Deciphering the XYZ States

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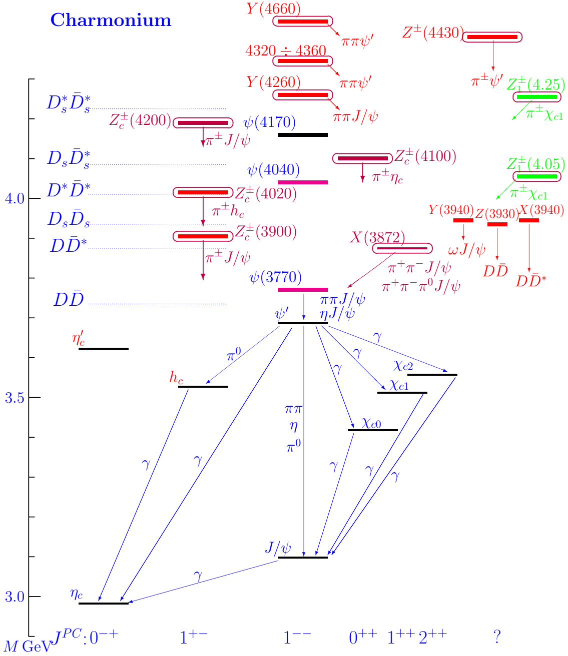
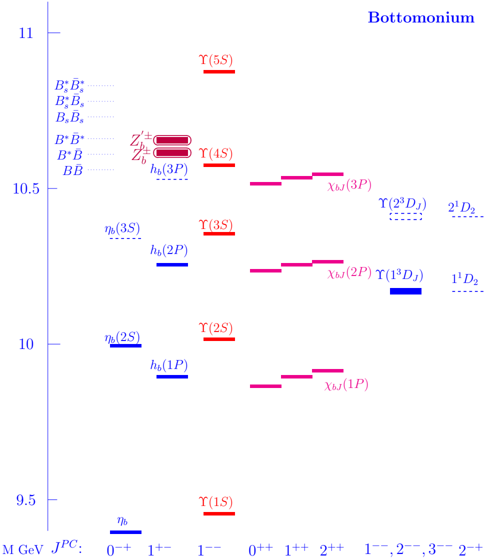
Charmonium


$Y(4660)$
$\pi\pi\psi'$
$4320 \div 4360$
$\pi\pi\psi'$
$Y(4260)$
$\pi\pi J/\psi$
$Z^{\pm}(4430)$
$\pi^{\pm}\psi'$
$Z_1^{\pm}(4.25)$
$\pi^{\pm}\chi_{c1}$
$D_s^*\bar{D}_s^*$
$Z_c^{\pm}(4200)$
$\pi^{\pm}J/\psi$
$\psi(4170)$
$D_s\bar{D}_s^*$
$Z_c^{\pm}(4100)$
$\pi^{\pm}\eta_c$
$\psi(4040)$
$Z_1^{\pm}(4.05)$
$\pi^{\pm}\chi_{c1}$
4.0
$D^*\bar{D}^*$
$Z_c^{\pm}(4020)$
$\pi^{\pm}h_c$
$D_s\bar{D}_s$
$Y(3940)$
$Z(3930)$
$X(3940)$
$D\bar{D}^*$
$Z_c^{\pm}(3900)$
$\pi^{\pm}J/\psi$
$X(3872)$
$\omega J/\psi$
$D\bar{D}$
$D\bar{D}^*$
$\pi^+\pi^-J/\psi$
$\pi^+\pi^-\pi^0J/\psi$
$\psi(3770)$
$D\bar{D}$
$\pi\pi J/\psi$
$\eta J/\psi$
ψ'
η_c'
γ
γ
γ
π^0
χ_{c2}
χ_{c1}
h_c
3.5
$\pi\pi$
η
π^0
χ_{c0}
γ
γ
γ
γ
γ
J/ψ
γ
3.0
η_c
M GeV
$J^{PC}: 0^{-+}$
1^{+-}
1^{--}
0^{++}
1^{++}
2^{++}
?


