XYZ States: A Theoretical Review

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- The theoretical description of XYZ States:
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    - High degree of symmetry: relations among states.
- Conclusions

The QCD Spectrum

There are two (main) types of Hadrons:

- Mesons: quark-antiquark states
- Baryons: 3-quark states

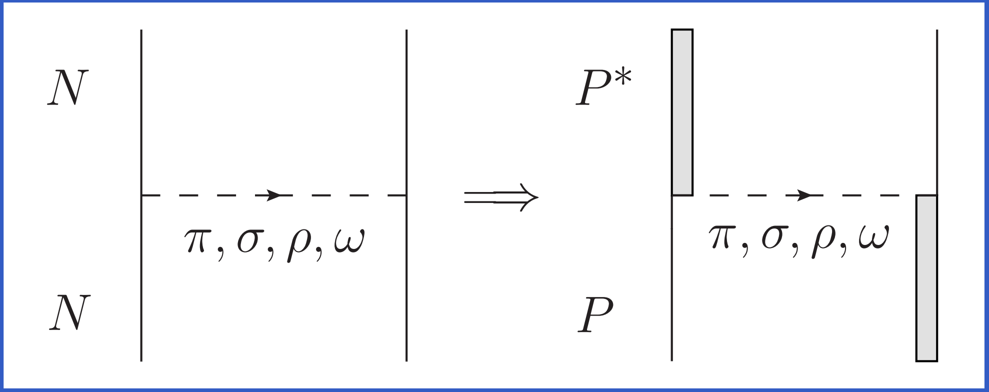
But we know that this is not the full story. The QCD Spectrum also contains states not complying to this classification:

- Nuclei: bound states of nucleons
- Molecules: bound states of hadrons, usually meson-antimeson
- Tetraquarks: $q\bar{q}\, q\bar{q}$, but more compact than a molecule
- Hadrocharmonia: $Q\bar{Q}$ core surrounded by $q\bar{q}$ cloud
- Glueballs, hybrids ...

What are Molecular States?

Heavy hadronic molecules are bound states of heavy hadrons.

- Observation: the force between two heavy mesons is similar to the nuclear forces (Voloshin and Okun, 76).

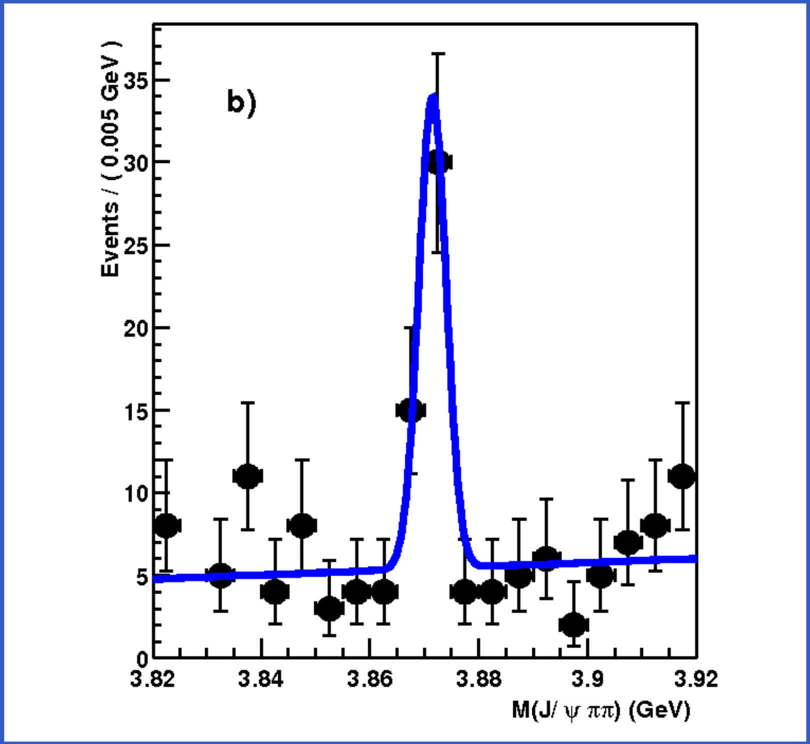


  They are just like the deuteron, but composed of heavy hadrons instead of nucleons.

- Early explorations by De Rújula, Georgi, Glashow (77), Törnqvist (93), Ericson and Karl (93), . . .

The X(3872)

But they were mere theoretical speculations until a discovery by the Belle collaboration in $B^{\pm} \to K^{\pm} J/\Psi \pi\pi$ (03):



... and later confirmed by D0 and CDF.

The X(3872)

Properties: $M_X = 3871.68 \pm 0.17\,\mathrm{MeV}$, $I^G = 0^+$, $J^{PC} = 1^{++}$.

- It's a hidden charm ($c\bar{c}$) state ($X \to J/\Psi\pi\pi$)
- It's very close to the $D^0\bar{D}^{0*}$ threshold ($M_{\rm th} = 3871.79 \pm 0.21\,\mathrm{MeV}$)

What could be its nature?

