Multiquark Resonances

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**EXOTIC RESONANCES**

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$X^0(3872)$

$1^{++}$

No charged partners observed: $X^\pm$?

Isospin violations: $X \rightarrow 4S / X \rightarrow 4\omega \sim 1$

Very narrow $\Gamma < 1 \text{ MeV}$

Almost degenerate w/ $\bar{D}^0D^{*0} \& 4\phi$

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$Z_c^{0,\pm}(3900)$

$Z_c^{0,\pm}(4020)$

$1^{-+}$

Charged & neutral!

The lowest is very close in mass to $X^0$

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$Z_c(10610)$

$Z_c(10650)$

$1^{+-}$

There is no $X_{b}^{0}(2\,10600)$

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$X^0(4140)$

$1^{++}$

Together w/ $X(4274), X(4500), X(4700)$

recently observed by LHCb.
HADRONIZATION OF EXOTIC RESONANCES

All should be searched in prompt pp collisions at LHC

The relative motion must be compatible with the formation of a compact tetraquark

\[ e_{ijm} c^j d^m \bar{E} \frac{i}{\sigma} \bar{c}_k \bar{u}_m \]

(Virial theorem \(\bar{T} = -\bar{E} = \frac{1}{2} m c^2 \alpha_s (2 m c) \approx 50 \text{ MeV}\))
'Hadronization State'

Superposition with unknown coefficients

\[ \Psi = \{ c d \} \{ q \bar{u} \} + \Psi^- + \Psi^\prime - + \gamma_\rho + \bar{D}D^* + \bar{D}^*D^* \]

\[ = \Psi_1 + \sum_i \Psi_m \]

\[ \Psi = \Psi_Q + \Psi_\rho = \Psi_\Phi + \Theta \Psi \]

\[ \Theta + \Theta = 1 \quad \& \quad \Theta \cdot \Phi = 0 \]

\[ H\Psi = E\Psi \begin{cases} (E - H_{\rho\rho})\Psi_\rho = H_{\rho\rho} \Psi_\rho \\ (E - H_{Q\rho})\Psi_Q = H_{Q\rho} \Psi_\rho \end{cases} \]

\[ H_{\rho\rho} = H_0 + V_1 \]

\[ H_{Q\rho} = H_0 + V_2 \]

\[ V_I = H_{Q\rho} \frac{1}{E - H_{Q\rho} + i\epsilon} H_{Q\rho} \]

Effective int. in the p space \((P \rightarrow Q \rightarrow P)\)
Because of $V_1$, the scattering length in $P$ is

$$a = a_p - c \left| \langle \psi_m | H_{qq} \psi_a \rangle \right|^2 \frac{E_m - E_a + i\epsilon}{E_m - E_a + i\epsilon}$$

$$(c > 0)$$

$$\equiv \left( 1 - \frac{2c}{\delta - E + i\epsilon} \right) a_p$$
Diquarkonium masses ($Q$-space)

$$H \approx 2k (\hat{S}_Q \cdot \hat{S}_q + \hat{S}_{\bar{Q}} \cdot \hat{S}_{\bar{q}})$$

The spectrum is as follows:

- $+k$
- $-k$
- $-3k$

$0^{++}$, $1^{++}$, $1^{--}$, $2^{++}$
Diquarkonium masses (Q-space)

\[ H \approx 2k (\vec{s}_q \cdot \vec{s}_q + \vec{s}_{\bar{q}} \cdot \vec{s}_{\bar{q}}) \]

The spectrum is as follows:

For \([c\bar{q}][c\bar{q}']\) diquarkonia:

- \(0^{++}\) \(-3k\)
- \(1^{++}\) \(1^{-+}\) \(2^{++}\)

\(X(3872)\) \(Z_c(3900)\) \(Z_c(4020)\)
### Diquarkonia & Molecules

#### 'CLOSED' SPACE $Q$

- $\Psi_d(x_0^0) = [\bar{c}d], [\bar{c}d], [\bar{c}d], [\bar{c}d]$  
  - $\sim \frac{D^*-D^+ - D^*+ D^-}{\sqrt{2}} + i \frac{\psi \psi^0}{\sqrt{2}}$

