. of J/ψ: 149 ± 37
mean: 3.09 ± 0.001
sigma: 0.0073 ± 0.0017

σ(π → J/ψ) Arbitrary Units

σ(π → J/ψ) nb

E_γ GeV

8 10 12 14 16 18 20 22

10^-1

SLAC 75
Cornell 75
Brodsky 2001 (2-gluon exchange)
ATHENNA* collaboration JLab @ 12 GeV

Hall A — E12-12-006
K. Hafidi, Z.-E. Meziani, N. Sparveris, Z.W. Zhao

Hall C — E-12-16-007 (Pentaquarks)

*A J/Ψ THreshold Electroproduction on the Nucleon and Nuclei Analysis
How About coalescence at the LHC?

— Chances of a charmed hadron meeting one or two nucleons not smaller than of two antinucleons and one antihyperon meeting to form an antihypernucleus

Need to detect in coincidence the decay products
Antiproton annihilation on deuteron, $J/\Psi$ re-scattering on spectator nucleon

@ FAIR
Funding