- It does not seem to fit in the known charmonium ($c\bar{c}$) spectrum.
- But it could be a tetraquark
- Yet, most probably it could be a shallow $D^0\bar{D}^{0*}$ bound state, in which case the binding energy will be merely $B_X \simeq 0.1\,\mathrm{MeV}$.

The perfect candidate for a $D\bar{D}^*$ molecular state! (if $J^{PC} = 1^{++}$)

E.g. Voloshin (03); Braaten, Kusunoki (03); X-EFT by Fleming et al. (04)

The XYZ States

Yet the X(3872) is not the only suprise. Since its discovery, about twenty additional XYZ states have been discovered.

What is an XYZ state?

- Hidden charm (bottom) states
- Located above the open charm (bottom) threshold, i.e. $2m_D(2m_B)$

What is their nature?

- A few are standard quarkonia: $Z(3930)$ as $\chi_{c2}(2P)$.
- But most of them are exotic: molecules, tetraquarks and so on.

Let's study a few cases...

Is the X(3872) really molecular? (I)

How can we determine whether the $X(3872)$ is a molecular state?

Apart from the threshold argument, the decays are interesting:

- Voloshin: if the X is shallow, we should expect characteristic patterns for the $X \to D\bar{D}\gamma$ and $X \to D\bar{D}\pi$ decays
  - Not only that, the $X \to D\bar{D}\pi$ decay could be used as signal of the existence of a predicted $X(3710)$ $D\bar{D}$ bound state.

The best clue may be provided by the large branching ratio:

$$\mathcal{B}_{\omega/\rho} = \frac{\Gamma(X \to J/\psi\, \pi^+\pi^-\pi^0)}{\Gamma(X \to J/\psi\, \pi^+\pi^-)} = 0.8 \pm 0.3\,,$$

which implies some sort of isospin violation at short distances (easy to achieve in the bound state picture).

Is the X(3872) really molecular? (II)

Notice that

$$\mathcal{B}_{\omega/\rho} = \frac{\Gamma(X \to J/\psi\,\pi^+\pi^-\pi^0)}{\Gamma(X \to J/\psi\,\pi^+\pi^-)} \simeq \frac{\Gamma(X \to J/\psi\,\omega)}{\Gamma(X \to J/\psi\,\rho)}$$

- If $X(3872)$ isoscalar molecule, $\mathcal{B}_{\omega/\rho} = \infty$
- If $X(3872)$ isovector molecule, $\mathcal{B}_{\omega/\rho} = 0$
- If we assume the naive identification (huge isospin violation)

$$|X\rangle = \frac{1}{\sqrt{2}}\left(|D^0\bar{D}^{0*}\rangle - |D^{*0}\bar{D}^0\rangle\right)$$

  to be valid at short distances, we get $\mathcal{B}_{\omega/\rho} \simeq 1/20$. If the X is isoscalar, a small $\sim 5\%$ isospin violation may be enough
- The interpretation of the X as 2^{-+} charmonium yields a $\mathcal{B}_{\omega/\rho}$ way too big. (Hanhart et al. (11))

Is the X(3872) really molecular? (III)

The trick is to consider the $X(3872)$ as a isoscalar molecule

$$|X\rangle = \frac{1}{2}\left(|D^0\bar{D}^{0*}\rangle - |D^{*0}\bar{D}^0\rangle + |D^+D^{-*}\rangle - |D^{*+}\bar{D}^-\rangle\right)$$

in which the mass difference between the neutral and charged channels generates a small isovector component at short distances.

Gamermann, Oset (09); Gamermann, Oset, Nieves, Arriola (09).

By assuming a contact interaction of the type

$$\langle\vec{k}|V_C|\vec{k}\,'\rangle = -\frac{1}{2f_D^2}\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

plus a natural sized cut-off $\Lambda = 0.5 - 1.0\,\mathrm{GeV}$, where channels 1 and 2 are $D^0\bar{D}^{*0}$ and D^+D^{*-}, one obtains $\mathcal{B}_{\omega/\rho} = 1.4$!

The $Z_b(10610)$ and $Z_b'(10650)$: Molecules?

The $Z_b(10610)$ and $Z_b'(10650)$ (discovered by Belle in 2011)

- They are hidden bottom ($b\bar{b}$) resonances: $Z_b^{(\prime)} \to \Upsilon(nS)\pi, h_b(nP)\pi$
- They are charged: Z_b^+, Z_b^0, Z_b^- (isospin triplet)
  $\Longrightarrow$ Bottomonium is excluded as explanation.
- Their masses are close to an open bottom threshold
  - $m_{Z_b} = 10607.2\,\mathrm{MeV}$ versus $m_B + m_{B^*} = 10604.4\,\mathrm{MeV}$
  - $m_{Z_b'} = 10652.3\,\mathrm{MeV}$ versus $2m_{B^*} = 10650.2\,\mathrm{MeV}$

It's seems to be the $X(3872)$ story repeated in the bottom sector.

The $Z_c(3900)$ and $Z_c'(4020)$: Molecules?

