The Heavy (and Light) Symmetries of Heavy Meson Molecules

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Quarkonium 2013, Beijing

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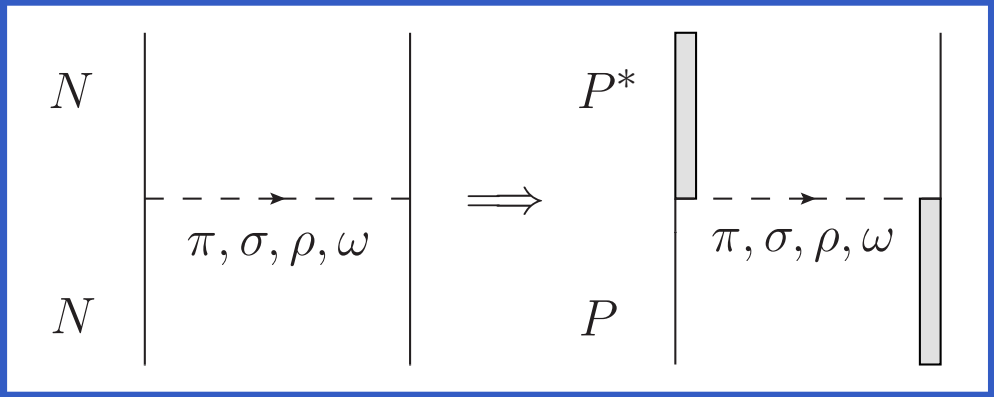
Biblio: PRD 85 (2012) 114037, PRD 86 (2012) 056004,
PRD 87 (2013) 076006, arXiv:1303.6608

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).

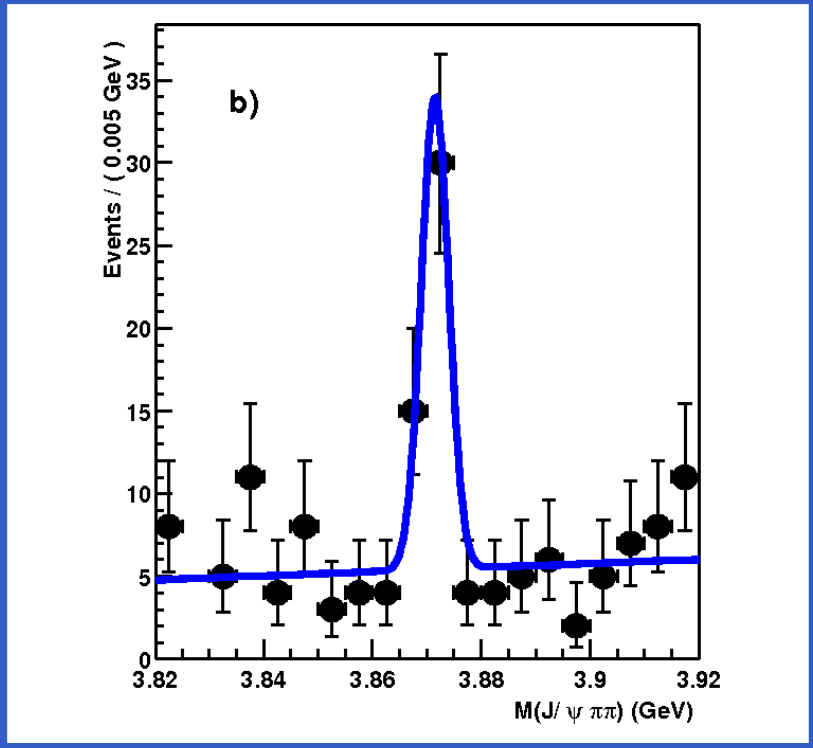


  They are just like the deuteron, but composed of heavy hadrons instead of nucleons.

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

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

...and the perfect playground for theoreticians.

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

Alternative explanations (tetraquark, charmonium, etc.) also possible.

But the X(3872) is not the only molecular candidate so far...

The XYZ States

There are many other X, Y and Z states:

- A few are standard quarkonia: $Z(3930)$ as $\chi_{c2}(2P)$.
- But other are more exotic. Some may be molecular:
  - E.g. $Y(4660)$ as $f_0(980)\psi'$, $X(3915)$ as $D^*\bar{D}^*$, $Y(4140)$ as $D_s^*\bar{D}_s{}^*$, $Y(4260)$ as $D\bar{D}_1$, plus many other proposals*.

Recent discoveries:

- $Z_b(10610/10650)$ by Belle: $I^G(J^{PC}) = 1^+(1^{+-})$, very close to BB^*/B^*B^* thresholds. Nice candidate!
- $Z_c(3900)$ by BESIII: $I^G(J^{PC}) = 1^+(1^{+-})$.
- $X(3823)$ by Belle: $C = -1$.