Bottomonium
11
10.5
10
9.5
$\Upsilon(5S)$
$B_s^*\bar{B}_s^*$
$B_s^*\bar{B}_s$
$B_s\bar{B}_s$
$B^*\bar{B}^*$
$B^*\bar{B}$
$B\bar{B}$
$Z_b'^{\pm}$
$Z_b^{\pm}$
$\Upsilon(4S)$
$h_b(3P)$
$\chi_{bJ}(3P)$
$\Upsilon(2^3D_J)$
2^1D_2
$\eta_b(3S)$
$\Upsilon(3S)$
$h_b(2P)$
$\chi_{bJ}(2P)$
$\Upsilon(1^3D_J)$
1^1D_2
$\eta_b(2S)$
$\Upsilon(2S)$
$h_b(1P)$
$\chi_{bJ}(1P)$
$\Upsilon(1S)$
η_b
M GeV
J^{PC}:
0^{-+}
1^{+-}
1^{--}
0^{++}
1^{++}
2^{++}
$1^{--}, 2^{--}, 3^{--}$
2^{-+}

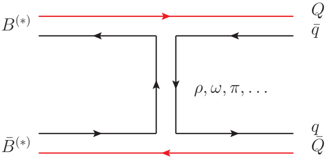
The exotic menu

Exotic: not fitting the template Mesons = $(q\tilde{q})$, Baryons = (qqq).

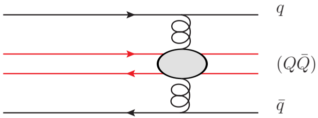
- Charmonium-like
  - $X(3872)$ $(D^0 D^{*0})$, $\to J/\psi\rho$ *and* $J/\psi\omega$, isospin badly broken,
  - $Z_c^{\pm,0}(3900)$ (DD^*), $\to J/\psi\pi$,
  - $Z_c^{\pm}(4020)$, $(D^*\bar{D}^*)$, $\to h_c\pi^{\pm}$,
  - $Z_1^{\pm}(4050)$, $Z_2^{\pm}(4250)$ $\to \chi_{c1}\pi^{\pm}$,
  - $Z_c^{\pm}(4100)$ $\to \eta_c\pi^{\pm}$,
  - $Z_c^{\pm}(4200)$ $\to J/\psi\pi^{\pm}$,
  - $Z^{\pm}(4430)$, $\to \psi(2S)\pi^{\pm}$,
  - $Y(4260)$[4220] $\to J/\psi\pi\pi, h_c\pi\pi$ (almost no open charm),
  - $Y(4360) \to \psi(2S)\pi\pi, h_c\pi\pi$ (almost no open charm),
  - Pentaquark(s):
    $P_c(4380)$, $P_c(4440)$, $P_c(4457)$, $P_c(4312)$ $\to J/\psi p$
- Bottomonium-like
  - $Z_b^{\pm,0}(10610)$, (BB^*), $\to \Upsilon(nS)\pi$ $(n = 1, 2, 3)$, $h_b(kP)\pi$ $(k = 1, 2)$,
  - $Z_b^{\pm,0}(10650)$, $(B^*\bar{B}^*)$, $\to \Upsilon(nS)\pi$ $(n = 1, 2, 3)$, $h_b(kP)\pi$ $(k = 1, 2)$

What is inside?

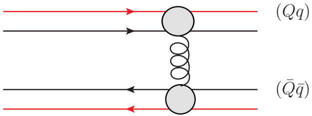
$Molecule:$



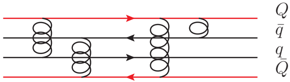
$Hadro-quarkonium:$



$Diquarkonium:$



$A\ \ mess:$



Likely all are present simultaneously. Dominant — different in different particles.

Recall: deuteron — mostly a *pn* molecule, and about 5% - a mess.

