XYZ states as hadronic molecules

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ФЕДЕРАЛЬНОЕ ГОСУДАРСТВЕННОЕ БЮДЖЕТНОЕ УЧРЕЖДЕНИЕ НАУКИ
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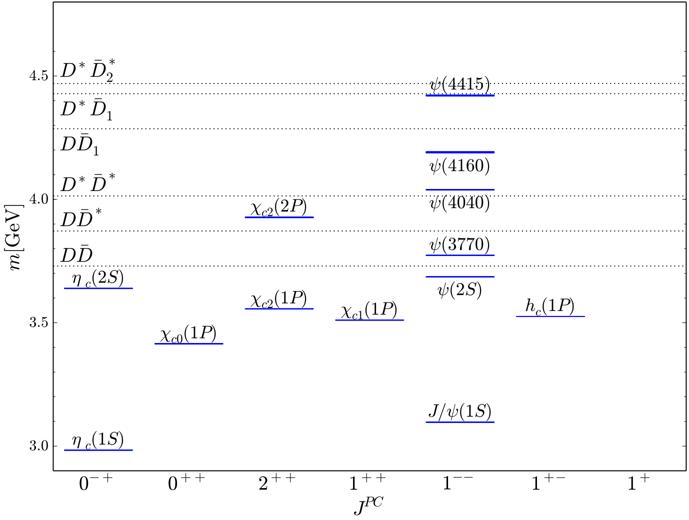
Spectrum of charmonium



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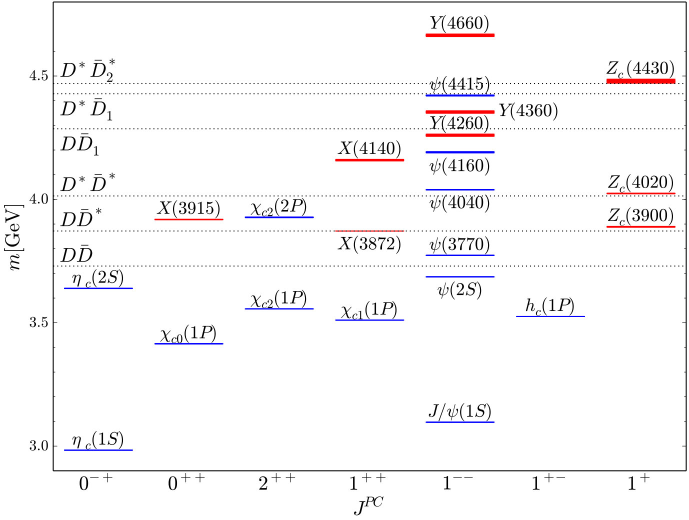
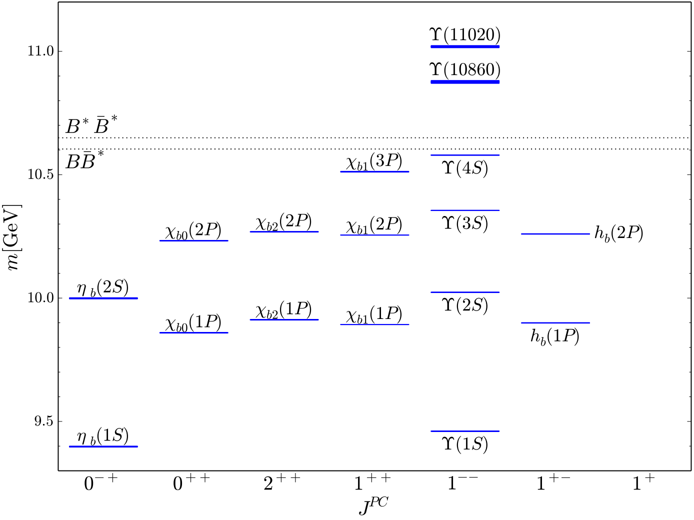