$\Psi_d(x_0^0)$ does not work $\rightarrow$ I violation

$M(x^+) \geq M(x^0) < M(D^+ \bar{D}^*0) \rightarrow$ no $x^+$

- $\Psi_d(z_c^+) \sim \frac{\eta_c S^+ + \psi \pi^+}{\sqrt{2}} - i \frac{D^*0 \land D^{*+}}{\sqrt{2}}$

$M(z_c^+) > M(D^+ \bar{D}^*0) \rightarrow$ yes $z^+$

### 'OPEN' SPACE $P$

- $\Psi_m \sim \bar{D}^0 D^{*0}$

- $\Psi_m \sim \bar{D}^0 D^{*0}$

- $\Psi_m \sim D^{*0} \bar{D}^{*0}$

*M(z_c^+) > M(D^{*+} \bar{D}^{*0}) \rightarrow$ yes $z^+$

*Same for Z_b resonances but $M(x_0^0)$ is estimated < $M(\bar{B}^0 B^{*0})$*

*deduced from the splitting $Z_c-x$*
**Diquarkonia & Molecules**

### 'Closed' Space Q

\[
\Psi_d(x^0) \equiv [c\bar{d}]_0 [\bar{c}d^+]_1 + [c\bar{d}]_1 [\bar{c}d^+]_0.
\]

\[
\sim \frac{\bar{D}^* - D^+ - D^{*+} \bar{D}^-}{\sqrt{2}} + i \frac{\psi_{\Lambda_{b}}}{\sqrt{2}}
\]

\(\psi_{\Lambda_{b}}\) does not work \(\rightarrow\) I violation

\(M(x^+) \approx M(x^0) < M(D^+ \bar{D}^{*0}) \rightarrow \text{no } x^\pm\)

### 'Open' Space P

\(\Psi_m \sim \bar{D}^0 D^{*0}\)

\[
\begin{array}{c}
\text{Diagram: } D^+ D^{*0} \\
\end{array}
\]

\(\psi_{\Lambda_{b}} \sim \bar{D}^0 D^{*0}\)

### \(\Psi_{d}(Z_c^+)\)

\[
\Psi_{d}(Z_c^+) \sim \frac{\eta_c \bar{c}^+ - \psi_{\pi^+}}{\sqrt{2}} - i \frac{\bar{D}^{*0} \Lambda D^{*+}}{\sqrt{2}}
\]

\(M(Z_c^+) > M(D^+ \bar{D}^{*0}) \rightarrow \text{yes } Z^+\)

### \(\Psi_{d}(Z_c^{1+})\)

\[
\Psi_{d}(Z_c^{1+}) \sim \frac{\eta_c \bar{c}^{1+} + \psi_{\pi^{1+}}}{\sqrt{2}} - \frac{\bar{D}^0 D^{*+} + D^+ \bar{D}^{*0}}{\sqrt{2}}
\]

\(M(Z_c^{1+}) > M(D^{*+} \bar{D}^{*0}) \rightarrow \text{yes } Z^{1+}\)

**SAME FOR \(\Sigma_b\) RESONANCES BUT \(M(x^0)\) IS ESTIMATED < \(M(\bar{B}^0 B^{*0})\)**

(deduced from the splitting \(Z_c - x\))
TOTAL WIDTHS

N.B. $\delta (\text{detuning}) = \text{distance of the level in } Q \text{ from the closest molecular threshold from } BELOW.

$\Gamma \sim \left(2m\right)^{\frac{1}{2}} \left|\alpha_q\right| \sqrt{\delta}$

$X(5568)$ claimed by DO in $B_s^0 \rightarrow \tau^+ \tau^-$ in Feb 2016

A. Esposito, A. Dillon, ADF 1603.07667 (PHB)
TOTAL WIDTHS

N.B. \( \delta \) (detuning) = distance of the level in Q from the closest molecular threshold from BELOW.

\[ \Gamma \sim (2m)^{1/2} |\alpha_a|^{1/2} \delta \]

\[ 0 < \delta < \epsilon_{\text{max}} < \frac{\pi}{2} \text{in } \Delta Q \]

\[ \text{LHCb few weeks later} \]

\[ X(5568) \text{ claimed by D0 in } B_s^0 \tau^+ \text{ in Feb 2016} \]

A. ESPOSITO, A. FILMONI, AOP 1603.07667 (PUB)
If $\rho_{X}^{LHCb} = \rho_{X}^{D\phi} = 8.6\%$, how would the X(5568) signal look like?