Molecules

- Must be very close to the threshold. At binding/excitation energy δ, the characteristic size

$$r \sim 1/\sqrt{M\,\delta} \approx \begin{cases} 4.5\,\mathrm{fm}\sqrt{\frac{1\,\mathrm{MeV}}{\delta}} & \mathrm{charmonium-like} \\ 2.8\,\mathrm{fm}\sqrt{\frac{1\,\mathrm{MeV}}{\delta}} & \mathrm{bottomonium-like} \end{cases}$$

- A clear-cut example: $Z_b(10610) = Z_b$, $Z_b(10650) = Z_b'$
  $M(Z_b) = 10607.2 \pm 2.0\,\mathrm{MeV}$ [$M(BB^*) = 10604.1 \pm 0.3\,\mathrm{MeV}$],
  $M(Z_b') = 10652.2 \pm 1.5\,\mathrm{MeV}$ [$M(B^*\bar{B}^*) = 10649.7 \pm 0.6\,\mathrm{MeV}$]

$$Z_b \sim \frac{B^*\bar{B} - \bar{B}^*B}{\sqrt{2}}, \qquad Z_b' \sim B^*\bar{B}^*$$

- Produced in $\Upsilon(5S) \to Z_b^{(\prime)}\pi$.
  Observed in $Z_b^{(\prime)} \to \Upsilon(1,2,3S)\pi$ and $Z_b^{(\prime)} \to h_b(1,2P)\pi$.
  Also $Z_b \to B^*\bar{B} + c.c.$, $Z_b' \to B^*\bar{B}^*$.
- In charmonium-like sector: $X(3872)$, $Z_c(3900)$, $Z_c(4020)$.

Heavy Quark Spin Symmetry (HQSS) and Molecules

- HQ spin-dependent interaction of heavy Q

$$H_s = -\frac{\vec{\sigma} \cdot \vec{B}}{2\, M_Q} \sim \frac{\Lambda_{QCD}^2}{M_Q} \ll \Lambda_{QCD}$$

- E.g. $\Upsilon(2S) \to \Upsilon(1S)\eta$ requires $b\bar{b}$ spin rotation (Ampl. $\propto (\vec{p}_\eta \cdot [\vec{\Upsilon}_2 \times \vec{\Upsilon}_1])$):

$$\Gamma[\Upsilon(2S) \to \Upsilon(1S)\eta] \sim 10^{-3}\, \Gamma[\Upsilon(2S) \to \Upsilon(1S)\pi\pi]$$

- In a widely separated $B^{(*)}\bar{B}^{(*)}$ pair the spin of b is not correlated with the spin of $\bar{b}$. Rather

$$H_{spin} = \mu\,(\vec{s}_b \cdot \vec{s}_{\bar{q}}) + \mu\,(\vec{s}_{\bar{b}} \cdot \vec{s}_q), \quad \mu = M(B^*) - M(B) \approx 45\,\mathrm{MeV}$$

- The spin of the $b\bar{b}$ pair (S_H) is mixed. In the $J^{PC} = 1^{+-}$ state:

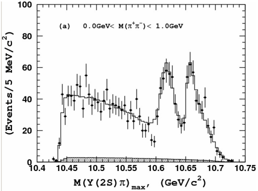
$$B^*\bar{B} - \bar{B}^*B \sim 0_H^- \otimes 1_L^- + 1_H^- \otimes 0_L^- \qquad B^*\bar{B}^* \sim 0_H^- \otimes 1_L^- - 1_H^- \otimes 0_L^-$$

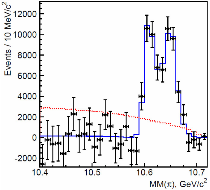
Spin structure of $Z_b^{(\prime)}$

- If the $H \otimes L$ spin composition of pairs of free mesons is retained in Z_b and Z_b',

$$Z_b \sim 0_H^- \otimes 1_L^- + 1_H^- \otimes 0_L^- \qquad Z_b' \sim 0_H^- \otimes 1_L^- - 1_H^- \otimes 0_L^- \; ,$$

