Summary of the Workshop on Exotic Hadrons

Tomasz Skwarnicki

Syracuse University

6th International Conference on New Frontiers in Physics, Κολυμβάρι, Ελλάδα, 26 August 2017
Monday Aug 21: Light hadron exotics

15:00 [1130] Exotic Baryons at MAMI (30 minutes)

16:30 [1326] light exotic hadrons at BESIII (40 minutes)

17:10 [1105] Structure of excited charmed baryons studied by pion emission decays (30 minutes)

17:40 [1114] Heavy hadron production for the study of their structure (20 minutes)

18:00 [1142] Strange and Charm Baryon Spectroscopy at J-PARC (40 minutes)

18:40 [1237] Excited vector mesons: phenomenology and predictions for a yet unknown vector Sibar(s)ss state with a mass of about 1.93 GeV (20 minutes)

Tuesday Aug 22: Heavy-quarkonium-like exotics (experimental)

11:00 [1339] The X(3872) and other charmonium puzzles (40 minutes)

11:40 [1110] Z_c states observed in ppi transitions to charmonium states (40 minutes)

12:20 [1239] Charged bottomonium-like states at Belle (40 minutes)

13:00 [1134] Vector states above open charm threshold (40 minutes)

15:00 [1238] Vector bottomonium-like states at Belle (40 minutes)

15:40 [1127] BES III future prospects in exotic hadron spectroscopy (20 minutes)

Wednesday Aug 23: Phenomenology of exotic hadrons

11:00 [1283] H unf for exotic doubly hidden-charm/bottom $Q\overline{Q}$bar $Q\overline{Q}$ bar Q8 tetraquark states (30 minutes)

11:30 [1096] Charmed states on the lattice (30 minutes)

12:00 [1176] Understanding X(3862), X(3872), and X(3930) in a Friedchts-model-like scheme (30 minutes)

12:30 [1117] Quark-Gluon Mixing in Abelian Decomposition of QCD (30 minutes)

13:00 [1331] Amplitude analysis of the exotic states (30 minutes)

15:00 [1062] Threshold effects in hadron spectrum: a new spectroscopy? (30 minutes)

15:30 [1179] Narrow-width tetraquarks in large-N_c QCD (30 minutes)

16:30 [1244] Issues at forefront of heavy quark spectroscopy (45 minutes)

17:15 [1444] Is there a common Ariaedne thread for all Exotic Hadrons? (45 minutes)

18:00 [1398] Round Table Discussion (30 minutes)
This talk

• Use elements of various talks given at the workshop to illustrate status of exotic hadron spectroscopy
• Neither a complete review of the field nor of all the talks given at the workshop
• I apologize to the workshop speakers not mentioned in the summary
• All talks were interesting and we often had animated discussions
"Exotic" multiquark states conceived already at the birth of Quark Model

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u_1$, $d_1$, and $s_1$ of the triplet as "quarks" $\bar{q}$ and the members of the anti-triplet as anti-quarks $q$. Baryons can now be constructed from quarks by using the combinations $(q\bar{q})$, $(q\bar{q}q\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(q\bar{q}q\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\bar{q})$ gives just the representations 1, 8, and 10 that have been observed, while

8419/TH.412
21 February 1964

AN SU$_3$ MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
II *)

G. Zweig
CERN—Geneva


6) In general, we would expect that baryons are built not only from the product of three mesons, $\Lambda\Lambda\Lambda$, but also from $\Lambda\Lambda\Lambda\Lambda\Lambda\Lambda$, etc., where $\Lambda$ denotes an anti-meson. Similarly, mesons could be formed from $\Lambda\Lambda$, $\Lambda\Lambda\Lambda\Lambda$, etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\Lambda\Lambda$ and $\Lambda\Lambda\Lambda$, that is, "douces and tresy".

Murray Gell-Mann

George Zweig
QCD

\[ \mathcal{L}_{\text{QCD}} = \sum_{q=u,d,s, \atop \text{c,b,t}} \bar{q} \left( i \gamma_\mu D^\mu - m_q \right) q - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \]

Hadrons = Non-perturbative QCD

Lattice QCD works well for lowest-excitations of \((qq), (qqq)\).