The $Z_c(3900)$ and $Z_c'(4020)$ (discovered by BESIII in 2013)

- They are hidden charm ($c\bar{c}$): $Z_c^{(\prime)} \to J/\Psi\pi, h_c\pi, D^{(*)}\bar{D}^*$
- They are charged: Z_c^+, Z_c^0, Z_b^- isospin triplet
  $\Longrightarrow$ Charmonium is excluded as explanation.
- Their masses are close to an open charm threshold
  - $m_{Z_c} = 3888.7\,\mathrm{MeV}$ versus $m_{D^0} + m_{D^{+*}} = 3875.1\,\mathrm{MeV}$
  - $m_{Z_c'} = 4023.9\,\mathrm{MeV}$ versus $m_{D^{*0}} + m_{D^{+*}} = 4017.2\,\mathrm{MeV}$

  PDG Averages, there has been discussion on whether all determinations corresponded to the same resonance: $Z_c(3885)$ = $Z_c(3900)$? $Z_c'(4020) = Z_c'(4024)$?

The Z_b, Z_b' story repeated in the charm sector. Yet this might indicate that they are molecular! Let's see why...

Symmetries in Heavy Meson Molecules (I)

Heavy Meson Molecules: $Q\bar{Q} \times q\bar{q}$

- Heavy quark-antiquark $Q\bar{Q}$: heavy quark symmetry
  - Heavy quark spin symmetry (HQSS):

$$Q\uparrow Q\uparrow \simeq Q\uparrow Q\downarrow \simeq Q\downarrow Q\uparrow \simeq Q\downarrow Q\downarrow$$

  - Heavy flavor symmetry (HFS):

$$b\bar{b} \simeq b\bar{c} \simeq c\bar{b} \simeq c\bar{c}$$

  - Heavy antiquark-diquark symmetry (HADS):

$$QQ \simeq \bar{Q}$$

- Light quark-antiquark: SU(3)-flavor multiplets.

This remarkable high degree of symmetry is probably the most amazing theoretical property of heavy meson molecules.

Symmetries in Heavy Meson Molecules (II)

Heavy Meson Molecules: $Q\bar{Q} \times q\bar{q}$

But this is also the quark content of tetraquarks.

How can we distinguish? Heavy Quark Symmetry is a symmetry of the QCD Lagrangian, can manifest at different levels:

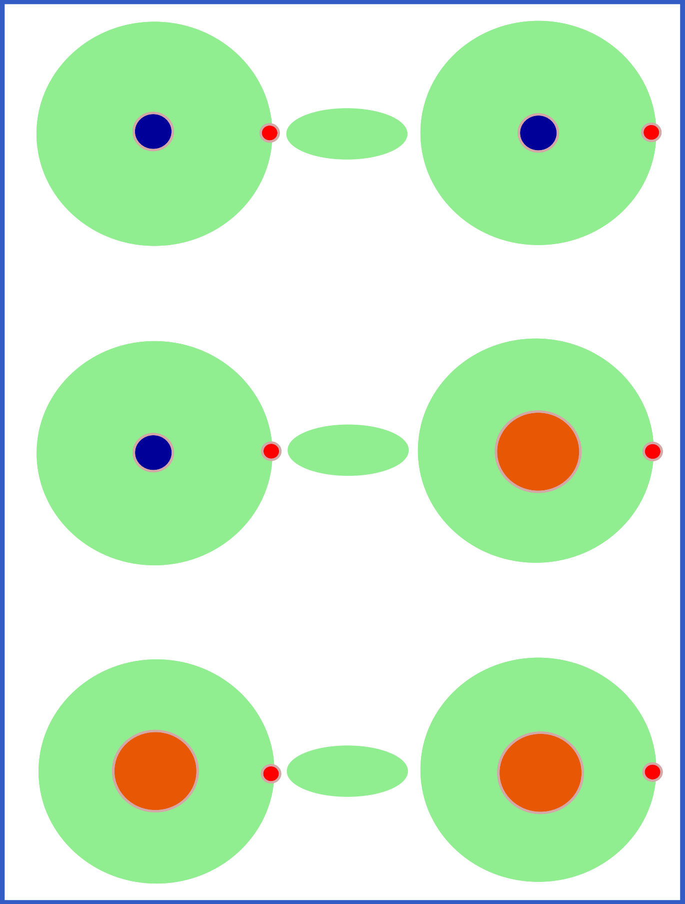
- Heavy Mesons: symmetry in the spectrum
- Heavy Meson Molecules: non-relativistic QM binding problem
  - Symmetry in the potential, but not in the spectrum!

For tetraquarks or hadrocharmonium, the manifestation of the symmetry will depend on the dynamics generating the binding.

One has to compare the different predictions for the spectrum!

HFS: Molecules

Heavy Flavor Symmetry: potential does not depend on heavy flavor.



The light quark cloud around the heavy quark is always the same.

Thus we have four flavor sectors

- $\mathrm{D\bar{D}}$, DB, $\mathrm{\bar{B}\bar{D}}$, $\mathrm{B\bar{B}}$

where the potentials are identical (modulo Λ_{QCD}/m_Q errors).

HFS: Predicting New States (I)

Heavy Flavor Symmetry: a molecule in a heavy flavor sector might have a partner in a different flavor sector.

