A New Dynamical Picture for Production and Decay of the XYZ Mesons

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Outline

1) The forest of exotics $X,Y,Z$

2) How are the tetraquarks assembled?

3) A new dynamical picture for the $X,Y,Z$

4) Puzzles resolved by the new picture

5) Next directions: Using constituent counting rules

6) Conclusions
Charmonium: November 2014
Esposito et al., 1411.5997

Black: Observed conventional $c\bar{c}$ states
Blue: Predicted conventional $c\bar{c}$ states
Red: Exotic $c\bar{c}$ states
How are tetraquarks assembled?

Trouble with the dynamical pictures

• Hybrids
  – Neutral states only; what are the $Z$'s?
  – Only certain quantum numbers (e.g., $J^{PC} = 1^{++}$) easily produced

• Diquark and hadrocharmonium pictures
  – What keeps states from instantly segregating into meson pairs?
  – Diquark models tend to overpredict the number of bound states
  – Why wouldn’t hadrocharmonium *always* decay into charmonium, instead of $D\bar{D}$?

• Cusp effect
  – Might be able to generate some resonances on its own, but >20 of them? And certainly not ones as narrow as $X(3872)$ ($\Gamma < 1.2$ MeV)
The hadron molecular picture

- Several XYZ states are *suspiciously* close to hadron thresholds
  - e.g., \( m_{X(3872)} - m_{D^{*0}} - m_{D^0} = -0.11 \pm 0.21 \text{ MeV} \)

- So we theorists have *hundreds* of papers analyzing the XYZ states as dimeson molecules

- But not all of them are!
  - e.g., \( Z(4475) \) is a prime example

- Also, some XYZ states lie slightly *above* a hadronic threshold
  - e.g., \( Y(4260) \) lies about 30 MeV above the \( D_{s}^{*} \bar{D}_{s}^{*} \) threshold
  - How can one have a bound state with *positive* binding energy?
Prompt production

- If hadronic molecules are really formed, they must be very weakly bound, with very low relative momentum between their mesonic components.
- They might appear in $B$ decays, but would almost always be blown apart in collider experiments.
- But CDF & CMS saw lots of them! [Prompt $X(3872)$ production, $\sigma \approx 30$ nb]
  - CMS Collaboration (S. Chatrchyan et al.), JHEP 1304, 154 (2013)
- Perhaps final-state interactions due to $\pi$ exchange between $D^0$ and $\bar{D}^{*0}$?
  - P. Artoisenet and E. Braaten, Phys. Rev. D 81, 114018 (2010); D 83, 014019 (2011)
- Such effects can be significant, but do not appear to be sufficient to explain the size of the prompt production
  - Hadronic molecules may exist, but $X(3872)$ does not seem to fit the profile
Amazing (well-known) fact about color:

- The short-distance color attraction of combining two color-$\mathbf{3}$ quarks into a color-$\mathbf{\bar{3}}$ diquark is fully half as strong as that of combining a $\mathbf{3}$ and a $\mathbf{\bar{3}}$ into a color singlet (i.e., diquark attraction is nearly as strong as the confining attraction).

- Just as one computes a spin-spin coupling,
\[
\mathbf{s}_1 \cdot \mathbf{s}_2 = \frac{1}{2} \left[ (\mathbf{s}_1 + \mathbf{s}_2)^2 - \mathbf{s}_1^2 - \mathbf{s}_2^2 \right],
\]
from two particles in representations $\mathbf{1}$ and $\mathbf{2}$ combined into representation $\mathbf{1+2}$,

- The generic rule in terms of quadratic Casimir $C_2$ of representation $R$ is
\[
\frac{1}{2} \left[ C_2(R_{1+2}) - C_2(R_1) - C_2(R_2) \right];
\]
this formula gives the result stated above.
A new tetraquark picture
Stanley J. Brodsky, Dae Sung Hwang, RFL

• CLAIM: At least some of the observed tetraquark states are bound states of diquark-antidiquark pairs
• BUT the pairs are not in a static configuration; they are created with a lot of relative energy, and rapidly separate from each other
• Diquarks are not color singlets! They are in either a $\bar{3}$ (attractive) or a 6 (repulsive) and cannot, due to confinement, separate asymptotically far
• They must hadronize via large-$r$ tails of mesonic wave functions, which suppresses decay widths
• Want to see this in action? Time for some cartoons!
Nonleptonic $\bar{B}^0$ meson decay