Only approximate lattice simulations for **unstable** higher excitations.

We have to **rely on data and QCD-motivated phenomenology** when trying to understand more complex hadronic structures.

---

**Asymptotic freedom**

**Confinement**

**Expect hadrons with gluons as constituents:**
- **Hybrids:** \((qqg), (qqqg), \ldots\)
- **Glueballs:** \((gg), \ldots\)

**SU(3)_{\text{color}}**

**Gluons** with **color-anticolor** charge

**1973**

Hugh David Politzer

Frank Wilczek

David Gross

\[ V(r) \approx 1/r \]

\[ V \approx r \]

**Static \(q\bar{q}\) potential in Lattice QCD**

**PDG**

\[ \alpha_s(Q^2) \]

\[ Q \text{ [GeV]} \]

\[ \alpha_s(Q^2) \approx 0.1181 \pm 0.0013 \]
Mesons from quarks & antiquarks in QCD

- Color triplet
- Color antitriplet
- Color singlet

Quark and antiquark:
- \( q \)
- \( \bar{q} \)

Meson (\( q\bar{q} \)): e.g. \( K^+ \)

Color flux tube stretched between quark and antiquark with attractive potential

- Attractive color force
- Repulsive color force

Color octet:
- \( \frac{1}{\sqrt{2}} \)
- \( i \frac{1}{\sqrt{2}} \)
- \( -\frac{2}{\sqrt{6}} \)
- \( -\frac{1}{\sqrt{2}} \)
- \( \frac{1}{\sqrt{6}} \)
- \( \frac{1}{\sqrt{6}} \)
- \( -\frac{1}{\sqrt{2}} \)
- \( \frac{i}{\sqrt{2}} \)

Quarks will pull apart in any octet configuration

Gluons happen to belong to the color octet
(Colored) diquarks in QCD

antisymmetric color antitriplet

\[ \begin{align*}
\frac{1}{\sqrt{2}} & \quad \frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{2}} & \quad -\frac{1}{\sqrt{2}}
\end{align*} \]

symmetric color triplet

\[ \begin{align*}
\frac{1}{\sqrt{2}} & \quad \frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{2}} & \quad \frac{1}{\sqrt{2}}
\end{align*} \]

Color flux tube stretched between the quarks and extending to other color partners

Not a particle, just a building block in QCD

Diquark can go in a place of antiquark in a hadron; antidiquark in place of quark.

See Maiani’s talk
Diaquarks can make tetraquarks!

Color flux tube stretched between the diquark and diantiquark.

However, it is not clear if an efficient mechanism to suppress the fall-apart mode to two mesons exists, especially when all quarks are light.
Conventional and “exotic” hadrons

**Conventional**

Strong binding. Compact systems.

- **K meson**
  - (sq)
- **Deuteron**
  - (u(ud)) (u(dd))
- **Lambda baryon**
  - ((sd)u)

Meson and baryons motivated Quark Model and QCD

Baryonic molecules exists!

**“Exotic”**

Strong binding. Compact systems.

- **Pentaquark**
  - ((q(sq))(qq))
- **Tetraquark**
  - ((sq)(sq))
- **Glueball**
  - (sqg)

- **KN molecule**
  - (u(ud)) (s\bar{u})
- **KK molecule**
  - (s\bar{q}) (s\bar{q})

QCD predicts attractive forces in some of such configurations. Do they live long enough to produce observable states/effects?

Are molecular forces in such systems strong enough to create bound states, or pronounced effects?
Tetraquarks vs meson-meson molecules

- The same quark content can, in principle, create a meson-meson molecule or a tetraquark
- However, mass spectrum from these two types of bindings are very different

We don’t know if either one exist (“exotic hadron”)

Typically expect only one state $n=1, L=0$.

Fall apart prevented by spatial separation – long-lived states if below threshold.

Mass and $J^P$ fairly constrained from the constituents.
**A2 Setup at MAMI**

- energy-tagged bremsstrahlung photons from 1.6 GeV MAMI electron beam
- \( \sim 4\pi \) calorimeter system (CB + TAPS)
- charged particle vetos / basic tracking
- available targets:
  - unpolarized: H, D, \(^3\)He, solid targets
  - polarized: (D)-butanol, \(^3\)He

---

Dominik Werthmüller on behalf of the A2 Collaboration at MAMI
N(1685) confirmed, N(1728)?

