Charmonium and exotics on the continuum

Fulvio Piccinini

INFN, Sezione di Pavia

based on work with
A. Esposito, A. Guerrieri, L. Maiani,
A. Pilloni, A.D. Polosa and V. Riquer

Disclaimer: not intended to be an exhaustive review
Few recent clue measurements: LHCb confirmed BELLE on \(Z(4430)\) and measured \(J^P = 1^+\)

- \(B^0 \rightarrow K^+ Z^- \rightarrow K^+ \psi(2S) \pi^-\) (LHCb)  
  \[M = 4485^{+22+28}_{-22-11} \text{ MeV, } \Gamma = 200^{+41+26}_{-46-35} \text{ MeV, } J^P = 1^+\)  
  PRL12 (2014) 222002

- \(B^0 \rightarrow K^\mp \psi(2S) \pi^\pm\) Belle  
  \[M = 4443^{+15+19}_{-12-13} \text{ MeV, } \Gamma = 107^{+86+74}_{-43-56} \text{ MeV}\]  

- Valence structure \(c\bar{c}ud\) required \(\implies\) true tetraquark
- \(\pi/2\) phase shift with energy crossing the mass \(\implies\) true resonance
and something also in the neutral sector

**BESIII:**

\[ e^+ e^- \rightarrow \chi_{c0} \omega \]

(and not \( \chi_{c1}, \chi_{c2} \))

---

**BESIII/BELLE:**

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

---


\[
\begin{align*}
M & = 4230 \pm 10 \text{ MeV} \\
\Gamma & = 38 \pm 12 \text{ MeV}
\end{align*}
\]

---


\[
\begin{align*}
M_1 & = 4216 \pm 18 \text{ MeV} \\
\Gamma_2 & = 39 \pm 22 \text{ MeV} \\
M_2 & = 4293 \pm 9 \text{ MeV} \\
\Gamma_2 & = 222 \pm 67 \text{ MeV}
\end{align*}
\]
**Y(4260) radiative decay to X(3872)**


**BESIII:** \( e^+ e^- \rightarrow Y(4260) \rightarrow X(3872) \gamma \)

With \( \mathcal{B}[X(3872) \rightarrow \pi^+ \pi^- J/\psi] = 5\% \)

\[
\frac{\mathcal{B}[Y(4260) \rightarrow \gamma X(3872)]}{\mathcal{B}(Y(4260) \rightarrow \pi^+ \pi^- J/\psi)} = 0.1
\]

Strong indication that \( Y(4260) \) and \( X(3872) \) share a similar structure
• All $c\bar{c}$ states below open $c$ threshold identified
• All $J^{PC} = 1^{--}$ $c\bar{c}$ states filled
• New neutral and charged particles above threshold
• Some may be charmonia, others not (exotica, $X$, $Y$, $Z$), in particular the charged ones (the neutral ones have quantum numbers compatible with charmonia)
Recent development on charmonium

L.-P. He, D.-Y. Chen, X. Liu, T. Matsuki, EPJC 74 (2014) 12, 3208

• $\psi(4S)$ could have been missed because too narrow for open charm searches and $R$ energy scans
• $\psi(4415)$ could be $\psi(5S)$ (but too small calculated width)

- looking at the spacings in the $b$ sector
- $M(\psi(4S)) \sim 4263$ MeV
- the width to open charm results to be small (even if model-dependent)
Recent development on charmonium (II)


- the authors propose that the cross section enhancement in $e^+e^- \rightarrow \omega \chi_{c0}$ is due to the $\psi(4S')$
- they propose to look also for the decay $\psi(4S') \rightarrow J/\psi \eta$
- following the same reasoning on the level spacings between $\eta_c(1S')-\eta_c(2S')$, very similar to $\psi(1S')-\psi(2S')$, they conclude that $X(3940)$ could be identified with $\eta_c(3S')$
main th. phenomenological models for exorica

overall picture still not clear
two extremes: molecules vs. tetraquarks

- brief summary of the present situation
  - molecular model is the most economic one but no firm predictions to be tested
  - on the contrary, for tetraquarks models two many predictions
- \( Z(4430) \), with \( J^P = 1^+ \), challenges the molecular interpretation
- closest threshold \( D^*(2010)\bar{D}_1(2420) \) would imply negative parity
  
  \[ \text{J. Rosner, PRD76 (2007) 114002} \]
- other molecular hypothesis would require unlikely excited components \( D^*\bar{D}(1S, 2S) \) or \( P \)-wave \( D^*\bar{D}_1 \)
  
  \[ \text{T. Barnes, F.E. Close and E.S. Swanson, Phys.Rev. D91 (2015) 1, 014004} \]
- on the other hand tetraquark models predict charged states, not necessarily close to thresholds
  