Spectrum of bottomonium



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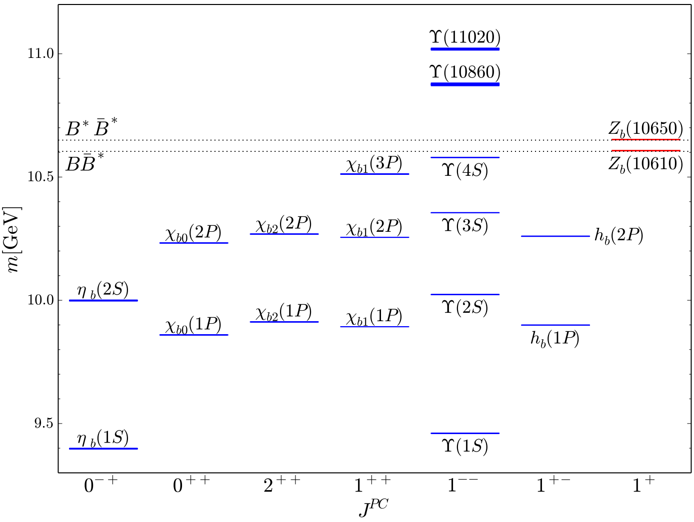

Meet XYZ states

- X's are new exotic states

$$X(3872) \quad X(3915) \quad X(4140) \quad \ldots$$

- Y's are exotic vector states (to tell from neat $\bar{c}c$ quarkonia ψ's)

$$Y(4230) \quad Y(4260) \quad Y(4360) \quad Y(4660) \quad \ldots$$

- Z's are charged exotic states

$$Z_c(3900) \quad Z_c(4020) \quad Z_c(4430) \quad Z_b(10610) \quad Z_b(10650) \quad \ldots$$

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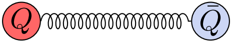
Naming scheme for XYZ states under review by PDG

Quark model



$$H = 2m_Q + \frac{p^2}{m_Q} + \sigma r - \frac{4\alpha_s}{3r} + C + V_{\text{spin-dep}}$$

Successes:

- Good description of spectrum below open-flavour threshold
- Reasonable description of leptonic, radiative, hadronic widths

Failure:

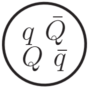
- Breakdown for higher quarkonia

What is missing?

- Constituent gluons
- Effects of light-quarks: loops, thresholds, pions

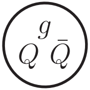
If not $\bar{Q}Q$ then what? Proposals...

- Tetraquark



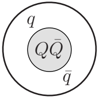
Compact object made of $(Qq)_{\bar{3}}$ and $(\bar{q}\bar{Q})_3$

- Hybrid



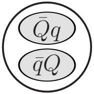
Compact object made of $(Q\bar{Q})_8$ + gluons

- Hadro-Quarkonium



$(Q\bar{Q})_1$ surrounded by light quarks

- Hadronic Molecule



Extended object made of $(\bar{Q}q)_1$ and $(\bar{q}Q)_1$

What is hadronic molecule?

Molecule = large probability to observe resonance in a given hadron-hadron channel

- Proximity of open-flavour thresholds $\Longrightarrow$ large admixture of meson-meson component in the w.f. of the resonance
- Nature of the resonance can be different:
  bound *versus* virtual state $\Longrightarrow$ dynamical problem

  Disclaimer: because of inelastic channels, poles in the complex E-plane are always on unphysical Riemann Sheets, away from the real axis $\Longrightarrow$ state = resonance
- Binding forces can be different:
  s- *versus* t-channel exchanges $\Longrightarrow$ different models

Have we met hadronic molecules so far?

Yes, we have! We know them for years in few nucleon systems

- $^3S_1$ NN system with $I = 0$:

$$a = 5.4 \text{ fm} \qquad r_e = 1.7 \text{ fm}$$

Pole on RS-I with $E_B = 2.23$ MeV $\Longrightarrow$ deuteron

- $^1S_0$ NN system with $I = 1$:

$$a = -24 \text{ fm} \qquad r_e = 2.7 \text{ fm}$$

Pole on RS-II with $E_B = 0.067$ MeV $\Longrightarrow$ virtual state

Composite or elementary?