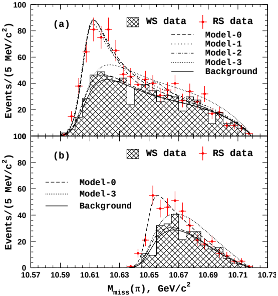
  then
  - $M(Z_b') - M(Z_b) \approx M(B^*) - M(B) \approx 45\,\text{MeV}$, $\Gamma(Z_b') \approx \Gamma(Z_b)$, in particular $\Gamma(Z_b') \to B^* \bar{B} + c.c.$ should be small;
  - $A[Z_b' \to \Upsilon(nS)\,\pi] \approx -A[Z_b \to \Upsilon(nS)\,\pi]$, $\quad A[Z_b' \to h_b(kP)\,\pi] \approx +A[Z_b \to h_b(kP)\,\pi]$;
  - $A[\Upsilon(5S) \to Z_b'\,\pi] \approx -A[\Upsilon(5S) \to Z_b\,\pi]$;
  - Definite and opposite sign of interference of Z_b and Z_b' in the $\pi\pi$ cascades from $\Upsilon(5S)$ to ortho- and para- states of $b\bar{b}$
- Well agrees with the data. In fact surprisingly well.





Interaction between heavy mesons in the $Z_b^{(\prime)}$

- No dependence on S_H (HQSS) — the interaction depends only on S_L.
$$V_0 = \langle 0_L^- | H | 0_L^- \rangle \,, \qquad V_1 = \langle 1_L^- | H | 1_L^- \rangle \,.$$
- Exact preservation of the spin structure $\Rightarrow$ $V_0 = V_1$. LQSS???
- Generally depends on the distance.
- Trivial at long distance (both vanishing).
- Surprising at short distance — interference in decays to bottomonium + pion, and



Apparent absence of decay $Z_b^{\prime} \to B^* \bar{B} + c.c.$
$V_0(q_0) \approx V_1(q_0)$,
$q_0 = \sqrt{M_B\,\mu} \approx 0.5\,\text{GeV}$

$V_0 = V_1 \Rightarrow$ All 4 other expected isovector threshold molecular states should exist

- S wave. $I^G = 1^-$ (C-even neutral component).
  Other diagonal states of the Hamiltonian H_s:

$$W_{b2}: \quad 1^-(2^+): \quad (1_H^- \otimes 1_L^-)\big|_{J=2}\,, \quad B^*\bar{B}^*\,;$$

$$W_{b1}: \quad 1^-(1^+): \quad (1_H^- \otimes 1_L^-)\big|_{J=1}\,, \quad B^*\bar{B} + \bar{B}^*B;$$

$$W'_{b0}: \quad 1^-(0^+): \quad \frac{\sqrt{3}}{2}\,(0_H^- \otimes 0_L^-) + \frac{1}{2}\,(1_H^- \otimes 1_L^-)\big|_{J=0}\,, \quad B^*\bar{B}^*\,;$$

$$W_{b0}: \quad 1^-(0^+): \quad \frac{1}{2}\,(0_H^- \otimes 0_L^-) - \frac{\sqrt{3}}{2}\,(1_H^- \otimes 1_L^-)\big|_{J=0}\,, \quad B\bar{B}\,;$$

- Each at the corresponding meson threshold. No cross-decays.
- Not accessible in single π transitions from $\Upsilon(5,6S)$.
- Accessible in $\Upsilon(5,6S) \to W_b + \gamma$ — small rate.
- W_{b0} maybe accessible in $\Upsilon(6S) \to W_{b0}\pi\pi$.
- Best: $e^+e^- \to W_b\,\rho$ starting at 11.4÷11.5 GeV.