- new data still required to clarify the picture
$X(3872)$, the oldest and still debated one

- $M(X(3872)) = 3871.68 \pm 0.17$ MeV  \hspace{1cm} $\Gamma_X \lesssim 1.2$ MeV
  \hspace{1cm} J^{PC} = 1^{++}$

LHCb 2014

- $\Delta M \equiv M(X(3872)) - (M_{D^0} + M_{D^*0}) = -3 \pm 192$ keV
  \hspace{1cm} Tomaradze et al. 2015

- production
  - production through $B$ decays at $e^+e^-$ and $p\bar{p}/pp$ colliders

- decay
  - $J/\psi \rho \to J/\psi \pi^+\pi^-$
  - $J/\psi \omega \to J/\psi \pi^+\pi^-\pi^0$
  - $D^0 D^{0*} \to D^0 D^{0*} \pi^0$
  - $D^0 D^{0*} \to D^{0*} \gamma$
  - $J/\psi \gamma, \psi' \gamma  \hspace{1cm} \frac{\text{BR}(\psi' \gamma)}{\text{BR}(J/\psi \gamma)} = 2.46 \pm 0.64 \pm 0.29$ (LHCb)

- $\Delta M \lesssim 0$ \hspace{1cm} \text{molecular interpretation natural}$

- isospin violation explained with the distance of $D^+ D^{*-}$ and $D^0 D^{0*}$
  thresholds of $\sim 8$ MeV

- $R = \frac{1}{\sqrt{2\mu(-\Delta M)}} \Rightarrow R \geq 10$ fm
$X(3872)$ at LHC

- large production cross section
- detected at large $p_T$
- prompt production dominant over $B$ decay ($\sim 84\%$ @Tevatron)
- features at odds with a loosely bound molecule
Prompt $X(3872)$ production: upper theoretical bounds


hypothesis: $X(3872)$ as an $S$-wave bound state of two $D$ mesons

$$
\sigma(p\bar{p} \to X(3872)) \sim \left| \int d^3k \langle X | D \bar{D}^*(k) \rangle \langle D \bar{D}^*(k) | p\bar{p} \rangle \right|^2 \\
\leq \int_\mathcal{R} d^3k |\langle D \bar{D}^*(k) | p\bar{p} \rangle|^2 \sim \sigma(p\bar{p} \to X(3872))^{\text{max prompt}}
$$

- $k$ is the rest-frame relative 3-momentum between the $D$ and $D^*$
- $|\langle D \bar{D}^*(k) | p\bar{p} \rangle|^2$ can be computed with MC simulations
- result: measured prompt cross section $\ll$ upper estimate by more than 2 orders of magnitude unless integration over $|k|$ extended up to $\sim 400$ MeV
- this could be made possible by FSI Artoisenet and Braaten, PRD81 (2010) 114018
- actually the large hadronic activity (mainly $\pi$) close to $D$ and $D^*$ could prevent the effectiveness of FSI (Bignamini et al., PLB684 (2010) 228)
- but the same $\pi$ could give an alternative contribution
Possible mechanism alternative to FSI


Expanding hadronization sphere

Plane $\pi - D$ rescattering

(a)

(b)
results

- additional pions close to $D^0(\ast)$ in momentum space can interact elastically and change the rel. momentum between $D^0$ and $D^0\ast$
- given the initial asymmetric distribution in $k_{rel}$ there could be a feed-down process from larger relative momenta to lower ones and bring $D$ pairs from positive to negative energies (bound state)
- there is a contribution but not enough
- additional ways to check the molecular hypothesis?
- deuterium is the known hadronic molecule, would be analog of $X(3872)$
- antideuterium production is measured at ALICE
- we could study the relation indicated by data between antideuterium and $X(3872)$ production
- unfortunately, up to now, they are measured in two completely different $p_\perp$ regimes. We can only have a qualitative idea through MC, referring to the coalescence model
A check with future precision measurements

