(Some) Theoretical Aspects on Open Charm Spectroscopy and Production

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Spectroscopy

✦ $c\bar{q}$  $c\bar{s}$

✦ Hadron Molecule

✦ Tetraquark

Production

✦ Approach for Molecule

✦ QCD factorization

✦ B decays
Open Charm Spectroscopy
Quark model has predicted a number of states with different quantum numbers. 

Quark model has predicted a number of states with different quantum numbers.

We used our results to identify recently observed charm and charm-strange mesons in terms of quark model spectroscopic states. Our results support the previously made assignment of the $D_{j}(2550)^{0}$ and $D_{j}^{*}(2600)^{0}$ as the $2^1S_{0}(c\bar{q})$ and $2^3S_{1}(c\bar{q})$ states respectively. We identify the $D_{1}^{*}(2760)^{0}$ and $D_{3}^{*}(2760)^{0}$ as the $1^3D_{1}(c\bar{q})$ and $1^3D_{3}(c\bar{q})$ respectively and tentatively identify the $D_{j}(2750)^{0}$ as the $1D_{2}(c\bar{q})$ state. In the latter case further measurements are needed to strengthen the assignment. We suggested that measurements of BRs to $D\rho$ and $D^*\pi$ would be useful. We tentatively identified the $D_{j}^{*}(3000)^{0}$ as the $D_{4}^{*}(1^3F_{4})$ state and favor the $D_{j}(3000)^{0}$ to be the $D(3^1S_{0})$ although we do not rule out the $1F_{3}$ and $1F_{5}$ assignments. For the recently observed charm-strange mesons we identify the $D_{s1}^{*}(2709)^{\pm}$, $D_{s1}(2860)^{-}$, and $D_{s3}^{*}(2860)^{-}$ as the $2^3S_{1}(c\tau)$, $1^3D_{1}(s\tau)$, and $1^3D_{3}(s\tau)$ respectively and suggest that the $D_{s2}(3044)^{\pm}$ is most likely the $D_{s1}(2P_{1}^{1})$ or $D_{s1}(2P_{1}^{1})$ although it might be the $D_{s2}(2^3P_{2})$ with the $DK$ final state too small to be observed with current statistics.
Data Vs Quark Model

$D_{s0}^* : 2484 \text{ MeV}$

$D_{s1} : 2549 \text{ MeV}$

$\Gamma = 220 \text{ MeV}$  \hspace{1cm} $\Gamma < 3.8 \text{ MeV}$

✓$D_{s0}(2317)$ and $D_{s1}(2460)$ are lighter and narrower than expected from quark models!
QCD allows many possible color singlets:

- Tetraquark
- Hadron Molecule
Hadron Molecule

- Hadronic molecule:
  the dominant component is 2 or more hadrons

- Concept at large distances, so that can be approximated by system of multi-hadrons at low energies

Consider a 2-body bound state with a mass \( M = m_1 + m_2 - E_B \)

size: \( R \sim \frac{1}{p} \sim \frac{1}{\sqrt{2\mu E_B}} \gg r_{\text{hadron}} \)

- Only narrow hadrons can be considered as components of hadronic molecules, \( \Gamma_h \ll 1/r, r: \text{range of forces} \)

Ds0(2317): DK; Ds1(2460): D*K
Hadron Molecule

\[ T = V + VG + GGV + GGGV + \ldots \]

Summing All order contributions:

\[ V + VGV + VGVGV + \cdots = \frac{V}{1 - GV} \]

\[ 1 - GV = 0 \]

\[ s = s_0 \]

Mass pole corresponds to a resonance structure

\[ \rightarrow \text{Hadron Molecule} \]
Hadron EFT can be used to study the DK scattering:

![Images of graphs showing scattering amplitudes vs. pion mass](image)

Yao, et al. 1502.05981

Graham Moir, Charmed Meson Scattering from Lattice QCD

**S-wave**

- **Bound-state** pole ≈ 2380 MeV; ≈ 55 MeV below DK threshold (at \( m_\pi = 391 \))

- Expt. \( D_{s0}^*(2317) \): 2317.7 ± 0.6 MeV; ≈ 45 MeV below DK threshold
A lot of versions for tetraquarks!