*$Y(4660)$: Guo, Hanhart, Meißner 08; $X(3915)$: Liu, Zhu 09; Branz, Gutsche, Lyubovitskij 09; Ding 09; Molina, Oset 09; $Y(4260)$: Wang, Hanhart, Zao 13; $Z_c(3900)$ Guo et al. 13

Heavy Meson Molecules and EFT

Genuine heavy meson molecule: mesons do not overlap too much

size of molecule ($r_{\rm bs}$) > size of mesons ($r_{\rm meson}$)

That is, there is a separation of scales: amenable to EFT treatment!

The EFT approach for molecular states:

- At leading order ($\rm LO$) the heavy mesons interact via a momentum and energy-independent (i.e. contact range) s-wave potential

$$V^{\rm LO}(\vec{q}) = C$$

  and calculations are easy (though renormalization is required).

- Description valid for momenta $p \leq M \sim 0.5\,{\rm GeV}$
- What about pion exchanges? Well, they are subleading!

  (see Valderrama (12) for instance)

Symmetries in Heavy Meson Molecules

But the really interesting property of molecules are their symmetries:

- Heavy quarks: heavy molecules have heavy quark symmetry
  - Heavy quark spin symmetry (HQSS): heavy molecules can be arranged into multiplets of up to six states.
  - Heavy flavor symmetry (HQSS): multiplets with hidden charm (bottom) might have hidden (bottom) charm counterparts.
- Light quarks:
  - Pion exchanges constrained by chiral symmetry.
  - Heavy molecules can also be classified within SU(3)-flavor multiplets.

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

HQSS and the LO Potential

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

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

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:

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

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 (without particle mixing) are small: $\Delta M = 2 - 3\,\mathrm{MeV}$.

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

Nieves, Valderrama (12).

HQSS: Predicting New States (I)

There are two counteterms at LO: C_{0a} and C_{0b}:

- The $X(3872)$ can fix a linear combination ($C_{0a} + C_{0b}$) and thus predict one HQSS partner, the $X(4012)$.
- We need to assume the molecular nature of another state to fix C_{0b} and predict the full spectrum of $D^{(*)}\bar{D}^{(*)}$ molecules.

Candidates:

- $X(3915)$ compatible with a $D^*\bar{D}^*$ 0^{++} molecule

  (Liu, Zhu 09; Branz, Gutsche, Lyubovitskij 09; Ding 09)
- $X(3940)$ could also be $D^*\bar{D}^*$ molecule. However:
  - Decays mostly to $D\bar{D}^*$: compatible with $J^{PC} = 1^{+-}$.
  - The most probable production mechanism, $e^+e^- \to \gamma^* \to J/\Psi X(3940)$, suggests $C = +1$ instead.

HQSS: Predicting New States (II)

Then, we assume the $X(3915)$ to be a $D^*\bar{D}^*$ 0^{++} molecule:

J^{PC}	$\mathrm{H}\bar{\mathrm{H}}$	E ($\Lambda = 0.5$ GeV)	E ($\Lambda = 1$ GeV)	Exp (PDG)
0^{++}	$D\bar{D}$	3706 ± 10	3712^{+13}_{-17}	?
1^{++}	$D^*\bar{D}$	Input	Input	3872
1^{+-}	$D^*\bar{D}$	3814 ± 17	3819^{+24}_{-27}	3823 (!?)
0^{++}	$D^*\bar{D}^*$	Input	Input	3917
1^{+-}	$D^*\bar{D}^*$	3953 ± 17	3956^{+25}_{-28}	3942 (!?)
2^{++}	$D^*\bar{D}^*$	4012 ± 3	4012^{+4}_{-9}	?

We predict a total of six states! (Curiously there is a state in the region of the $X(3940)$, maybe resuggesting $C = -1$ after all; yet mass alone is not enough to identify a molecule!)

$SU(3)_F$ + HQSS: Predicting New States (I)

Extension to the isovector (and strange) molecular states:

Four couplings: C_{0a}, C_{0b} (isoscalar) and C_{1a}, C_{1b} (isovector).