- Explanations:
  - interference of $N(1535)1/2^-$ and $N(1650)1/2^-$
  - strangeness threshold openings
  - exotic antidecuplet baryon i.e. pentaquark

Studies in progress:

Proton target
Defamed $\Theta(1540)^+$

$\Theta^+(1540)$ in $\gamma d \rightarrow \Lambda K N$

(uudds) pentaquark candidate

A2 experiment

negative result from CLAS


**d*(2380) dibaryon candidate**

**The d*(2380) Dibaryon Candidate**

- **photodesintegration**
- coherent $\pi\pi$ production
- small ‘conventional’ coherent background in neutral channel
- large quasifree background near threshold to be dealt with

\[ I(J^P) = 0(3^+) \]

\[ \gamma d \rightarrow d\pi^0\pi^0 \]


Double-pole structure of $\Lambda(1405)$

The Puzzling $\Lambda(1405)$

**Unitary Chiral Theories**
- dynamical generation
- two poles near $\Sigma\pi$ (1327 MeV) and $\bar{K}N$ (1432 MeV) thresholds
- observables have contributions from both poles
- coupling to poles depends on reaction

**Regge-Analysis**
- only higher-lying $\Lambda(1405)_a$ fits three-quark picture
- nonordinary nature of $\Lambda(1405)_b$

Radiative Decays of the $\Lambda(1405)$
- relatively clean way of probing the internal structure of baryons
- radiative decay via meson-baryon loops $\Rightarrow$ access to $\bar{K}N$

A2 expects to improve over earlier photo-production experiments

See also Noumi’s talk (J-PARC)
X(1835) observed in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

$X(1835)$ $J^{PC}=0^{-+}$

$M = 1844 \pm 9^{+16}_{-25}$ MeV/$c^2$

$\Gamma = 192^{+20+62}_{-17-43}$ MeV/$c^2$

- What is the role of the ppbar threshold (and other thresholds)?
- Patterns in the production and decay modes
Summary of the Workshop on Exotic Hadrons, Kolymbari 2017, Tomasz Skwarnicki

Model 1:
Flat line shape with strong coupling to $p\bar{p}$ and one additional, narrow Breit-Wigner at \( \sim 1920 \text{ MeV}/c^2 \)

Model 2:
Coherent sum of $X(1835)$ Breit-Wigner and one additional, narrow Breit-Wigner at \( \sim 1870 \text{ MeV}/c^2 \)

- Suggest the existence of a state, either a broad one with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold.
- Support the existence of a $p\bar{p}$ molecule-like state or bound state.
Glueball studies in BES III

- **Pure scalar-glueball rate in J/ψ radiative decays**
  - BR(J/ψ → γG(0⁺)) = 3.8(9)×10⁻³
  - BR(J/ψ → γf₀(1710) → γKK) = (8.5^{+1.7}_{-0.9})×10⁻⁴
  - BR(J/ψ → γf₀(1710) → γππ) = (4.0 ± 1.0)×10⁻⁴
  - BR(J/ψ → γf₀(1710) → γωω) = (3.0 ± 1.0)×10⁻⁴
  - BR(J/ψ → γf₀(1710) → γηη) = (2.35^{+1.24}_{-0.74})×10⁻⁴

- **Pure Tensor-glueball rate in J/ψ radiative decays**
  - BR(J/ψ → γG(2⁺)) = 1.1(2)×10⁻²

  Large decay rate is predicted
  - BR(J/ψ → γf₂(2340) → γηη) = (5.6^{+0.62}_{-0.65})×10⁻⁴
  - BR(J/ψ → γf₂(2340) → γϕϕ) = (1.91 ± 0.07^{+0.72}_{-0.65})×10⁻⁴
  - f₁(2220)? Need to be confirmed!
  - Need more experimental information!