Tetraquark

In a constituent (di)quark model, we can think of a diquark-antidiquark compact state

\[[cq]_{S=0} [\bar{c}\bar{q}]_{S=1} + \text{h.c.}\]

Maiani, Piccinini, Polosa, Riquer PRD71 014028
Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 111102
Maiani, Piccinini, Polosa, Riquer PRD89 114010

Spectrum according to color-spin hamiltonian
(all the terms of the Breit-Fermi hamiltonian are absorbed into a constant diquark mass):

\[H = \sum_{dq} m_{dq} + 2 \sum_{i<j} \kappa_{ij} \bar{S}_i \cdot \bar{S}_j \frac{\lambda_i^a \lambda_j^a}{2} \]

Decay pattern mostly driven by HQSS ✓
Fair understanding of existing spectrum ✓
A full nonet for each level is expected ✗

New ansatz: the diquarks are compact objects spacially separated from each other,
only \(\kappa_{cq} \neq 0\)
Existing spectrum is fitted if \(\kappa_{cq} = 67\) MeV

A. Pilloni – Introduction to charmonium and exotic physics
form a fit in the restricted range of data below the threshold.

Such as background processes not present in our MC calculations, gain extraction using the default background model. Additional contribution from a ground function that agrees with data for masses above 10 GeV/c^2.

These results confirm the use of a background function that gives a signal to background ratio greater than those with the default background function for events due to the X(5568) state mass, natural width, and the yield for the no-cone cut case.

For the X(5568) signal, the production in generating the mass spectrum is performed using different models of bottom pair production, with an average of (8.6 ± 1.9)% reduction in generating the ratio of the MC to the sideband events within 1σ. The Wigner function, a third-order polynomial, and a fourth-order polynomial in Eq. (1) with a third-order polynomial in the exponential are used.

The invariant mass spectra of the X(5568) state are measured with the ratio of the MC to the sideband events within 1σ. The systematic uncertainties due to the signal shape are evaluated using the ratio of the MC to the sideband events within 1σ. The stability of the result is verified by examining subsets with different signs of the fit and different models of bottom pair production. The look-elsewhere effect is included, and the significance of the observed signal, including the look-elsewhere effect, is calculated.

The uncertainties are added in quadrature separately for positive and negative values. The uncertainties are added in quadrature separately for positive and negative values. The uncertainties are added in quadrature separately for positive and negative values. The uncertainties are added in quadrature separately for positive and negative values. The uncertainties are added in quadrature separately for positive and negative values. The uncertainties are added in quadrature separately for positive and negative values. The uncertainties are added in quadrature separately for positive and negative values.

For the X(5568) state, LHCb did not confirm, as reported in 1608.00435. How about the charm sector?

D0: 1602.07588

LHCb did not confirm, 1608.00435
Open Charm Tetraquarks

\[3 \otimes 3 \otimes \bar{3} = 3 \oplus 3 \oplus \bar{6} \oplus 15\]

**Sextet:**

\[
m(X'_{ds\bar{u}}) = m(X'_{sud}) = m(Y'_{(u\bar{u},d\bar{d})s}) = \begin{cases} 
2.44\text{GeV} , & J^P = 0^+ , \\
2.48\text{GeV} , & J^P = 1^+ , 
\end{cases}
\]

\[
m(X'_{uds}) = \begin{cases} 
2.36\text{GeV} , & J^P = 0^+ , \\
2.41\text{GeV} , & J^P = 1^+ , 
\end{cases}
\]

\[
m(Y'_{(u\bar{u},s\bar{s})d}) = m(Y'_{(d\bar{d},s\bar{s})u}) = \begin{cases} 
2.40\text{GeV} , & J^P = 0^+ , \\
2.45\text{GeV} , & J^P = 1^+ . 
\end{cases}
\]