$Z_c(3900)$, $Z_c(4020)$ similar to $Z_b(10610)$, $Z_b(10650)$?

- $Z_c(3900) \to \eta_c\rho$ — seen $(2.1 \pm 0.8)\, Z_c \to J/\psi\pi \Rightarrow$ "‘healthy" mixing of $c\bar{c}$ spin states in a molecule
- $Z_c(4020) \to D^*\bar{D}^*$ “seen”, $Z_c(4020) \to D^*\bar{D}$ “not seen”
- Questions
    - $Z_c(4020) \to \eta_c\rho$ — ?
    - $Z_c(3900) \to J/\psi\pi$ “seen”, $Z_c(3900) \to h_c\pi$ “not seen”
    - $Z_c(4020) \to h_c\pi$ “seen”, $Z_c(4020) \to J/\psi\pi$ “not seen”
- “Not seen" perhaps does not mean “does not exist"
- Something interesting is going on with spin symmetries in the $c\bar{c}$ sector? Another example $Y(4260)$[4220] $\to J/\psi\pi\pi, h_c\pi\pi$, $Y(4360) \to \psi(2S)\pi\pi, h_c\pi\pi$.

Food for thought . . .

A side remark on diquarkonium $[Qq][\bar{Q}\bar{q}]$

- Driving idea: in antisymmetric $[Qq]$ attraction, in symmetric $\{Qq\}$ repulsion. Inspired by Coulomb-like one gluon exchange.
- However generally there are transitions $[Qq][\bar{Q}\bar{q}] \leftrightarrow \{Qq\}\{\bar{Q}\bar{q}\}$
- One gluon exchange in $Q(1)\bar{Q}(2)q(3)\bar{q}(4)$ in terms of $c_{ij} = \alpha_s/r_{ij}$:

$$V \begin{pmatrix} [Qq][\bar{Q}\bar{q}] \\ \{Qq\}\{\bar{Q}\bar{q}\} \end{pmatrix} = -\frac{1}{4} \begin{pmatrix} \frac{N_c^2-1}{N_c}\, r + \frac{N_c+1}{N_c}\, t & \sqrt{N_c^2-1}\, s \\ \sqrt{N_c^2-1}\, s & \frac{N_c^2-1}{N_c}\, r - \frac{N_c-1}{N_c}\, t \end{pmatrix} \begin{pmatrix} [Qq][\bar{Q}\bar{q}] \\ \{Qq\}\{\bar{Q}\bar{q}\} \end{pmatrix}$$

N_c - number of colors, $r = c_{12} + c_{34} + c_{14} + c_{23}$,
$s = c_{12} + c_{34} - c_{14} - c_{23}$, $t = 2c_{13} + 2c_{24} - c_{12} - c_{14} - c_{23} - c_{34}$

- s — attraction between the diquarks (zero overall color), t — attraction/repulsion within $[Qq]/\{Qq\}$, r — mixing $[Qq][\bar{Q}\bar{q}] \leftrightarrow \{Qq\}\{\bar{Q}\bar{q}\}$
- difference attraction - repulsion within $[Qq]/Qq \propto 2N_c/N_c = 2$; mixing term $\propto \sqrt{N_c^2-1} = O(N_c) \Rightarrow$ parametrically mixing $\gg$ difference.
- There is no parameter that would keep diquarks color antysymmetric in a $Q\bar{Q}q\bar{q}$ system!