- The $X_c(3872)$ will have a $0^+(1^{++})$ $B^*\bar{B}$ partner, the X_b.
- The $Z_b(10610)$ might have a $1^+(1^{+-})$ $D^*\bar{D}$ partner, the Z_c.

Caveat: is a symmetry on the potential, not on the binding energy. However, we have the relationship:

$$\frac{dB}{dm_Q} > 0\,,$$

that is, binding increases with the heavy quark mass!

Guo, Hidalgo, Nieves, Valderrama (13)

HFS: Predicting New States (II)

$I(J^{PC})$	$\mathrm{H\bar{H}}$	M ($\Lambda = 0.5$)	M ($\Lambda = 1$ GeV)	Exp.
$0(1^{++})$	$D\bar{D}^*$	Input	Input	3871.86
$0(1^{++})$	$B\bar{B}^*$	10580^{+7}_{-6}	10539^{+19}_{-20}	-
$0(2^{++})$	$B^*\bar{B}^*$	10626^{+6}_{-6}	10584^{+19}_{-20}	-
$1(1^{+-})$	$B\bar{B}^*$	10602.4 ± 2.0	10602.4 ± 2.0	10604
$1(1^{+-})$	$B^*\bar{B}^*$	10648.2 ± 2.1	10648.1 ± 2.2	10650.0
$1(1^{+-})$	$D\bar{D}^*$	3870^{+4}_{-20} (V)	3836^{+13}_{-30} (V)	3885/3899
$1(1^{+-})$	$D^*\bar{D}^*$	4013^{+3}_{-9} (V)	3983^{+14}_{-28} (V)	4020/4025

Not perfect determination for the Z_c and Z_c' location, but points out in the right direction.

HFS: Predicting New States (III)

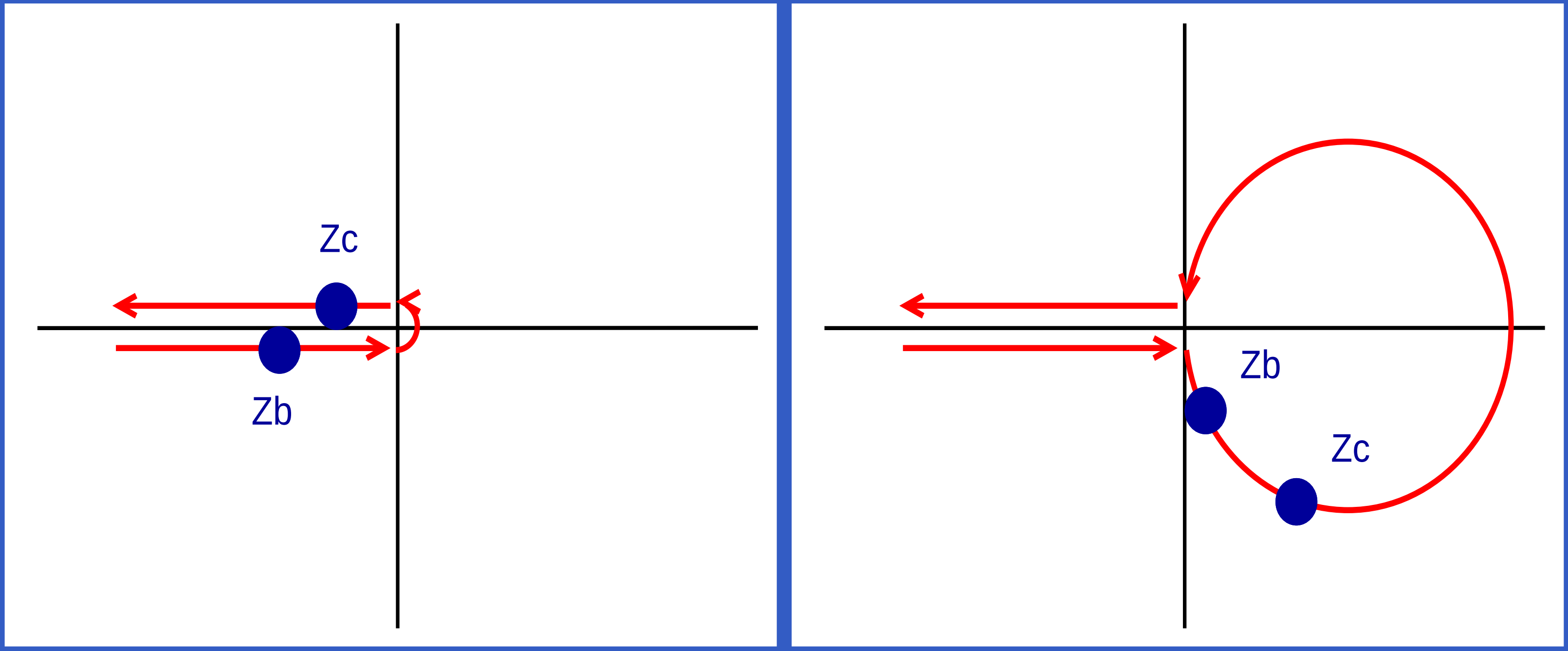
The previous predictions correspond to the LO of a really simple EFT that only contains contact interactions.