(Both modes combined: $p_T(B_s) > 10$ GeV/c)
**DiQuarkonium & \( X_b(5568) \)**

\[
M_{Z_b'} - M_{Z_b} = 2k_{bq}
\]

\[
M_{Z_b'} + M_{Z_b} = 4m_{[bq]}
\]

\[
M(X_b[\bar{c}\bar{c}][\bar{b}\bar{b}]) = m_{[bq]} + m_{[cq]} + 2k_{bq} \vec{s}_b \cdot \vec{s}_q
\]

Both diquarks with \( S = 0 \) \( 0^+ \)

\[
= m_{[bq]} - \frac{3}{2} k_{bq} + \frac{m_{[cq]} - \frac{3}{2} k_{cq}}{m_{x_0}/2}
\]

\[
\approx 5331 \text{ MeV}
\]

- Too large detuning \( \delta \) wrt \( B_s \pi \) threshold \( (\delta > E_{\text{max}}) \)

- Very close to \( B_K \) threshold. If underestimated by a few MeV, a resonance might appear just above the \( B_K \) (same quark content). **Search in \( B_K^+ \)!**
TOTAL WIDTHS

N.B. \( \delta \) (detuning) = distance of the level in \( Q \) from the closest molecular threshold from BELOW.

\[ \Gamma \sim (2m)^{\frac{1}{2}} |Z_{\alpha\phi}| \sqrt{\delta} \]

\( 0 < \delta < E_{\text{max}} < \Gamma_{\text{im}} \) [\( Z_{\alpha\phi} \)]

\( \gamma \rightarrow J/\psi \phi \)

\( \text{LHCb} \) few weeks later

\( \Psi_d \) (\( X(4140) \)) \sim \frac{\bar{D}^+_s D^-_s - D^+_s \bar{D}^-_s + i \Psi \Lambda \phi}{\sqrt{2}} \)

\( \Psi_m \) might be taken orthogonal but there will be no single threshold dominance; \( \delta \) from the lower \( \bar{D}^+_s D^-_s \)
\[ X(4140), X(4270), X(4500), X(4700) \]

as from LHCb @ Blois (xu S. Stone)

\[ X(4140) = \{ \bar{c}s \bar{b}, \bar{c}\bar{s} \bar{s}, \bar{c}s, \bar{c}\bar{s} \bar{s} \} \]

\[
\begin{align*}
X(4140) &: 1++ \\
X(4270) &: 0^{++} V_{2^{++}} \\
X(4500) &: 0^{++} \\
X(4700) &: 0^{++}
\end{align*}
\]

\[ 2m_{[c\bar{s}]} - k \]
\[ 2m_{[c\bar{s}]} + k \]
\[ 2m_{[c\bar{s}]} - 3k + \delta_k \]
\[ 2m_{[c\bar{s}]} + k + \delta_k \]

\[ 3/4 \phi \]

Below Threshold
$\chi(4140), \chi(4274), \chi(4500), \chi(4300)$

as from LHCb @ BLOIS (see S. Stone)

$\chi(4140) = [\psi(2s) \bar{\psi}(2s)] + [\psi(2s), \bar{\psi}(2s)]$

$\chi(4140)$ \(1^{++}\)

\[2m_{\psi(2s)} - k\] \(4146\) (MeV)

$\chi(4270)$ \(0^{++} \vee 2^{++}\)

\[2m_{\psi(2s)} + k\] \(4273\) (MeV)

$\chi(4500)$ \(0^{++}\)

\[2m_{\psi(2s)} - 3k + \delta_{\chi}\] \(4506\)

$\chi(4700)$ \(0^{++}\)

\[2m_{\psi(2s)} + k + \delta_{\chi}\] \(4704\)

with

$\quad m_{\psi(2s)} = 2100$ MeV

$k_{\psi(2s)} = 54$ MeV

$\delta_{\chi} = 460$ MeV

N.B.