A. Esposito, A. Guerrieri, F.P., A. Pilloni, A. Polosa, IJMPA30 (2014) 04n05, 1530002

by considering the scattering amplitude
\[ f(D\bar{D}^* \rightarrow D\bar{D}^*) \], assuming it proceeds through a pole \[ f(D\bar{D}^* \rightarrow X \rightarrow D\bar{D}^*) \] in the soft limit,

\[ f \sim \frac{g^2}{\varepsilon + T} \]

in NRQM the amplitude for the scattering of two slow particles interacting through an attractive potential with superficial discrete level \(-\varepsilon\) has the universal form

\[ f \sim \frac{\sqrt{\varepsilon} - i\sqrt{T}}{\varepsilon + T} \]

\[ \varepsilon = \frac{g^4}{512\pi^2} \frac{\mu^5}{M^4_D M^4_{D*}} \]

with \( g \) the coupling \( XD\bar{D}^* \)

future measurements of \( \Delta M, \Gamma_X, BR(X \rightarrow D\bar{D}^*) \) at LHC and BELLEII, crucial to test the molecular hypothesis
The absence of charged partners of the $X(3872)$ made many people skeptical on the original model

$$\mathcal{B}(B^+ \rightarrow K^+ X) \times \mathcal{B}(X \rightarrow \rho^0 J/\psi)$$

$$= (8.4 \pm 1.5 \pm 0.7) \times 10^{-6} \quad \text{(BaBar)}$$

$$= (8.6 \pm 0.8 \pm 0.5) \times 10^{-6} \quad \text{(Belle)}$$

$$\mathcal{B}(\bar{B}^0 \rightarrow K^- X^+) \times \mathcal{B}(X^+ \rightarrow \rho^+ J/\psi) < 5.4 \times 10^{-6} \quad \text{(BaBar)},$$

$$< 4.2 \times 10^{-6} \quad \text{(Belle)},$$

$$\mathcal{B}(B^+ \rightarrow K^0 X^+) \times \mathcal{B}(X^+ \rightarrow \rho^+ J/\psi) < 22 \times 10^{-6} \quad \text{(BaBar)}$$

$$< 6.1 \times 10^{-6} \quad \text{(Belle)}$$

after discovering several new charged states, there is now renewed interest in the tetraquark model

studying the tetraquark in large-N QCD, S. Weinberg showed

1 that the Coleman theorem (tetraquark correlators reduce to disconnected propagators) does not apply if the connected tetraquark correlator develops a pole

2 that the decay amplitude $\sim \frac{1}{\sqrt{N}}$. 
in the original version a “democratic” hypothesis was made on spin-spin interactions

\[ H = \sum_i m_i + \sum_{i<j} 2\kappa_{ij} \mathbf{S}_i \cdot \mathbf{S}_j \]

From conventional \( S \)-wave mesons and baryons

\[ H \approx 2\kappa_{q\bar{q}} \mathbf{S}_q \cdot \mathbf{S}_{\bar{q}} \]

with the accumulated data it has been necessary to revisit the model, w.r.t. the hierarchy within the spin interactions
new ansatz: only spin-spin coupling inside the diquark is leading

\[ H \approx 2\kappa_{qc} (S_q \cdot S_c + S_{\bar{q}} \cdot S_{\bar{c}}) \]

<table>
<thead>
<tr>
<th>( J^{PC} )</th>
<th>( cq , \bar{c}q )</th>
<th>( c\bar{c} , q\bar{q} )</th>
<th>Resonance Assign.</th>
<th>Decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>0^{++}</td>
<td>(</td>
<td>0, 0\rangle )</td>
<td>( \frac{1}{2}</td>
<td>0, 0\rangle + \sqrt{3}/2</td>
</tr>
<tr>
<td>0^{++}</td>
<td>(</td>
<td>1, 1\rangle_0 )</td>
<td>( \sqrt{3}/2</td>
<td>0, 0\rangle - 1/2</td>
</tr>
<tr>
<td>1^{++}</td>
<td>( \frac{1}{\sqrt{2}}(</td>
<td>1, 0\rangle +</td>
<td>0, 1\rangle) )</td>
<td>(</td>
</tr>
<tr>
<td>1^{+-}</td>
<td>( \frac{1}{\sqrt{2}}(</td>
<td>1, 0\rangle -</td>
<td>0, 1\rangle) )</td>
<td>( \frac{1}{\sqrt{2}}(</td>
</tr>
<tr>
<td>1^{+-}</td>
<td>(</td>
<td>1, 1\rangle_1 )</td>
<td>( \frac{1}{\sqrt{2}}(</td>
<td>1, 0\rangle +</td>
</tr>
<tr>
<td>2^{++}</td>
<td>(</td>
<td>1, 1\rangle_2 )</td>
<td>(</td>
<td>1, 1\rangle_2 )</td>
</tr>
</tbody>
</table>

with a value of the coupling \( \kappa_{qc} = 67 \text{ MeV} \) (cfr. 22 MeV of type I)