There are several effects that can change the spectrum:

- The X_b's receive significant corrections from OPE exchange
- The Z_c and Z_c' might change their position:
  - A short-range repulsive barrier does not enter till NLO.
  - Z_c-Z_c' couple: Z_c gets attraction (more binding), Z_c' repulsion (less binding, more virtual), but the effect is modest and also subleading (NNLO).
  - Maybe not the most adequate EFT: the Z_c's are shallow resonances, not bound states. We require an EFT that includes their finite width at leading order.

HFS: Predicting New States (IV)

With a more sophisticated EFT results would change to:



In the second case, the predictions for the Z_c's improve considerably.

But a consistent formulation of this kind of EFT is not simple.

HFS: Predicting New States (V)

Conclusion: the molecular Z_c's are moderately close to threshold.

Are the molecular Z_c/Z_c' the physical $Z_c(3900)$/$Z_c'(4020)$?

- Spectroscopy: promising candidates!
  - Tetraquark predictions for Z_c/Z_c' are: $3752/3882\,\mathrm{MeV}$

    Ali, Hambrock, Wang 12
  - Molecular predictions have yet room for improvement.
- Decays: they provide further insight on the nature of the Z_c's.

  X: Voloshin 04; Braaten, Lu 07; Z_b's: Mehen, Powell 13; Z_c's production: Wang, Hanhart, Zhao 13; Chen, Liu, Matsuki 13; Wang, Sun, CLM 13; Martinez-Torres et al. 13; plus many other works.

Yet the molecular interpretarion links the Z_b's and the $Z_c's$, pointing strongly in favor of this interpretation.

The $Y's(4260/4360/\ldots)$: Hadrocharmonia?

Set of broad resonances with $\Psi(nS)$ charmonium quantum numbers:

- $Y(4260)$: $M_Y = 4251 \pm 9\,\mathrm{MeV}$, $J^p = 1^{--}$
- $Y(4360)$: $M_Y = 4361 \pm 13\,\mathrm{MeV}$, $J^p = 1^{--}$
- They contain hidden charm ($c\bar{c}$):
  - $Y(4260) \to J/\Psi\, 2\pi\,,\ J/\Psi +$ "light stuff"
  - $Y(4360) \to \Psi(2S)\, 2\pi\,,\ \Psi(2S) +$ "light stuff"

Originally, most of the decays where to a $\Psi(nS)$ plus light hadrons. Dubyinskiy and Voloshin proposed hadrocharmonium:

- $c\bar{c}$ compact core in a $\Psi(nS)$ configuration
- $q\bar{q}$ light cloud, which is the one that decays

Thus explaining the regularities in the decays.

The $Y's(4260/4360/\dots)$: or Molecular?

However the decay modes:

$$
\begin{aligned}
Y(4260) &\rightarrow Z_c^{\pm}(3900)\,\pi^{\mp} \\
Y(4260) &\rightarrow Z_c^{\pm}(4020)\,\pi^{\mp}
\end{aligned}
$$

which were discovered later, lead to:

- discovery of the probably molecular Z_c's.
- molecular interpretation of the $Y(4260)$ as a $D_1\bar{D}$ bound state.

  Wang, Hanhart, Zhao 13; Guo, Hanhart, Meißner, Wang, Zhao 13; Liu, Li 13

Prediction of New XYZ States

Heavy Quark Symmetry can explain patterns of the XYZ spectrum:

- The $Z_c^{(\prime)}$ is a HFS partner of the $Z_b^{(\prime)}$ resonance.
- The Z_c, Z_c' (Z_b, Z_b') come in pairs (HQSS).

  We will see this in a moment

However, we have also seen that HFS predicts a hidden bottom partner of the $X(3872)$:

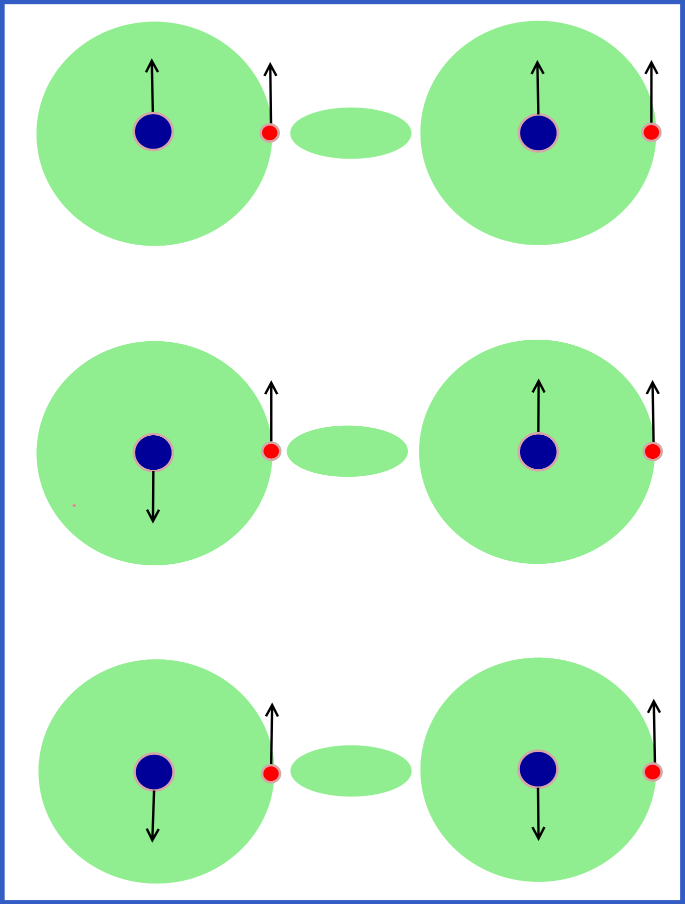
- Molecular X_b: $M \sim 10580\,\mathrm{MeV}$, $I^G = 0^+ \; J^{pc} = 1^{++}$
- Tetraquark X_b: $M \sim 10504\,\mathrm{MeV}$ Ali et al. 09