B.R.$\sim 22\%$

Powerpoint version containing animations available by request, richard.lebed@asu.edu
What happens next?
Option 1: Color-allowed

B.R. \( \sim 5\% \)
(& similar 2-body)
What happens next?
Option 1: Color-allowed

B.R.~5%
(& similar 2-body)

Each has $P$ 
~1700 MeV

$D_s^{(*)-}$ $\bar{D}^{(*)0}$
What happens next?
Option 2: Color-suppressed

B.R. ~2.3%
What happens next?

Option 2: Color-suppressed

B.R. $\sim$ 2.3%

$\bar{K}^{(*)0}$
What happens next?
Option 3: Diquark formation

\[ K^{(*)-} \]
What happens next?
Option 3: Diquark formation

$K^{(*)-}$
Driven apart by kinematics, yet bound together by confinement, our star-crossed diquarks must somehow hadronize as one.
Why doesn’t this just happen?
It’s called baryonium

It *does* happen, as soon as the threshold $2M_{\Lambda_c} = 4573$ MeV is passed.
The lightest exotic above this threshold, $X(4632)$, decays into $\Lambda_c + \bar{\Lambda}_c$. 
How far apart do the diquarks actually get?

• Since this is still a $3 \leftrightarrow \bar{3}$ color interaction, just use the Cornell potential:

$$V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + br + \frac{32\pi \alpha_s}{9m_{cq}^2} \left( \frac{\sigma}{\sqrt{\pi}} \right)^3 e^{-\sigma^2 r^2} \mathbf{s}_{cq} \cdot \mathbf{s}_{\bar{cq}},$$

[This variant: Barnes et al., PRD 72, 054026 (2005)]

• Use that the kinetic energy released in $\bar{B}^0 \rightarrow K^- + Z^+(4475)$ converts into potential energy until the diquarks come to rest

• Hadronization most effective at this point (WKB turning point)

$r_Z = 1.16 \text{ fm}$
Fascinating $Z(4475)$ fact:

Belle [K. Chilikin et al., PRD 90, 112009 (2014)] says:

$$\frac{\text{B. R.} [Z^- (4475) \rightarrow \psi(2S)\pi^-]}{\text{B. R.} [Z^- (4475) \rightarrow J/\psi\pi^-]} > 10$$

and LHCb has never even reported seeing the $J/\psi$ mode

$$\langle r_{\psi(2S)} \rangle = 0.80 \text{ fm}$$

$$\langle r_{J/\psi} \rangle = 0.39 \text{ fm}$$

$$r_Z = 1.16 \text{ fm}$$
The large-\(r\) wave function tails and resonance widths

- The simple fact that the diquark-antidiquark pair is capable of separating further than the typical mean size of ordinary hadrons before coming to rest implies:
  - The hadronization overlap matrix elements are suppressed, SO
  - The hadronization rate is suppressed, SO
  - The width is smaller than predicted by generic dimensional analysis (i.e., by phase space alone)

- \textit{e.g.}, \(\Gamma[Z(4475)] = 180 \pm 31\) MeV
  (\textit{cf.} \(\Gamma[\rho(770)] = 150\) MeV)

- But why would these diquark-antidiquark states behave like resonances at all?
For one thing,

- Diquark-antidiquark pairs create their own bound-state spectroscopy [L. Maiani et al., PRD 71 (2005) 014028]

- Original 2005 version predicts states with quantum numbers and multiplicities not found to exist, but a new version of the model [L. Maiani et al., PRD 89 (2014) 114010] appears to be much more successful

  - *e.g.*, \( Z(4475) \) is radial excitation of \( Z(3900) \); \( Y \) states are \( L=1 \) color flux tube excitations
And furthermore,

- The presence of nearby hadronic thresholds can attract nearby diquark resonances: *Cusp effect*
The Cusp

\[ P(s) = \frac{i}{s - M_0^2 + \Pi(s)} \]

(Normalized to unity at \( s_{th} \))
Example cusp effects
S. Blitz & RFL, arXiv:1503.04802
(accepted to appear in PRD)

\(M_0\): Bare resonant pole mass
\(S_{th}\): Threshold s value [here \((3.872 \text{ GeV})^2\)]
\(M_{pole}\): Shifted pole mass

Relative size of pole shift (about 0.12% near \(S_{th}\), or 5 MeV)

At the charm scale, a cusp from an opening diquark pair threshold is more effective than one from a meson pair!
How closely can cusps attract thresholds?