**At BESIII**

- f₀(1710) and f₀(2100) are observed in J/ψ → γηη, γπ⁰π⁰
- f₂(2340) is observed in J/ψ → γηη/ϕϕ/π⁰π⁰
- X(2120) and X(2370) in of J/ψ → γπ⁺π⁻η'

Systematic studies needed
- J/ψ → γηη'
- J/ψ → γη'η'
- J/ψ → γK_sK_s
- J/ψ → ϕX, ωX

**Low lying glueballs have ordinary quantum number mixing with q̅q mesons**

See also Y.M.Cho’s talk
Beginning of XYZ saga

The $X(3872)$ & other charmonium puzzles

The most cited Belle paper (1369 citations)

Observation of a narrow charmonium-like state in exclusive $B^\pm \to K^{\pm} \pi^+\pi^- J/\psi$ decays

S.-K. Choi,8 S. L. Olsen,6 K. Abe,5 T. Abe,5 I. Adachi,7 Byoungh Sup Ahn,14 H. Aihara,8 K. Akai,7 M. Akatsu,20 M. Asamoto,7 Y. Asano,48 T. Aso,47 V. Aulchenko,1 ⋯

Preference for $\gamma \psi'$ over $\gamma J/\psi$ points to $2^3P_1$ component

Large isospin violation in these decays, due to $m(D^0)-m(D^-)$?

Molecule?

Huge fall-apart mode from the resonance tail above the $D^0D^{*0}$ threshold

$X(3872)$ Belle $DD^*<1.2$ MeV

very narrow $\Gamma_{X(3872)}<1.2$ MeV

$D^0\bar{D}^{*0}$

$J^{PC}=1^{++}$
Prompt production of X(3872)

$X_{3872}$ produced like $\psi'$; very unlike $^3\text{He}$, etc.

See Esposito et al., PRD 92, 034028 (2015).

Can’t be a molecule! It is a tightly bound-tetraquark.

Agree, can’t be a pure molecule! It is a mixture of a molecule and $2^3P_1$ charmomium.

Wednesday talks/discussion:

See also Xiao's talk
Can a large molecule mix with a compact charmonium?

\[ X(3872) - \chi'_{c1} \text{ mixture } \Leftrightarrow \text{ pretty bizarre} \]

Wednesday discussion session:

It is not plausible for such a large molecular state to mix with such a compact charmonium state.

For such a long-lived state as \( X(3872) \), even small overlap of wave functions can lead to mixing.

- Luciano Maiani
- Alex Bondar

\[ d_{\text{rms}}(64\text{Zn nucleus}) \approx 8 \text{ fm} \]

\[ d_{\text{rms}}(X_{3872}) > 10 \text{ fm} \]

\[ d_{\text{rms}}(\chi'_{c1}) \approx 1 \text{ fm} \]

\[ \frac{\text{Volume}(\chi'_{c1})}{\text{Volume}(X_{3872})} \approx 10^{-3} \]
Hadronic decay of a $q\bar{q}$ resonance

Thinking about a state oscillating back-and-fourth between $(c\bar{c})$ and $(c\bar{u}) - (\bar{c}u)$ is not necessarily the right picture. A different possibility:

$$pp \to \cdots + \chi'_{c1}$$

then $\chi'_{c1} \to D^0\bar{D}^{*0}$

Adopted from Michael Pennington’s slides at Modern Exotic Hadrons
INT 15-60W workshop
November 2015
Resonance decay
Resonance decay
Resonance decay
Resonance decay
Resonance decay
Resonance decay

Decaying $q\bar{q}$ meson resonance can go through tetraquark and/or molecular configurations.

This can sometimes lead to

Dynamically generated state; an extra pole in the scattering matrix
**Discovery of Z(4430)^+**

**Belle 2008**

PRL 100, 142001 (2008)