- \( M(X_1) \sim M(Z) \)
- \( M(Z') - M(Z) \sim 2\kappa_{qc} = 134 \text{ MeV} \)
- \( M(X_2) \sim M(X'_0) \sim 4000 \text{ MeV} \)
- \( M(X_0) \sim 3770 \text{ MeV} \)
in this scheme $Z(4430)$ is the first radial excitation of $Z(3900)$

- note that $M(Z(4430)) - M(Z(3900)) = 593 \text{ MeV} \sim M(\psi(2S)) - M(J/\psi) = 589 \text{ MeV}$

both $Z(3900)$ and $Z(4020)$ have $s_{c\bar{c}} = 1, 0$

$\implies Z(4020) \rightarrow \pi h_c(^1P_1)$
\( Y \) states: tetraquarks with \( L = 1 \)

\[
H \approx 2\kappa'(S_q \cdot S_c + S_{\bar{q}} \cdot S_{\bar{c}}) - 2A S \cdot L + \frac{1}{2}B L^2
\]

<table>
<thead>
<tr>
<th>State</th>
<th>( P(S_{c\bar{c}} = 1) : P(S_{c\bar{c}} = 0) )</th>
<th>Assignment</th>
<th>Radiative Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Y_1 )</td>
<td>3:1</td>
<td>( Y(4008) )</td>
<td>( \gamma + X_0 )</td>
</tr>
<tr>
<td>( Y_2 )</td>
<td>1:0</td>
<td>( Y(4260) )</td>
<td>( \gamma + X )</td>
</tr>
<tr>
<td>( Y_3 )</td>
<td>1:3</td>
<td>( Y(4290) / Y(4220) )</td>
<td>( \gamma + X'_0 )</td>
</tr>
<tr>
<td>( Y_4 )</td>
<td>1:0</td>
<td>( Y(4630) )</td>
<td>( \gamma + X_2 )</td>
</tr>
</tbody>
</table>

- \( Y(4360) \): radial excitation of \( Y(4008) \); \( Y(4660) \): radial excitation of \( Y(4260) \), since both decay to \( \psi(2S) \)

- \( Y(4260) \) and \( X(3872) \) have the same spin structure \( \Rightarrow \) the observed radiative decay \( Y(4260) \rightarrow \gamma X(3872) \) is an \( E1 \) transition (\( \Delta L = 1 \) and \( \Delta S = 0 \)) as in radiative decays of \( \chi \) states
some predictions on radiative decays

• type-II tetraquark model seems to capture several features making also additional predictions

\[
\begin{align*}
Y_4 &= Y(4630) \rightarrow \gamma + X_2 \quad (J^{PC} = 2^{++}) = \gamma + X(3940), \quad ?? \\
Y_3 &= Y(4290/4220) \rightarrow \gamma + X'_0 \quad (J^{PC} = 0^{++}) = \gamma + X(3916), \quad ?? \\
Y_2 &= Y(4260) \rightarrow \gamma + X_1 \quad (J^{PC} = 1^{++}) = \gamma + X(3872), \quad \text{seen} \\
Y_1 &= Y(4008) \rightarrow \gamma + X_0 \quad (J^{PC} = 0^{++}) = \gamma + X(3770 ??), \quad ??
\end{align*}
\]

• important to select channels able to distinguish between models

see talk by A. Esposito
$Y(4220)$ phenomenology in the tetraquark model


$|Y(4220)\rangle = \frac{\sqrt{3}}{2} |0, 0\rangle - \frac{1}{2} |1, 1\rangle$

$|Z'_c\rangle = \frac{1}{\sqrt{2}} (|1, 0\rangle + |0, 1\rangle)$

with

$|h_c\rangle = |s_{c\bar{c}} = 0\rangle$

$|\chi_{cJ}\rangle = |s_{c\bar{c}} = 1\rangle$

more data needed
Ab initio approach with LQCD

- recently first attempts to investigate tetraquarks with heavy quarks on the lattice
- not yet firm conclusions because of several difficulties, e.g.
  - very difficult the separation of the diquark-antidiquark contribution from the meson-meson one
  - lattices with dimensions of few fm’s not suited for the simulation of extended objects such as the $X(3872)$
  - extrapolation from few hundreds MeV to the physical point can be critical

see the following talk by S. Prelovsek for an update