Yet this is not the only prediction in this line. We will now check:

- Heavy Quark Spin Symmetry
- Heavy Antiquark Diquark Symmetry

HQSS in Molecules

HQSS: potential does not depend on the spins of the heavy quarks



Six S-wave configurations

- $\mathrm{D\bar{D}}$, $J^{PC} = 0^{++}$
- $\mathrm{D\bar{D}^* + D^*\bar{D}}$, $J^{PC} = 1^{+-}$
- $\mathrm{D\bar{D}^* - D^*\bar{D}}$, $J^{PC} = 1^{++}$
- $\mathrm{D^*\bar{D}^*}$, $J^{PC} = 0^{++}$
- $\mathrm{D^*\bar{D}^*}$, $J^{PC} = 1^{+-}$
- $\mathrm{D^*\bar{D}^*}$, $J^{PC} = 2^{++}$

where the interactions can be related by HQSS.

HQSS and the LO Potential

Alfiky, Gabbiani, Petrov (06): only two s-wave couplings from HQSS

$$
\begin{aligned}
V^{(-1)}_{\mathrm{P\bar{P}}}(\vec{q},\, 0^{++}) &= C_{Ia}\,, \\
V^{(-1)}_{\mathrm{P^*\bar{P}/P\bar{P}^*}}(\vec{q},\, 1^{+-}) &= C_{Ia} - C_{Ib}\,, \\
V^{(-1)}_{\mathrm{P^*\bar{P}/P\bar{P}^*}}(\vec{q},\, 1^{++}) &= C_{Ia} + C_{Ib}\,, \\
V^{(-1)}_{\mathrm{P^*\bar{P}^*}}(\vec{q},\, 0^{++}) &= C_{Ia} - 2\,C_{Ib}\,, \\
V^{(-1)}_{\mathrm{P^*\bar{P}^*}}(\vec{q},\, 1^{+-}) &= C_{Ia} - C_{Ib}\,, \\
V^{(-1)}_{\mathrm{P^*\bar{P}^*}}(\vec{q},\, 2^{++}) &= C_{Ia} + C_{Ib}\,.
\end{aligned}
$$

where we can appreciate certain patterns, for example:

- $V^{(-1)}(1^{+-})$: similar binding for $Z_b(10610)$ and $Z_b(10650)$.

  Bondar et al. (11); Cleven et al. (11); Voloshin (11); Mehen and Powell (11).

HQSS, the $X(3872)$ and the $X(4012)$

There is another pair of quantum numbers with identical LO potentials:

- $V^{(-1)}_{\mathrm{P^*\bar{P}/P\bar{P}^*}}(1^{++}) = V^{(-1)}_{\mathrm{P^*\bar{P}^*}}(2^{++})$

which implies the following:

> If the $X(3872)$ is a $D\bar{D}^*/D^*\bar{D}$ molecule with $J^{PC} = 1^{++}$,
> then there should be a $X(4012)$ $D^*\bar{D}^*$ molecule with $J^{PC} = 2^{++}$.

Comments:

- Isospin symmetric limit: the $X(3872)$ is a $D\bar{D}^*/D^*\bar{D}$ molecular state with binding $B_X \simeq 4\,\mathrm{MeV}$.
- HQSS violations ($\sim \frac{\Lambda_{\mathrm{QCD}}}{m_c}$): $M = 4012^{+4}_{-9}\,\mathrm{MeV}$.
- OPE effects small ($2-3\,\mathrm{MeV}$) but generate width ($\sim 10\,\mathrm{MeV}$).

Bottomline: the $X(4012)$ prediction looks relatively solid.

Nieves, Valderrama (12).