1D $M(\psi'\pi^-)$ mass fit

"K* veto region": suppress $K^*(892)$ and $K^*_{2}(1430)$

$M(Z) = 4433 \pm 4 \pm 2$ MeV

$\Gamma(Z) = 45^{+18}_{-13}^{+30}_{-13}$ MeV

significance 6.5$\sigma$
### LHCb confirmed $Z_c(4430)$ in 2014

**Table:**

<table>
<thead>
<tr>
<th>$Z(4430)^-$</th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(Z)$ [MeV]</td>
<td>$4475 \pm 7^{+15}_{-26}$</td>
<td>$4485 \pm 22^{+28}_{-11}$</td>
</tr>
<tr>
<td>$\Gamma(Z)$ [MeV]</td>
<td>$172 \pm 13^{+37}_{-34}$</td>
<td>$200^{+41+26}_{-40-35}$</td>
</tr>
<tr>
<td>$f_Z$ [%]</td>
<td>$5.9 \pm 0.9^{+1.5}_{-3.3}$</td>
<td>$10.3^{+3.0+4.3}_{-3.5-2.3}$</td>
</tr>
<tr>
<td>$f_{1-Z}$ [%]</td>
<td>$16.7 \pm 1.6^{+2.6}_{-1.2}$</td>
<td></td>
</tr>
</tbody>
</table>

**Significance:**

<table>
<thead>
<tr>
<th>JP</th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J^P=1^+$</td>
<td>$9.7\sigma$</td>
<td>$3.4\sigma$</td>
</tr>
</tbody>
</table>

Excellent agreement!

**Diagram:**

- **Breit-Wigner amplitude**
- **Argand diagram of $Z_c(4430)^+$ is consistent with this structure being a resonance**

2nd $Z^-$ at lower mass?

- $J^P=0^-$
  - $M(Z_0) = 4239 \pm 18^{+45}_{-40}$ MeV
  - $\Gamma(Z_0) = 220 \pm 47^{+108}_{-74}$ MeV
- $f_{Z^0} = 1.6 \pm 0.5^{+1.8}_{-0.4} \%$
- $f_{1-Z^0} = 2.4 \pm 1.1^{+1.7}_{-0.2} \%$

6σ significance (with systematics)

$J^P=1^+$ also possible $\Gamma = 660 \pm 150$ MeV
Belle

PR D90, 112009 (2014)

4D amplitude analysis

Belle

$\overline{B}^0 \rightarrow J/\psi \pi^+K^-$ in Belle

Small fit fractions!

- The $Z_c(4430)^+$ observed in the 2nd decay mode!
- A broad but significant 2nd $1^+$ resonances at the lower mass, $Z_c(4200)^+$
  - Possibly the same structure as observed by the LHCb in $\overline{B}^0 \rightarrow \psi ' \pi^+K^-$ ($1^+$ was not ruled out by LHCb)
Proliferation of near-threshold states: \(Z_b^{+,*0}\) states in bottomonium

- Likely molecular states of \(B\bar{B}^*, B^*\bar{B}^*\) (very weakly bound or slightly virtual)
- Tightly bound diquark tetraquarks advocated by Maiani and collaborators

**Masses near the \(BB^*, B^*B^*\) thresholds**

- \(Z_b(10650)\) with \(\Delta M_{th} = +3\pm 2\) MeV
- \(Z_b(10610)\) with \(\Delta M_{th} = +3\pm 2\) MeV
- \(\Gamma = 11.5\pm 2.2\) MeV for \(BB^*\)
- \(\Gamma = 18.4\pm 2.4\) MeV for \(B^*B^*\)

Both \(J^P(C)=1^{+(-)}\)

**Charged and neutral versions detected** \(I^G = 1^+\)

Large rate to fall-apart modes observed

See Bondar’s talk

Karliner’s talk

Maiani’s talk
More near-threshold states: many of $Z_c^{+,0}$ charmonium states

- Expected from $Z_b$ states and Heavy Quark Symmetry

Masses a few MeV above the $D\bar{D}^*$, $D^*\bar{D}^*$ thresholds

<table>
<thead>
<tr>
<th>State</th>
<th>$\Delta M_{th}$</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_c(4020)$</td>
<td>$+11\pm3$ MeV</td>
<td>$28.1\pm2.6$ MeV</td>
</tr>
<tr>
<td>$Z_c(3900)$</td>
<td>$+7\pm2$ MeV</td>
<td>$13\pm5$ MeV</td>
</tr>
</tbody>
</table>

Large rate to fall-apart modes

$$\frac{\Gamma[Z_c(4025)\rightarrow D^*\bar{D}^*]}{\Gamma[Z_c(4020)\rightarrow \pi h_c]} \sim 9,$$

$$\frac{\Gamma[Z_c(3900)\rightarrow DD^*]}{\Gamma[Z_c(3900)\rightarrow \pi J/\psi]} = 6.2 \pm 1.1_{\text{stat}} \pm 2.7_{\text{sys}}.$$

Charged and neutral versions detected $I^G=1^+$

Molecular states of $D\bar{D}^*$, $D^*\bar{D}^*$ ?