**15-plet:**

\[
m(X_{ds\bar{u}}) = m(X_{sud}) = m(Y_{\pi s}) = \begin{cases} 
2.47\text{GeV} , & J^P = 0^+ , \\
2.51\text{GeV}, 2.60\text{GeV} , & J^P = 1^+ , \\
2.67\text{GeV} , & J^P = 2^+ , 
\end{cases}
\]

\[
m(X_{uds}) = m(Z_{u\bar{u}s}) = m(Z_{d\bar{d}s}) = \begin{cases} 
2.49\text{GeV} , & J^P = 0^+ , \\
2.52\text{GeV}, 2.61\text{GeV} , & J^P = 1^+ , \\
2.69\text{GeV} , & J^P = 2^+ , 
\end{cases}
\]

**All can be produced in B decays!!**

*He, WW, Zhu, 1606.00097*
Open Charm Production

Andrea Beraudo
Open charm physics with Heavy Ions: theoretical overview
In the past charm conferences, there are rare theoretical talks on open charm productions.
In the past charm conferences, there are rare theoretical talks on open charm productions.

➡ The production is not interesting/important?

➡ The production mechanism is too simple for every participant?

➡ The production mechanism is too difficult?
Is the production interesting/important? Yes!

Experimental talks:

❖ Achim Geiser, Charm production at HERA, proton structure, the charm mass, and Higgs Yukawa couplings
❖ Bilas Pal, Open charm Production and Spectroscopy at B-factories
❖ George Wei-Shu Hou, Open charm production and spectroscopy at ATLAS and CMS
❖ Patrick Spradlin, Open charm production and spectroscopy at LHCb
❖ …
The production mechanism is too simple for every participant?
The production mechanism is too simple for every participant?

A few simplest example:

\[ pp \rightarrow D_{s0}^*(2317) \]

\[ e^+e^-\rightarrow D_sD_{s0}^*(2317) \]
The production mechanism is too simple for every participant?

A few simplest example:

\[ pp \rightarrow D_{s0}^*(2317) \]

\[ e^+e^- \rightarrow \rho\pi \]

\[ e^+e^- \rightarrow D_sD_{s0}^*(2317) \]

SCET

???

NRQCD
Prompt production of $X(3872)$

$X(3872)$ is the Queen of exotic resonances, the most popular interpretation is a $D^0\bar{D}^{0*}$ molecule (bound state, pole in the 1st Riemann sheet?) but it is copiously promptly produced at hadron colliders.

$\sigma_{MC}(p\bar{p} \to DD^* | k < k_{max}) \approx 0.1 \text{ nb}$

$\sigma_{exp}(p\bar{p} \to X(3872)) \approx 30 - 70 \text{ nb!!}$

Bignamini et al. PRL103 (2009) 162001

A solution can be FSI (rescattering of $DD^*$), which allow $k_{max}$ to be as large as $5m_\pi$.

$\sigma(p\bar{p} \to DD^* | k < k_{max}) \approx 230 \text{ nb}$

Artoisenet and Braaten, PRD81, 114018

However, the rescattering is flawed by the presence of pions that interfere with $DD^*$ propagation. Estimating the effect of these pions increases $\sigma$, but not enough.

Bignamini et al. PLB684, 228-230
Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003
A key assumption:

\[ \sigma(p\bar{p} \to X(3872)) \leq \int d^3k \left| \langle DD^*(k) | p\bar{p} \rangle \right|^2 \]

Production rate of X(3872) is equivalent to production rate of the DD* in limited phase space

**Local Constituent-Molecule Duality**

Production rate of a hadron is equivalent to that of quark pairs
The Born cross section of $e^+e^-$ annihilation into hadrons normalized by theoretical $\mu^+\mu^-$ cross section.