Hadro-charmonium

No obvious nearby threshold

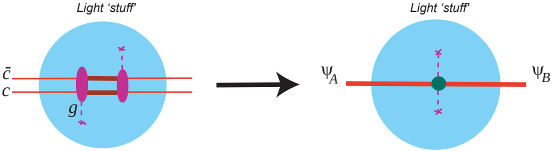
- $Z_1^\pm(4050)$, $Z_2^\pm(4250)$ $\rightarrow \chi_{c1}\pi^\pm$ (status unclear),
- $Z_c^\pm(4100)$ $\rightarrow \eta_c\pi^\pm$,
- $Z_c^\pm(4200)$ $\rightarrow J/\psi\pi^\pm$,
- $Z^\pm(4430)$, $\rightarrow \psi(2S)\pi^\pm$,
- Pentaquark(s):
  $P_c(4380)$, $P_c(4440)$, $P_c(4457)$, $P_c(4312)$ $\rightarrow J/\psi p$

Still under discussion [$D_1\left(\frac{3}{2}^+\right)\bar{D}$ nearby threshold but S wave in e^+e^- forbidden by HQSS]:

- $Y(4260)$[4220] $\rightarrow J/\psi\pi\pi, h_c\pi\pi$ (almost no open charm),
- $Y(4360) \rightarrow \psi(2S)\pi\pi, h_c\pi\pi$ (almost no open charm)

To me these all look like 'a charmonium stuck in a light hadron'. At least this can explain why a specific charmonium state e.g. J/ψ, or ψ', or η_c appears in the decay.

Here's what I mean:



A van der Waals type interaction due to chromo-polarizability

$$\langle B|H_{eff}|A\rangle = -\frac{1}{2}\,\alpha_{AB}\,\vec{E}^a\cdot\vec{E}^a \qquad \mathrm{Chromo-polarizability}:\alpha_{AB}$$

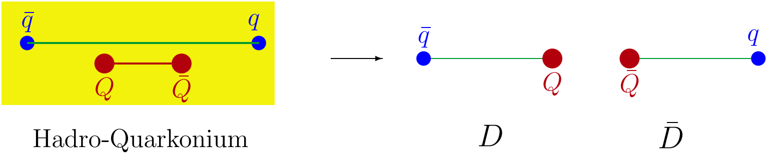
$|\alpha_{\psi' J/\psi}| \approx 2\,GeV^{-3}$ is known from $\psi' \to \pi\pi\, J/\psi$. Schwartz inequality $\alpha_{J/\psi}\alpha_{\psi'} \geq \alpha^2_{\psi' J/\psi}$.

$$\langle X|\vec{E}^a\cdot\vec{E}^a\,|X\rangle \geq \langle X|\vec{E}^a\cdot\vec{E}^a - \vec{B}^a\cdot\vec{B}^a|X\rangle = -\frac{1}{2}\langle X|(F^a_{\mu\nu})^2|X\rangle = \frac{32\pi^2}{9}\,M_X^2$$

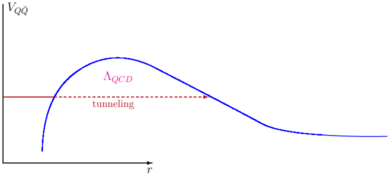
X=(Light hadron) $\Rightarrow$ strong interaction with heavier hadronic states made of light quarks and gluons.

E.g. J/ψ binding potential in heavy nuclei $V < -27$ MeV.

Decay to open heavy flavor requires reconnection of the couplings



Born-Oppenheimer potential between heavy:



The tunneling momentum $|p_Q| = \sqrt{M_Q\,(V_{Q\bar Q} - E)} \sim \sqrt{M_Q\,\Lambda_{QCD}} \Rightarrow$

$$\Gamma(\to \text{open flavor}) \propto \exp(-\sqrt{M_Q/\Lambda_{QCD}})$$

If such interpretation of Y's and Z's has anything to do with reality, there should be:

- bound states of J/ψ and/or ψ' with light nuclei and with baryonic resonances, i.e. baryo-charmonium decaying to e.g. pJ/ψ (+ pions) $\Rightarrow$ pentaquarks
- resonances containing χ_{cJ} charmonium, i.e. in χ_{cJ}+pion(s) $Z_1^\pm(4050)$, $Z_2^\pm(4250)$ $\quad \to \chi_{c1}\pi^\pm$
- decays (moderately suppressed) into non-preferred charmonium states, e.g. $Y(4260) \to \pi\pi\psi'$, or $Y(4.36) \to \pi\pi J/\psi$
- Contain compact charmonium inside $\Rightarrow$ can be produced in hard processes: B decays, $p\bar{p}$, LHC, ...