• Consider the \( X(3872) \), with \( \Gamma < 1.2 \text{ MeV} \)
  
  – Recall \( m_{X(3872)} - m_{D^*} - m_{D^0} = -0.11 \pm 0.21 \text{ MeV} \)
  
  – Also,
    \[
    m_{X(3872)} - m_{J/\psi} - m_{\rho_{\text{peak}}} = -0.50 \text{ MeV}
    \]
    \[
    m_{X(3872)} - m_{J/\psi} - m_{\omega_{\text{peak}}} = -7.89 \text{ MeV}
    \]
  
    \( X(3872) \) is far too narrow to be a cusp alone—\( X(3872) \) is far too narrow to be a cusp alone—
    Some sort of resonance must be present
  
  – Several channels all open up very near 3.872 GeV
  
  ➢ All contribute to a big cusp that can drag diquark-antidiquark resonance from perhaps 10’s of MeV away to become the \( X(3872) \)
What determines cusp shapes?

- **Mesons:** Traditional phenomenological exponential form factor:
  \[ F_{\text{mes}}^2(s) = \exp \left( -\frac{s - s_{th}}{\beta^2} \right), \]
  where \( \beta \) is a typical hadronic scale (~0.5-1.0 GeV)

- **High-energy \( s \) processes, or when large-\( s \) tails of form factors important (as in dispersion relations): Use *constituent counting rules* [Matveev *et al.*, Lett. Nuovo Cim. 7, 719 (1973); Brodsky & Farrar, PRL 31, 1153 (1973)]

- In hard processes in which constituents are diverted through a finite angle, each virtual propagator redirecting them contributes a factor \( 1/s \) (or \( 1/t \))

  - Form factor \( F(s) \) of particle with 4 quark constituents scales as
    \[ F_{\text{diq}}(s) \sim \left( \frac{\alpha_s}{s} \right)^3 \rightarrow F_{\text{diq}}(s) = \left( \frac{S_{th}}{s} \right)^3 \]
Can the counting rules be used for cross sections as well?

• **With ease:** S. Brodsky and RFL, arXiv:1505.00803

• Exotic states can be produced in threshold regions in $e^+e^-$ (BES, Belle), electroproduction (JLab 12), hadronic beam facilities (PANDA at FAIR, AFTER@LHC) and are best characterized by cross section ratios

• Two examples:

1) \[
\frac{\sigma(e^+e^-\rightarrow Z_c^+(\bar{c}c\bar{d}u)+\pi^-(\bar{u}d))}{\sigma(e^+e^-\rightarrow \mu^+\mu^-)} \propto \frac{1}{s^6} \text{ as } s \rightarrow \infty
\]

2) \[
\frac{\sigma(e^+e^-\rightarrow Z_c^+(\bar{c}c\bar{d}u)+\pi^-(\bar{u}d))}{\sigma(e^+e^-\rightarrow \Lambda_c(cud)+\bar{\Lambda}_c(\bar{c}\bar{u}d))} \rightarrow \text{const as } s \rightarrow \infty
\]

− Ratio numerically smaller if $Z_c$ behaves like weakly-bound dimeson molecule instead of diquark-antidiquark bound state due to weaker meson color van der Waals forces
Conclusions

• For the 20 or so exotic states (X, Y, Z) that have thus far been observed, all of the popular physical pictures for describing their structure seem to suffer some imperfection

• We propose an entirely new dynamical picture based on a diquark-antidiquark pair rapidly separating until forced to hadronize due to confinement

• Then several problems, e.g., the widths of X, Y, Z states and their couplings to hadrons, become much less mysterious

• The latest work exploits a cusp effect from diquark pairs, and constituent counting rules. But much more remains to be explored!