- Isoscalar:
  - $X(3872)$: $C_{0a} + C_{0b}$
  - $X(3915)$: $C_{0a} - 2C_{0b}$
- Isovector:
  - $Y(4140)$ as a $D_s^* \bar{D}_s^*$ molecule: $\frac{1}{2}(C_{0a} - 2C_{0b}) + \frac{1}{2}(C_{1a} - 2C_{1b})$
  - Isospin breaking decays of the $X(3872)$:

$$\mathcal{B}_X \equiv \frac{\Gamma(X \to J/\Psi 3\pi)}{\Gamma(X \to J/\Psi 2\pi)} = 0.8 \pm 0.3$$

determines the isovector 1^{++} coupling: $C_{1a} + C_{1b}$

Hidalgo-Duque, Nieves, Valderrama (13)

$SU(3)_F$ + HQSS: Predicting New States (II)

About 15 (of 24) states predicted:

- No exact isovector partner of the $X(3872)$: $1^-(1^{++})$ $D\bar{D}^*$ molecule does not bind.
- There are two $1^+(1^{+-})$ $D\bar{D}^*/D^*\bar{D}^*$ molecule (Z_c's) at:

$$M = 3848 \underbrace{{}^{+12}_{-11}}_{\text{HQS}} \underbrace{{}^{+22}_{-40}}_{\text{SU(3)}} \qquad M' = 3988 \underbrace{{}^{+13}_{-13}}_{\text{HQS}} \underbrace{{}^{+22}_{-41}}_{\text{SU(3)}}$$

  But this is not the most reliable way to determine the location of a molecular Z_c. Why? Well...

- Predictions exploratory. Subjected to uncertainties:
  - Is $X(3915)$ really molecular? Does the $Y(4140)$ even exist?
  - Apart from approximate HQSS, we also have SU(3) violations.

HFS: Predicting New States (I)

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

$$V_{D^{(*)}\bar{D}^{(*)}}(J^{PC}) = V_{\bar{B}^{(*)}B^{(*)}}(J^{PC}) = V_{D^{(*)}B^{(*)}}(J^{PC}) = \dots$$

A pattern in a given heavy flavor channel may very likely repeat itself in the other flavor channels:

- If the $X_c(3872)$ is in fact a $0(1^{++})$ $D^*\bar{D}$ molecule, we should expect a $0(1^{++})$ $B^*\bar{B}$ molecular partner, the X_b.
- Conversely if there is a $Z_b(10610)$ we can expect that there will be a $1(1^{+-})$ $D^*\bar{D}$ molecular partner.

Caveat: binding depends on the reduced potential and hence deviations are expected from a naive repetition of patterns.

Guo, Hidalgo, Nieves, Valderrama (13)

HFS: Predicting New States (II)

$I(J^{PC})$	$\mathrm{H}\bar{\mathrm{H}}$	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}	-
$0(2^{+})$	D^*B^*	7322^{+4}_{-6}	7308^{+12}_{-15}	-
$1(1^{+-})$	$B\bar{B}^*$	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)	3899
$1(1^{+-})$	$D^*\bar{D}^*$	4013^{+3}_{-9} (V)	3983^{+14}_{-28} (V)	-
$1(1^{+})$	D^*B^*	$7333.5^{+0.2}_{-1.6}$ (V)	7328^{+4}_{-13} (V)	-

HFS: Predicting New States (III)

Well, 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:
  - Close to threshold: fine tuning? might they move away?
  - Z_c-Z_c' couple: Z_c gets attraction (more binding), Z_c' repulsion (less binding, more virtual), but the effect is modest.
  - Z_c might move above threshold owing to coupling to other, more nearby channels ($h_c\pi$, $\psi\pi$, ...).

Conclusion: apart from moderately close to threshold, little can be said about the mass of the molecular Z_c. Promising candidate for the $Z_c(3900)$, but a molecular identification requires more than the mass.

Comparison with Other Works

- Isoscalar hidden charm sector: similar spectrum also found in hidden gauge and in quark model.
  - Exception: $X(4012)$, usually predicted to be more bound.
    (Maiani et al. 05; Molina, Oset 09)
- Isovector hidden charm sector: no states predicted in hidden gauge. In potential models they do not usually bind either. But there was a tetraquark prediction of the Z_c's!
  (Ali, Hambrock, Wang (12))
- Finally, the molecular nature of the $X(3915)$ and $Y(4140)$ (our input) have been proposed in many previous works.
  (Maiani et al 05; Liu, Zhu 09; Branz, Gutsche, Lyubovitskij 09; Ding 09)

Quite probably there are other works with similar predictions.

Conclusions

- EFT formalism of heavy meson molecules:
  - Contact interactions dominate the low energy description.
- HQS allows the prediction of new molecular states from previously known ones:
  - HQSS: The $X(3872)$ implies the existence of a 2^{++} $X(4012)$
  - SU(3): If the $X(3915)$ and $Y(4140)$ molecular, expect around 15 isoscalar, isovector, strange and hidden strange states.
  - HFS: The $X(3872)$ probably has hidden bottom partners.
  - HFS: The $Z_c(3900)$ might be a partner of the $Z_b(10610)$.
- Theoretically robust against HQS violations and subleading order corrections (OPE and coupled channels).