$$F(k) = \frac{1}{-\frac{1}{a} + \frac{1}{2}k^2 r_e - ik}$$

Define probability to observe compact state $0 \leqslant Z \leqslant 1$:

$$a = \frac{2(1-Z)}{(2-Z)} \frac{1}{\sqrt{2\mu E_B}} \qquad r_e = -\frac{Z}{(1-Z)} \frac{1}{\sqrt{2\mu E_B}} + O\left(\frac{1}{\beta}\right)$$

β ($\gg k$) — (inverse) range of force

Deuteron: $Z \to 0 \implies$ molecule (Weinberg'60's)

Elementary (confined) state

- Effective range is large
- Scattering length is small
- Two near-threshold poles

Composite (molecular) state

- Effective range is small
- Scattering length is large
- One near-threshold pole

$\implies$ pole counting rules (Morgan'1992)

What to expect from molecules?

- Predominantly S-wave bound or virtual state of $(\bar{Q}q)$ and $(\bar{q}Q)$ mesons
- Seen in elastic $((\bar{Q}q)+(\bar{q}Q))$ and inelastic (e.g. $(\bar{Q}Q)+(\bar{q}q)$) channels
- Bound state molecule:
  - below-threshold peak in inelastic channels
  - above-threshold hump in elastic channels
- Virtual state molecule:
  - threshold cusp in inelastic channels
  - above-threshold hump in elastic channels

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Hard to distinguish

Impossible to distinguish

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Hard to distinguish

Impossible to distinguish

Combined analysis of all measured production and decay channels for a given resonance is necessary to reveal its nature

Heavy-quark spin symmetry

- Exotic XYZ states contain heavy quarks (HQ)
- In the limit $m_Q \to \infty$ $(m_Q \gg \Lambda_{\rm QCD})$ spin of HQ decouples

  $\Longrightarrow$ Heavy Quark Spin Symmetry (HQSS)
- For realistic m_Q's HQSS is approximate but rather accurate symmetry of QCD
- Predictions of HQSS depend crucially on the nature of states under study

  (Cleven et al.'2015)
- Quarkonium component of the w.f. (if exists) may impact the predictions

  (Cincioglu et al.'2016)
- HQSS is a tool to relate properties of states with different HQ spin orientation

  $\Longrightarrow$ Spin partners

  (Guo et al.'2009,Bondar et al.'2011,Voloshin et al.'2010,Mehen et al.'2011,Nieves et al.'2012,Guo et al.'2013,Albaladejo et al.'2015, Baru et al.'2016)

The X family

$X(3872)$: Experimental status

- Quantum numbers: $J^{PC} = 1^{++}$, $I = 0$
- Mass and width:

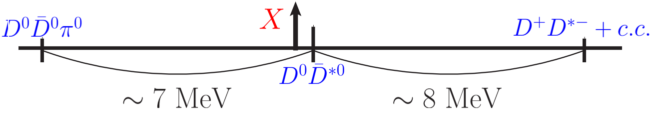
$$M_X = 3871.68 \pm 0.17 \text{ MeV} \qquad \Gamma_X < 1.2 \text{ MeV}$$

$$M_{D^0} + M_{\bar{D}^{*0}} - M_X = (0.00 \pm 0.18) \text{ MeV}$$

- Observation modes:
  - $X \to \pi^+\pi^- J/\psi$
    (Belle 2003, CDF, DØ, BABAR 2004-2006, LHCb 2013)
  - $X \to \pi^+\pi^-\pi^0 J/\psi$
    (Belle 2005, BABAR 2010)
  - $X \to D\bar{D}^* \nearrow D\bar{D}\pi$, $\searrow D\bar{D}\gamma$
    (Belle 2006, BABAR 2007)
  - $X \to \gamma J/\psi \qquad X \to \gamma\psi'(3686)$
    (BABAR 2008, Belle 2010/2011, LHCb 2014)
  - $e^+e^- \to \gamma X(3872)$
    (BESIII 2014)