\[ R = \frac{\sigma_{\text{had}}^0(e^+e^- \rightarrow \gamma^* \rightarrow \text{hadrons})}{\sigma_{\mu\mu}^0(e^+e^- \rightarrow \gamma^* \rightarrow \mu^+\mu^-)} \]

\[ R \equiv \sum Q_f^2 \]

\[ 3 \left[ \left( \frac{2}{3} \right)^2 + \left( \frac{1}{3} \right)^2 + \left( \frac{1}{3} \right)^2 \right] = 2 \]

\[ 3 \left[ \left( \frac{2}{3} \right)^2 + \left( \frac{1}{3} \right)^2 + \left( \frac{1}{3} \right)^2 + \left( \frac{2}{3} \right)^2 + \left( \frac{1}{3} \right)^2 \right] = \frac{11}{3} \]
See Xiaoyan Shen’s talk on BES-III
Color Evaporation Model

- Fritsch (1977); Halzen (1977); Glück, Owens, Reya (1978):
  \[ \sigma = F_H \int \frac{(2m_D)^2}{(2m_c)^2} \frac{d\sigma_{c\bar{c}}}{dm^2_{c\bar{c}}} \]

- Consider open $c+\bar{c}$ production, regardless of $c+\bar{c}$ color, spin, momenta.
- Integrate over invariant $c+\bar{c}$ mass up to formation of next heavier meson pair.
- $F_H$: Number describing formation of quarkonium $H$ by color "evaporation".
- Qualitative picture rather than rigorous theory.

CEM Predictions
For RHIC data
[Nelson, Voigt, Frawley (2013)]:

For $X(3872)$, this amounts to adjust the phase-space cutoff

Artoisenet, Braaten, 0911.2016;1007.2868
NRQCD

\[ \sigma(H) = \sum F_n(\Lambda) \langle 0 | \mathcal{O}_n^H(\Lambda) | 0 \rangle. \]
\[ \mathcal{O}_n^H(\Lambda) = \langle 0 | \chi^\dagger \kappa_n \psi \left( \sum \chi |H + X\rangle \langle H + X| \right) \psi^\dagger \kappa'_n \chi |0\rangle \]

Bodwin, Braaten, Lepage, Brambilla, et al.

Hadron Level EFT

\[ \sigma(D_{s0}) \sim \sigma(DK) \langle D_{s0} | DK | 0 \rangle^2 \]
\[ \Gamma + \Gamma G V + \Gamma G V G V + \ldots = \frac{\Gamma}{1 - GV} \]

\( \Gamma \) is tree-level amplitude

\[ 1 - GV = 0 \]

Herwig/Pythia: simulate production rates of constituents
Hadron Molecule Production at Hadron Collider

Table 2. Integrated normalized cross sections (in units of µb) for the inclusive processes $pp \rightarrow D_{s0}^{*}(2317), D_{s1}(2460), D_{s0}(2860)$ and $D_{s2}(2910)$ at LHC. The results outside (inside) brackets are obtained using Herwig (Pythia). Here the rapidity range $|y| < 2.5$ has been assumed for the LHC experiments (ATLAS and CMS), while the rapidity range $2.0 < y < 4.5$ is used for the LHCb.

<table>
<thead>
<tr>
<th></th>
<th>$D_{s0}^{*}(2317)$</th>
<th>$D_{s1}(2460)$</th>
<th>$D_{s0}(2860)$</th>
<th>$D_{s2}(2910)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC 7</td>
<td>2.5(0.83)</td>
<td>2.1(0.91)</td>
<td>0.21(-)</td>
<td>0.27(-)</td>
</tr>
<tr>
<td>LHCb 7</td>
<td>0.61(0.15)</td>
<td>0.5(0.17)</td>
<td>0.05(-)</td>
<td>0.06(-)</td>
</tr>
<tr>
<td>LHC 8</td>
<td>2.9(0.94)</td>
<td>2.4(1.0)</td>
<td>0.24(-)</td>
<td>0.32(-)</td>
</tr>
<tr>
<td>LHCb 8</td>
<td>0.74(0.18)</td>
<td>0.61(0.2)</td>
<td>0.06(-)</td>
<td>0.08(-)</td>
</tr>
<tr>
<td>LHC 14</td>
<td>5.5(1.6)</td>
<td>4.7(1.7)</td>
<td>0.5(-)</td>
<td>0.65(-)</td>
</tr>
<tr>
<td>LHCb 14</td>
<td>1.6(0.35)</td>
<td>1.3(0.38)</td>
<td>0.13(-)</td>
<td>0.17(-)</td>
</tr>
</tbody>
</table>