HQSS: More Predictions

Other predicted state in this line is:

- $X(3700)$: a 0^{++} $D\bar{D}$ bound state
  - HQSS + EFT (Nieves, Valderrama 12)
  - Hidden Gauge Model (Gamerman et al. 07)

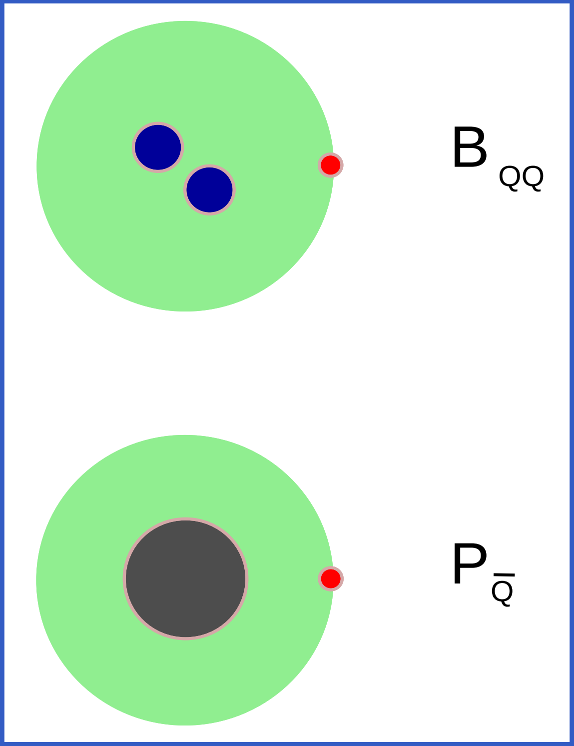
Other state that has been proposed to be molecular is:

- $X(3915)$ compatible with a $D^*\bar{D}^*$ 0^{++} molecule (Liu, Zhu 09; Branz, Gutsche, Lyubovitskij 09; Ding 09)
  - Also proposed to be the $\chi_{c0}(2P)$ charmonium. However, that leads to a width of the order of $100 - 200\,\mathrm{MeV}$ versus the experimental one of $20\,\mathrm{MeV}$

    Guo, Meißner 12

HADS: Mesons

Heavy antiquark-diquark symmetry: a heavy quark pair approximately behaves as a single heavy antiquark.

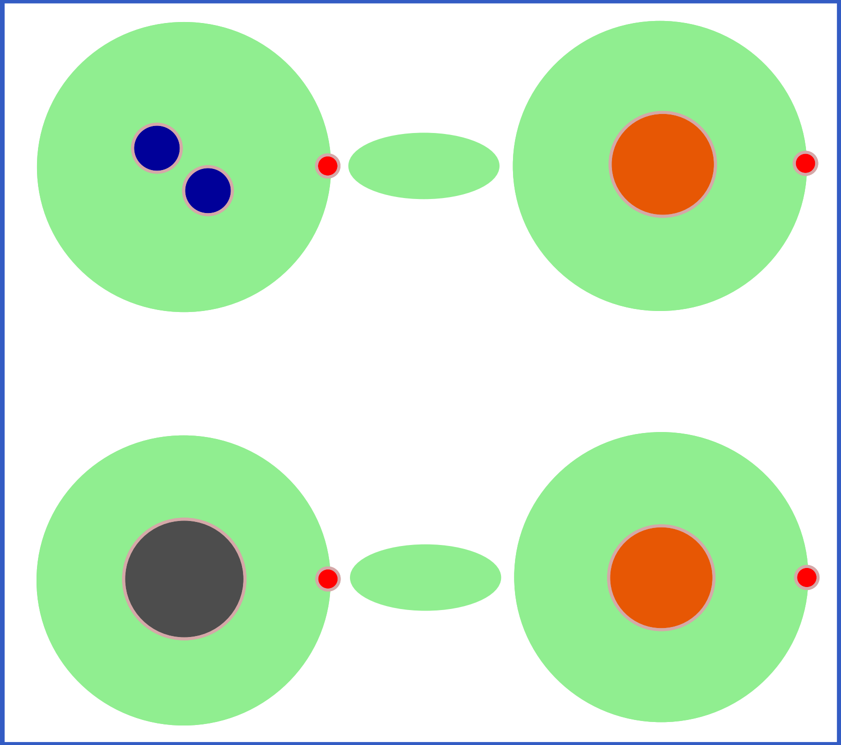


The light quark cloud around the heavy quark pair of a doubly heavy baryon is the same as the one around a heavy antimeson...

...with an error of $\Lambda_{\mathrm{QCD}}/(m_Q v)$ (40% in the charm sector, 20% in the bottom one).

HADS: Molecules

Heavy antiquark-diquark symmetry: a heavy quark pair approximately behaves as a single heavy antiquark.



And the potentials can be related by HADS and HQSS.

HADS: The Potentials

The meson-baryon potential is related to the meson-antimeson one:

$$
\begin{aligned}
V_C^{\rm LO}(\vec{q}, \Xi_{QQ} P, J = \frac{1}{2}) &= C_{Ia} \, , \\
V_C^{\rm LO}(\vec{q}, \Xi_{QQ} P^*, J = \frac{1}{2}) &= C_{Ia} + \frac{2}{3} C_{Ib} \, , \\
V_C^{\rm LO}(\vec{q}, \Xi_{QQ} P^*, J = \frac{3}{2}) &= C_{Ia} - \frac{1}{3} C_{Ib} \, , \\
V_C^{\rm LO}(\vec{q}, \Xi^*_{QQ} P, J = \frac{3}{2}) &= C_{Ia} \, , \\
V_C^{\rm LO}(\vec{q}, \Xi^*_{QQ} P^*, J = \frac{1}{2}) &= C_{Ia} - \frac{5}{3} C_{0b} \, , \\
V_C^{\rm LO}(\vec{q}, \Xi^*_{QQ} P^*, J = \frac{3}{2}) &= C_{Ia} - \frac{2}{3} C_{0b} \, , \\
V_C^{\rm LO}(\vec{q}, \Xi^*_{QQ} P^*, J = \frac{5}{2}) &= C_{Ia} + C_{Ib} \, ,
\end{aligned}
$$