Approach to $X(3872)$

- $X(3872)$ is a shallow bound state ($E_B \ll 1$ MeV) with a large admixture of the $D\bar{D}^*$ component in the w.f.
- The short-range component of the w.f. is responsible for the $X(3872)$ production at high energies, for radiative decays and decays to light hadrons
- Hadronic (long-range) component is responsible for open-charm decays
- Three-body ($D\bar{D}\pi$) dynamics is important in $X(3872)$ because of a very specific ordering of thresholds



(Suzuki'2005,Fleming et al.'2007,Baru et al.'2011,Guo et al.'2014)

$X(3915)$

Experimental background (Belle & BaBar)

- Seen in $B \to KX \to K(\omega J/\psi)$ and $\gamma\gamma \to X \to \omega J/\psi$
- Not seen in $D\bar{D}$
- Belle: 0^{++} or 2^{++} ($\chi_{c0}(2P)$ or $\chi_{c2}(2P)$ charmonium?)
- BaBar: 2^{++} ruled out by angular analysis in $\omega J/\psi$ ($\chi_{c0}(2P)$?)
- Good candidate for $\chi_{c0}(2P)$ exists: $X^*(3860)$ (Belle'2017)

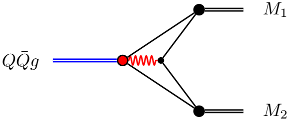
Theoretical insights

- $\chi_{c0}(2P)$ assignement for $X(3915)$ is questionable
  (Guo&Meißner'2012,Olsen'2014,Zhou et al.'2015)
- 2^{++} ruled out for $\bar{c}c$ charmonium, not for exotics
  (Liu et al.'2010)
- Current data not compatible with 2^{++} $D^*\bar{D}^*$ molecule
  (Baru et al.'2017)
- 0^{++} $D_s\bar{D}_s$ molecule assignement is plausible $\Longleftarrow$ To be verified
  (Li&Voloshin'2015)

The Y family

$Y(4260)$

- Small e^+e^- width, dip in R-ratio $\Longrightarrow$ hybrid?
  - Quantum numbers OK (vector hybrid)
  - Mass OK (compatible with lattice and models)
  - Decay modes unclear yet



Specific pattern of open-flavour decays to be verified in experiment

- Resides near S-wave $D_1\bar{D}$ threshold $\Longrightarrow$ molecule?
  - Good description of data in $J/\psi\pi\pi$, $h_c\pi\pi$ and $D\bar{D}^*\pi$ final states
  - Natural explanation of $Z_c(3900)$ appearance in $Y(4260)$ decays (Wang et al.'2013)
  - Confirmed prediction of $e^+e^- \to \gamma X(3872)$ in energy region near $Y(4260)$ (Guo et al.'2013)

The Z family

$Z_c(3900)$

Experimental status:

- Quantum numbers: $J^{PC} = 1^{+-}$, $I = 1$
- Mass and width:

$$M = 3886.6 \pm 2.4 \text{ MeV} \qquad \Gamma = 28.1 \pm 2.6 \text{ MeV}$$

- Observation modes: $J/\psi\pi$, $D\bar{D}^*$

Theoretical insights:

- Cannot be $\bar{c}c$ state — minimal quark contents four-quark
- Resides close to the $D\bar{D}^*$ threshold $\Longrightarrow$ molecule?
- Isovector cousin of $X(3872)$? (opposite C-parity)
- If confirmed to reside above threshold
  $\Longrightarrow$ Nontrivial interplay of different dynamics needed!

$Z_b(10610)$ & $Z_b(10650)$: Experimental status

- Quantum numbers: $J^{PC} = 1^{+-}$, $I = 1$
- Masses and widths:

$$M = 10607.2 \pm 2.0 \text{ MeV} \qquad \Gamma = 18.4 \pm 2.4 \text{ MeV}$$

$$M = 10652.2 \pm 1.5 \text{ MeV} \qquad \Gamma = 11.5 \pm 2.2 \text{ MeV}$$

- Production and decay modes:

$$\Upsilon(10860) \rightarrow \pi Z_b^{(\prime)} \rightarrow \pi B^{(*)}\bar{B}^*$$

$$\Upsilon(10860) \rightarrow \pi Z_b^{(\prime)} \rightarrow \pi\pi\Upsilon(nS) \quad n = 1, 2, 3$$

$$\Upsilon(10860) \rightarrow \pi Z_b^{(\prime)} \rightarrow \pi\pi h_b(mP) \quad m = 1, 2$$