Diquark tetraquarks ?

See Lyu's talk

(also seen be Belle)

Karliner's talk

Maiani's talk

\[ J^{P(C)}=1^{+(-)} \]
Good discussion about $Z_b$ and corresponding $Z_c$ states

Easy to understand if $Z_b(10610)$ is a $B^*\overline{B}^*$ molecule, but not in a tetraquark model

$Z_b(10610) \rightarrow B\overline{B}^*$  $Z_b(10650) \rightarrow B\overline{B}^*$

- Why the differences in decay pattern of $Z_b$ and $Z_c$ states?
  - Some of it can be misinterpretations of the data e.g.

Mass, width not determined properly since did not allow for $Z_c$ – NR bkg interference hinted by the Dalitz plot. This is likely $Z_c(4020) \rightarrow \psi(2S)\pi^+$ expected from $Z_b(10650) \rightarrow \Upsilon(2S)\pi^+$

Xiao-Rui Lyu

Summary of the Workshop on Exotic Hadrons, Kolymbiari 2017, Tomasz Skwarnicki

Alex Bondar
Anomalous $1^-$ states above open charm threshold

First observed by BaBar in 2005

Famous $Y(4260)$ is now $Y(4220) + Y(4320)$

For much more on this see Z.Wang’s talk
Anomalous behavior of $1^{-}$ states above open bottom threshold

$e^+e^- \rightarrow \Upsilon(1S,2S,3S) \pi^+\pi^- $ and $h_b(1P,2P) \pi^+\pi^-$ proceed via $\Upsilon(5S), \Upsilon(6S)$

Unlike in charmonium!

However, $\Upsilon(5S), \Upsilon(6S) \rightarrow \Upsilon(1S,2S,3S) \pi^+\pi^-$ widths are 100 larger than $\Upsilon(3S), \Upsilon(2S) \rightarrow \Upsilon(1S) \pi^+\pi^-$

OZI-rule violation

Also widths for $\Upsilon(5S), \Upsilon(6S) \rightarrow h_b(1P), h_b(2P) \pi^+\pi^-$ are comparable, but require heavy quark spin flip

HQSS violation

Like in charmonium!
**Interpretation?**

Bottomonium-like states
- open flavor decays dominate
- transition to various bottomonia
- admixture + rescattering

Molecules are not eigenstates of the total \(bb\) spin

\[
Z_b = B\bar{B}^* \\
Z_b' = B^*\bar{B}^*
\]

\[
|Z'_b\rangle = (0_{\bar{b}b} \otimes 1_{\bar{q}q} - 1_{\bar{b}b} \otimes 0_{\bar{q}q})/\sqrt{2} \\
|Z_b\rangle = (0_{\bar{b}b} \otimes 1_{\bar{q}q} + 1_{\bar{b}b} \otimes 0_{\bar{q}q})/\sqrt{2}
\]

Decomposition \(\Rightarrow\)

- Decays via \(Z_b\) states explain HQSS violation

\(\text{OZI} \Rightarrow \text{light d.o.f.}\)

**Roman Mizuk**

Simonov JETP Lett 87,147(2008)
Meng Chao PRD77,074003(2008)
Interpretations of $Z_c^+$ states observed in B decays

No molecular thresholds can explain $Z_c(3900)^+$ while it has been suggested $Z_c(4200)^+$ is a tetraquark, no tetraquark model can accommodate it together with $Z_c(4430)^+$.

$Z_c(4200)^+$ needs confirmation!
X(4140) first observed by CDF
PRL 102, 242002 (2009)

X(4140) was previously observed by CDF, CMS, D0. Hints of X(4274) in CDF data.

Postdiction by L. Maiani, A. D. Polosa, V. Riquer
PRD94, 054026 (2016)
Possibly radially excited 0++ tetraquarks. However, only one 1++ state with color triplet diquarks.