Guo, Meissner, WW, Yang, 1403.4032
\[
\frac{d\sigma}{dk}(DK) \quad \text{(\mu b/GeV)}
\]

**Table:**

<table>
<thead>
<tr>
<th>[ pp/\bar{p}\bar{p} \to X(3872) ]</th>
<th>Reference [16]</th>
<th>Reference [18]</th>
<th>[ \Lambda = 0.5 \text{ GeV} ]</th>
<th>[ \Lambda = 1 \text{ GeV} ]</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>(&lt;0.085)</td>
<td>1.5–23</td>
<td>10 (7)</td>
<td>47 (33)</td>
<td>37–115 [43]</td>
</tr>
<tr>
<td>LHC7</td>
<td>(&lt;)</td>
<td>45–100(^a)</td>
<td>16 (7)</td>
<td>72 (32)</td>
<td>13–39 [6]</td>
</tr>
</tbody>
</table>

\(^a\) Estimate based on non-relativistic QCD

*Guo, Meissner, WW, Yang, 1402.6236*
B decays
Three-body B decays
Consider a generic correlation function

\[ \Pi(p_{K\pi}, q) = i \int d^4x e^{iq \cdot x} \langle (K\pi)_0(p_{K\pi})|T \{ j_{\Gamma_1}(x), j_{\Gamma_2}(0) \}|0 \rangle \]

**Hadron level:**

\[
\frac{\langle (K\pi)_0(p_{K\pi})|j_{\Gamma_1}|\overline{B}(p_{K\pi}+q)\rangle \langle \overline{B}(p_{K\pi}+q)|j_{\Gamma_2}|0 \rangle}{m_B^2 - (p_{K\pi}+q)^2} + \int_{s_0}^{\infty} ds \frac{\rho^h(s,q^2)}{s - (p_{K\pi}+q)^2},
\]

**Quark level:** Light cone OPE

\[
\langle (K\pi)_0|\bar{s}(x)\gamma_\mu d(0)|0 \rangle
\]

\[
\langle (K\pi)_0|\bar{s}(x)\sigma_{\mu\nu} d(0)|0 \rangle
\]

**Quark-Hadron Duality**

Meissner, WW, 1312.3087
Scalar form factors

\[ \langle 0| \bar{s}d| K\pi \rangle = C_X B_0 F_{K\pi}(m_{K\pi}^2) \]

\[ \text{In elastic region:} \]

\[ \text{Im}[F] = F \sigma_i T^* \]

\( F \) and \( T \) carry the same strong phase!
Scalar form factors in $\chi$PT

\[ \langle 0 | \bar{s}d | K\pi \rangle = C X B_0 F_{K\pi} (m_{K\pi}^2) \]

twice-subtracted Omnes solution matched onto $\chi$PT

Imaginary part
Real part
Magnitude
It simultaneously combines the perturbation theory at the \( m_b \) scale based on the operator product expansion and the low-energy effective theory inspired by the chiral symmetry to describe the S-wave \( \pi\pi \) and \( K\pi \) scattering.
$B_s \rightarrow \pi^+\pi^-\mu^+\mu^-$ & $D_s \rightarrow \pi^+\pi^-\text{ev}$

Y.J. Shi, WW, 1507.07692

$B_s \rightarrow \pi^+\pi^-\mu^+\mu^-$ LHCb:1412.6433

$D_s \rightarrow \pi^+\pi^-\text{ev}$ CLEO:0907.3201

BES-III & Belle-II?
B decays into $D_{s0}(2317)$

$\rightarrow e^+e^- \rightarrow D_{s0}(2317)\ D_s$ at Belle-II?
Summary

Open Charm Spectroscopy
- Quark Model
- Hadron Molecule
- Tetraquark

Production
- Hadron Level Approach
- QCD factorization
- B decays

Apologize for a lot others not covered here

Many thanks for your attention!