- No suppression from heavy quark spin flip

$$\text{BF}(\Upsilon(10860) \rightarrow h_b(mP)\pi\pi) \simeq \text{BF}(\Upsilon(10860) \rightarrow \Upsilon(nS)\pi\pi)$$

$Z_b(10610)$ & $Z_b(10650)$ as molecules

$m_b \gg \Lambda_{\rm QCD} \implies$ Heavy Quark Spin Symmetry

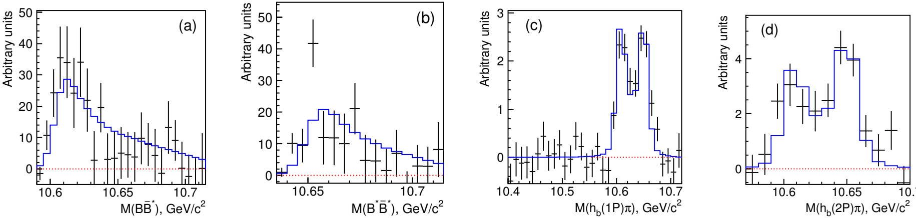
Molecule Z_b and Z_b' spin w.f.'s are ($B = 0^-_{\bar{b}q}$, $\bar{B} = 0^-_{\bar{q}b}$, $B^* = 1^-_{\bar{b}q}$, $\bar{B}^* = 1^-_{\bar{q}b}$)

$$|Z_b\rangle = \frac{1}{\sqrt{2}}\left[(1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q})_{S=1} + (0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q})_{S=1}\right]$$

$$|Z_b'\rangle = \frac{1}{\sqrt{2}}\left[(1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q})_{S=1} - (0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q})_{S=1}\right]$$

(Bondar et al.'2011)

Line shapes of the Z_b's can be described well in the molecule picture



(Hanhart et al.'2015,Guo et al.'2016)

$Z_b(10610)$ & $Z_b(10650)$ as molecules

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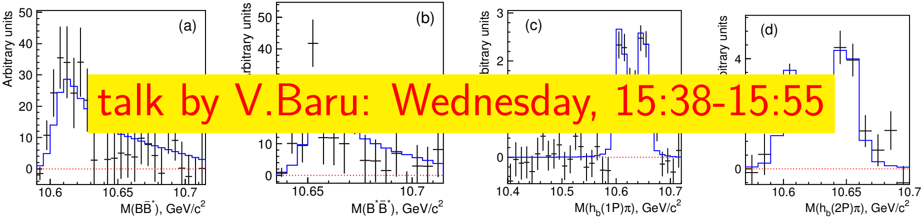


talk by V.Baru: Wednesday, 15:38-15:55

(Hanhart et al.'2015,Guo et al.'2016)

Spin partners (c-sector)

$Y(4260) = D_1\bar{D}$ molecule $\Longrightarrow$ $Y(4360) = D_1\bar{D}^*/D_2\bar{D}^*$ molecule

(Wang et al.'2013)

$Z_c(3900) = D\bar{D}^*$ molecule $\Longrightarrow$ $Z_c(4020) = D^*\bar{D}^*$ molecule

(Voloshin'2013)

$X(3872) = D\bar{D}^*$ molecule $\Longrightarrow$ $X_{c2} = D^*\bar{D}^*$ molecule

(Nieves&Valderrama'2012,Guo et al.'2013,Baru et al.'2016)

To be verified by...