HADS: Predicting New States (I)

If we restrict ourselves to the most solid input – X(3872) and its isospin breaking decays, plus the Z_b's – we arrive at (isoscalars):

State	$I(J^P)$	Mass ($\Lambda = 0.5$ GeV)	Mass ($\Lambda = 1$ GeV)
$\Xi_{cc}^* D^*$	$0(\frac{5}{2}^-)$	$(M_{\rm th} - 10)^{+9}_{-14}$	$(M_{\rm th} - 19)^{\dagger}_{-40}$
$\Xi_{cc}^* \bar{B}^*$	$0(\frac{5}{2}^-)$	$(M_{\rm th} - 21)^{+15}_{-18}$	$(M_{\rm th} - 53)^{+43}_{-55}$
$\Xi_{bb}^* D^*$	$0(\frac{5}{2}^-)$	$(M_{\rm th} - 15)^{+8}_{-10}$	$(M_{\rm th} - 35)^{+23}_{-28}$
$\Xi_{bb}^* \bar{B}^*$	$0(\frac{5}{2}^-)$	$(M_{\rm th} - 29)^{+11}_{-11}$	$(M_{\rm th} - 83)^{+34}_{-36}$
$\Xi_{bc}' D^*$	$0(\frac{3}{2}^-)$	$(M_{\rm th} - 14)^{+10}_{-11}$	$(M_{\rm th} - 30)^{+24}_{-35}$
$\Xi_{bc}' \bar{B}^*$	$0(\frac{3}{2}^-)$	$(M_{\rm th} - 27)^{+14}_{-14}$	$(M_{\rm th} - 74)^{+40}_{-45}$
$\Xi_{bc}^* D^*$	$0(\frac{5}{2}^-)$	$(M_{\rm th} - 14)^{+10}_{-12}$	$(M_{\rm th} - 30)^{+25}_{-36}$
$\Xi_{bc}^* \bar{B}^*$	$0(\frac{5}{2}^-)$	$(M_{\rm th} - 27)^{+14}_{-14}$	$(M_{\rm th} - 74)^{+42}_{-47}$

HADS: Predicting New States (II)

While in the isovector sector (actual pentaquarks) we have:

State	$I(J^P)$	Mass ($\Lambda = 0.5$ GeV)	Mass ($\Lambda = 1$ GeV)
$\Xi_{bb}\bar{B}$	$1(\frac{1}{2}^-)$	$(M_{\rm th} - 0.3)^{\dagger}_{-2.1}$	$(M_{\rm th} - 13)^{+10}_{-13}$
$\Xi_{bb}\bar{B}^*$	$1(\frac{1}{2}^-)$	$(M_{\rm th} - 0.9)$[V]$^{\rm N/A}_{\dagger\dagger}$	$(M_{\rm th} - 17)^{+11}_{-17}$
$\Xi_{bb}\bar{B}^*$	$1(\frac{3}{2}^-)$	$(M_{\rm th} - 1.2)^{\dagger}_{-2.6}$	$(M_{\rm th} - 11)^{+8}_{-11}$
$\Xi^*_{bb}\bar{B}$	$1(\frac{3}{2}^-)$	$(M_{\rm th} - 0.3)^{\dagger}_{-2.1}$	$(M_{\rm th} - 13)^{+10}_{-12}$
$\Xi^*_{bb}\bar{B}^*$	$1(\frac{1}{2}^-)$	$(M_{\rm th} - 8)^{+7}_{-7}$	$(M_{\rm th} - 4)^{\dagger}_{-9}$
$\Xi^*_{bb}\bar{B}^*$	$1(\frac{3}{2}^-)$	$(M_{\rm th} - 2.5)^{\dagger}_{-3.2}$	$(M_{\rm th} - 9)^{+8}_{-10}$
$\Xi^*_{bb}\bar{B}^*$	$1(\frac{5}{2}^-)$	$(M_{\rm th} - 4.4)$[V]$^{\rm N/A}_{+3.5}$	$(M_{\rm th} - 20)^{+14}_{-18}$

Conclusions

- XYZ States have opened new vistas in hadron spectroscopy
  - Not all is charmonium, there might also be molecules, tetraquarks, hadrocharmonium, hybrids and so on.
  - It's very probable that a few XYZ are molecules indeed: $X(3872)$, Z_c's and $Z_b's$
- Molecular picture together with HQS is predictive
  - HFS: The $Z_c(3900)$ might be a partner of the $Z_b(10610)$.
  - HFS: The $X(3872)$ probably has hidden bottom partners.
  - HQSS: The $X(3872)$ implies the existence of a 2^{++} $X(4012)$
- Much work yet to be done, more so concerning decays.

Time to Finish

Thanks for your attention!

The End.