$Z_c(4100)$, $Z_c(4200)$

- Belle 2014: $B^0 \to J/\psi\pi^- K^+$ resonance in $J/\psi\pi^-$ (6.2σ), $Z_c(4200)$, $M = 4196^{+35}_{-32}$ MeV, $\Gamma = 370^{+170}_{-150}$ MeV, $\mathcal{B}[B^0 \to Z_c(4200)^- K^+ \to J/\psi\pi^- K^+] \approx 2.2 \times 10^{-5}$, $J^P = 1^+$ preferred.
- LHCb 2018: $B^0 \to \eta_c\pi^- K^+$ resonance in $\eta_c\pi^-$ ($> 3\sigma$), $Z_c(4100)$, $M = 4096 \pm 20^{+18}_{-22}$ MeV, $\Gamma = 152 \pm 58^{+60}_{-35}$ MeV $\mathcal{B}[B^0 \to Z_c(4100)^- K^+ \to \eta_c\pi^- K^+] \approx 1.9 \times 10^{-5}$, $J^P = 0^+$ preferred

Strongly suggests: $Z_c(4100)$ = η_c embedded in S wave in an 'excited pion' $I^G(J^P) = 1^-(0^-)$, $Z_c(4200)$ = J/ψ embedded in an 'excited pion' $I^G(J^P) = 1^-(0^-)$. Expected:

- The same embeddings — HQSS partners, like η_c and $J/\psi \Rightarrow$

$$M[Z_c(4200)] - M[Z_c(4100)] \approx M(J/\psi) - M(\eta_c) = 112\,\mathrm{MeV}$$

- $\Gamma[Z_c(4100) \to \eta_c\pi] \approx \Gamma[Z_c(4200) \to J/\psi\pi]$
-

$$\frac{\mathcal{B}[B^0 \to Z_c(4100)^- K^+]}{\mathcal{B}[B^0 \to Z_c(4200)^- K^+]} \approx \left.\frac{\mathcal{B}[B^0 \to \eta_c\pi^- K^+]}{\mathcal{B}[B^0 \to J/\psi\pi^- K^+]}\right|_{M(c\bar{c}\pi)\approx M(Z_c)}$$

HQSS breaking processes

Leading HQSS breaking — M1 chromomagnetic interaction

$$H_{M1} = -\frac{1}{2m_c}\left(t_c^a - t_{\bar{c}}^a\right)\left(\vec{\Delta}\cdot\vec{B}^a\right)$$

$\vec{\Delta} = \vec{s}_1 - \vec{s}_2$ spin operator: $\langle {}^1S_0|\Delta|{}^3S_1\rangle = \langle {}^3S_1|\Delta|{}^1S_0\rangle \Rightarrow$ same coefficient C in the HQSS breaking amplitudes:

$$A[Z_c(4100) \to J/\psi\rho] = C\,(\vec{\psi}\cdot\vec{\rho})\,; \quad A[Z_c(4200) \to \eta_c\rho] = C\,(\vec{Z}\cdot\vec{\rho})$$

Implies

$$\Gamma[Z_c(4100) \to J/\psi\rho] \approx 3\,\Gamma[Z_c(4200) \to \eta_c\rho]$$

HQSS breaking in charmonium $\sim$ 10% in the rate ($\psi' \to J/\psi\eta$ vs. $\psi' \to J/\psi\pi\pi$)

Other related processes

- Same embedding — the same admixture of excited states $\eta_c(2S)$, $\psi(2S) \Rightarrow$

$$\Gamma[Z_c(4100) \to \eta_c(2S)\pi] \approx \Gamma[Z_c(4200) \to \psi(2S)\pi]$$