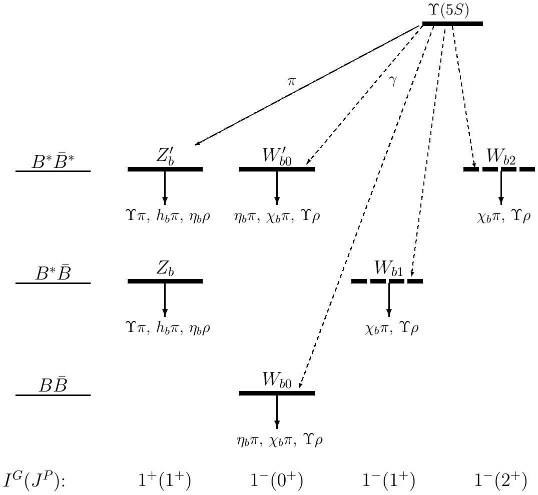
- Investigating decay modes

$$\begin{array}{lcl} Y(4260) & \rightarrow & D\bar{D}^*\pi, \pi\pi J/\psi \\ Y(4360) & \rightarrow & D^*\bar{D}^*\pi \\ Z_c(3900) & \rightarrow & D\bar{D}^*, \pi J/\psi, \pi\psi', \pi h_c, \rho\eta_c \end{array}$$

- Building systematic theoretical approach to $D^{(*)}D_J$ molecules
- Investigating HQSS breaking effects in c-sector
- Investigating role of pions

Spin partners (b-sector)

Prediction of Heavy Quark Spin Symmetry: J^{++} spin partner molecular states W_{bJ} $(J = 0, 1, 2)$ should exist



(Bondar et al.'2011,Voloshin'2011)

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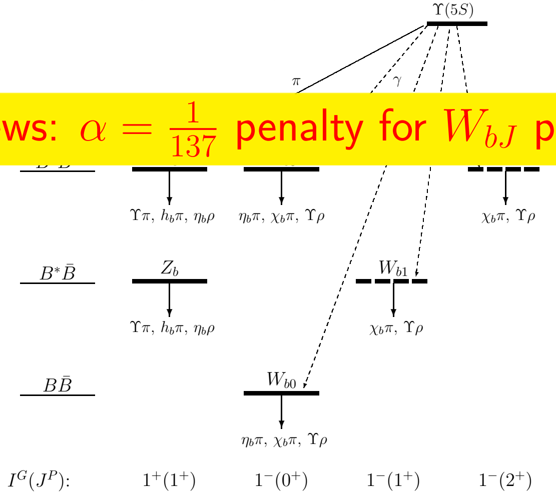

Bad news: $\alpha = \frac{1}{137}$ penalty for W_{bJ} production

(Bondar et al.'2011,Voloshin'2011)

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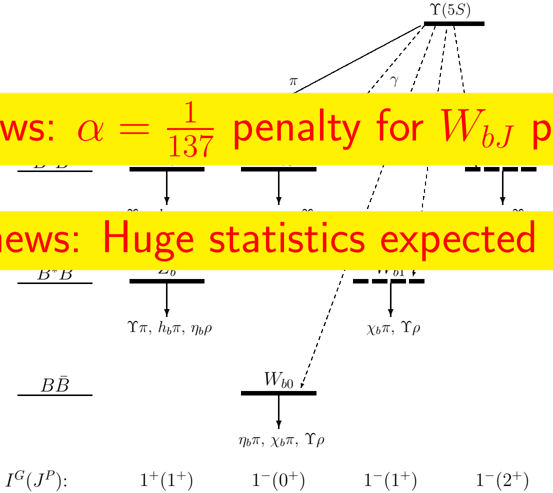

Bad news: $\alpha = \frac{1}{137}$ penalty for W_{bJ} production

Good news: Huge statistics expected at Belle-II

(Bondar et al.'2011, Voloshin'2011)

Conclusions

Molecule model is a commonly accepted and phenomenologically successful description of exotic states:

- Describes specific line shapes
- Predicts spin partners
- Explains mass splittings:

$$M_{Y(4260)} - M_{X(3872)} \approx M_{D_1(2420)} - M_{D^*}$$

$$M_{Z_b(10650)} - M_{Z_b(10610)} \approx M_{B^*} - M_B$$

Further developments:

- Relation between different heavy-quark sectors
- Proper inclusion of pions and compact components
- Generalisation to $SU(3)$ flavour group for light quarks
- Tests of accuracy of HQSS, especially in the charm sector