$\quad m_{\psi\bar{\psi}} = m_{\psi\bar{\psi}} + (m_s - m_q) \approx 2100$ MeV

(120 MeV from \( \bar{s}\) of 5013)

$\quad k_{\psi(2s)} = k_{\psi(2s)} \frac{m_q}{m_s} \approx 45 \pm 3$ MeV
EXOTIC RESONANCES

\[ \bar{X}^0 (3872) \]
\[ 1^{++} \]
No charged partners observed: \( X^\pm \)

\[ X \rightarrow \psi^\prime / X \rightarrow \psi \omega \sim \pm \]

Very narrow: \( \Gamma < 1 \text{ MeV} \)

Almost degenerate with \( \bar{D}_0 D^{*0} \) & \( \psi^\prime \)

\[ Z_c^0, \pm (3900) \]
\[ Z_c^0 (4020) \]
\[ 1^{+-} \]

Charged & neutral!

The lowest is very close in mass to \( X^0 \)

\[ Z_b (10610) \]
\[ Z_6 (10650) \]
\[ 1^{+-} \]

There is no \( X_b^0 (\sim 10600) \)

\[ X^0 (4140) \]
\[ 1^{++} \]

Together w/ \( X(4274), X(4500), X(4700) \)
recently observed by LHCb.

Hat's one of \( 1^{++} \) states is \( 0^{++} \) or \( 2^{++} \).
For those who think that we are observing only hadron molecules

A Esposito et al. PRD 92 (2015) 034028
Pentaquarks

based on 1507.04980 with L. Maiani and V. Riquer (Sapienza U.)
THE PENTAQUARK

Highly undesirable option for molecules (before discovery)
Perfect molecule (after discovery)

LHCb 2015

$\Lambda_b(budd) \to K^- P^+$
$L \to J/\Psi p$

$P^+ = \bar{c} c u u d e \Rightarrow$ negative parity

Two states observed

$J^P = 3/2^- @ 4380 \text{ MeV}$
$J^P = 5/2^+ @ 4550 \text{ MeV}$

$L = 0 \& L = 1$ Pentaquarks?

Note: Lower baryons have $P = +$ / pentaq. have $P = -$ / tetraq. have $P = +$.
Isn’t $\Delta M = 170 \text{ MeV}$ too small for one unit of $L$?

($\Delta M = 300 \text{ MeV}$ for $\Lambda(1405) - \Lambda(1116)$)

On the other hand, from $\Sigma_c - \Lambda_c$ we find

$$M_{[qq']^1_s=0} - M_{[qq']^1_s=0} \approx 200 \text{ MeV}$$

So

$$P(3/2^-) = \Xi [cq]_{s=1} [q'q'']_{s=1} \otimes L = 0$$

$$P(5/2^+) = \Xi [cq]_{s=0} [q'q'']_{s=0} \otimes L = 1$$

... combine diquark spin & orbital angular momentum – other states?
A baryon might contain a $\{ud\} S_z = 0$, "good" diquark. But $\Pi (3^{2-})$ should contain $\{ud\} S_z = 1$, whereas $\Phi (5^{2+})$ has $\{ud\} S_z = 0$.

One can show that both pentaquarks have $S_{c\bar c} = 1$ so that HQ spin cons. allows decay into $\Upsilon/\psi$. 

Flavor

\[ \left< {\mathcal{P}, M} \right| H_{\text{w}} (\Delta I = 0, \Delta S = -1) \left| \Lambda_b \right> \]

\[ 8_f \quad \overline{3}_f \quad \overline{3}_f \quad (\text{from } s, d, u) \quad (\text{from } [u d]) \]

therefore \( \Lambda_b \) is either 8 or 10. \( ^{(A)} \)

We might expect

\[ \Lambda_b \rightarrow \pi \overline{\mathcal{P}}^{S=-1}_{10} \rightarrow \pi \overline{\mathcal{J}/4} \Sigma (1385) \]

\[ \Lambda_b \rightarrow K \overline{\mathcal{P}}^{S=-2}_{10} \rightarrow K \overline{\mathcal{J}/4} \Xi (1530) \]

or even

\[ \Sigma \Lambda_b \rightarrow \phi \overline{\mathcal{P}}^{S=-3}_{10} \rightarrow \phi \overline{\mathcal{J}/4} \Sigma^- (1672) \]

\[ (*) \quad \left\{ \begin{array}{c}
8 \otimes 10 = 8 \phi 10 \oplus 27 \oplus 35 \\
8 \otimes 8 = 1 \oplus 3 \oplus 8 \oplus 10 \oplus \overline{10} \oplus 27
\end{array} \right\]