Predicted two 1++ tetraquarks in this mass range (S=0,1 diquarks in color triplet and sextet)

Not enough data to test resonant amplitudes on Argand diagrams.
\( \Lambda_b^0 \to J/\psi pK^- \)

5D amplitude analysis

\( \Lambda_b^0 \to J/\psi pK^- \)

- \( \Gamma = 39 \pm 20 \text{ MeV} \)
- \( P_c(4450)^+ \to J/\psi p \)
- \( P_c(4380)^+ \to J/\psi p \)
- \( \Gamma = 205 \pm 88 \text{ MeV} \)

No \( \frac{5}{2}^- \) molecules in this mass range

- \( P_c(4450) \) too broad to be a molecule

\[ \Sigma_c^+ D_s^0 \]

\[ 4500 \pm 10 \pm 3 \text{ MeV} \]

\( P_c(4380)^+ \) is too broad to be a molecule

- \( P_c(4380) \) can accommodate \( \frac{5}{2}^- \) when at least one diquark in \( S=1 \) state

\[ 1^- \]

\[ 2^- \]

\[ 3^- \]

\[ 4500 \pm 10 \pm 3 \text{ MeV} \]

\( J^P \) “preferred” rather than definitely determined

- \( D_{s0}^* \)

\( 4300 \)

- \( P_c(4450)^+ \)

- \( P_c(4380)^+ \)

\( M \) and \( L \) and many others

\( \Lambda \) baryon excitations

\[ m_{\Lambda b^0}^2 \text{ [GeV}^2]\]
Tomography of $J^{PC}M^e = 1^{++}0^+ (\pi\pi)_S P$-wave

Possibility of triangle anomalies should be explored via amplitude fits to the data which yielded XYZ, Pc states.
**Doubly heavy systems**

baryon

Consistent results predicted by LQCD:
Francis, Hudspith, Lewis, Maltman
PRL 1118, 142001 (2017)

See also Chen’s talk on quadruple-heavy tetraquarks

Stable tetraquark,
will decay weakly

The lightest $1^+$ state

<table>
<thead>
<tr>
<th>State</th>
<th>Quark content</th>
<th>$M(J = 1/2)$</th>
<th>$M(J = 3/2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi_{cc}^{(*)}$</td>
<td>$ccq$</td>
<td>3627 ± 12</td>
<td>3690 ± 12</td>
</tr>
<tr>
<td>$\Xi_{bc}$</td>
<td>$b(cq)$</td>
<td>6914 ± 13</td>
<td>6969 ± 14</td>
</tr>
<tr>
<td>$\Xi_{bc}'$</td>
<td>$b(cq)$</td>
<td>6933 ± 12</td>
<td>…</td>
</tr>
<tr>
<td>$\Xi_{bb}$</td>
<td>$bbg$</td>
<td>10162 ± 12</td>
<td>10184 ± 12</td>
</tr>
</tbody>
</table>

LHCb: 3621 ± 1

Marek Karliner

the same toolkit

Karliner, Rosner PRD90, 094007 (2014)

Karliner, Rosner arXiv:1707.07666

consistent results predicted by LQCD:
Mesons are $q\bar{q}$ bound states. They are predominantly $q\bar{q}$ bound states below the open flavor threshold. They are more complex structures above it, and we have not yet understood them.
Claim most (all?) of XYZ states are tetraquarks or pentaquarks

Necessarily claim there are many more to be discovered

Proliferation of threshold states requires mixing with virtual hadron pairs

Predict prompt production of all XYZ states at hadron colliders

No width predictions so far

Proliferation of threshold states is the main feature of this model (supported also by lighter meson spectroscopy).

Narrow widths expected!

Cannot account for some observed XYZ,P_c states. Leave room for other dynamics to play a role.

More threshold states expected, but predictive power somewhat limited. No agreement on exact dynamical model (only π-exchange?).

No prompt production, unless mix with compact hadron.

Crucial difference.
Lack of experimental reports on prompt production of most of XYZ,P_c states anecdotally favors molecular forces (need experiments to publish limits!)
Summary III

• Need more data to settle the phenomenological disputes

• More data are forthcoming!

Upgraded LHCb

See K.Zhu’s talk