- Orbitally excited. P and G conservation allows only $Z_c(4100) \to \chi_{c1}\pi$ and $Z_c(4200) \to h_c\pi$

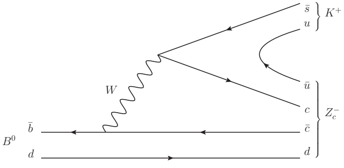
$$\frac{\Gamma[Z_c(4200) \to h_c\pi]}{\Gamma[Z_c(4100) \to \chi_{c1}\pi]} \approx \left(\frac{p_2}{p_1}\right)^3 \approx 1.5$$

  (P wave decays. Thus the kinematical difference is more important than in the previous.) Both processes are suppressed by both HQSS and the (orbital) excitation.

- Neutral isotopic partners of both Z_c can be S wave resonances in $\bar{p}p$ annihilation (PANDA). (The charged ones, Z_c^-, would require a deuterium target, $\bar{p}d$.)

Strange hadrocharmonium

- If $Z_c(4100)$ and $Z_c(4200)$ are (respectively) η_c and J/ψ embedded in an ‘excited pion’ — then what about embedding in an excited Kaon: Z_{cs}?
- Looking at $\sim$160 MeV between K(1460) and $\pi(1300)$ one might expect $j^P = 0^+$ $Z_{cs}(4250)$ and $J^P = 1^+$ $Z_{cs}(4350)$.
- Similarity and dissimilariry between production in B decays



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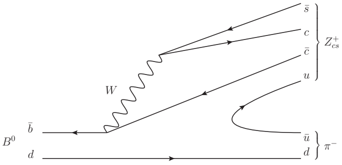

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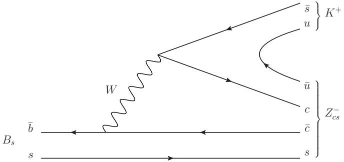
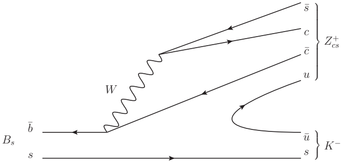


(a)



(b)

- In SU(3) limit

$$A(B^0 \to Z_c^- K^+) = A(B_s \to Z_{cs}^- K^+) = A$$

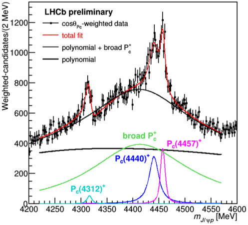
$$A(B^0 \to Z_{cs}^+ \pi^-) = A(B_s \to Z_{cs}^+ K^-) = B$$

- Only $|A|^2$ is measured: $\Gamma(B^0 \to Z_c^- K^+) = |A|^2$.
- $\Gamma(B^0 \to Z_{cs}^+ \pi^-) = |B|^2$ unknown
- Due to the $B_s \leftrightarrow \bar{B}_s$ oscillations only an 'averaged' B_s decay can be seen at LHCb:

$$\Gamma[B_s \to Z_{cs}^- K^+] = \frac{1}{2}\left(|A|^2 + |B|^2\right) = \frac{1}{2}\left[\Gamma(B^0 \to Z_c^- K^+) + \Gamma(B^0 \to Z_{cs}^+ \pi^-)\right]$$

- $\Rightarrow \mathcal{B}(B_s \to Z_{cs}^- K^+) > \mathcal{B}(B^0 \to Z_c^- K^+) \approx 1 \times 10^{-5}$ (Approximately the same fraction of the known decay $B_s \to J/\psi K^+ K^-$ as $Z_c(4200)$ in $B^0 \to J/\psi \pi^- K^+$.) Current data on B_s decay are insufficient.

$P_c(4312)$, $P_c(4440)$, $P_c(4457)$ — $\Sigma_c(2455)\bar{D}^{(*)}$ molecules ?

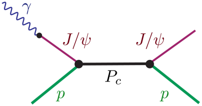


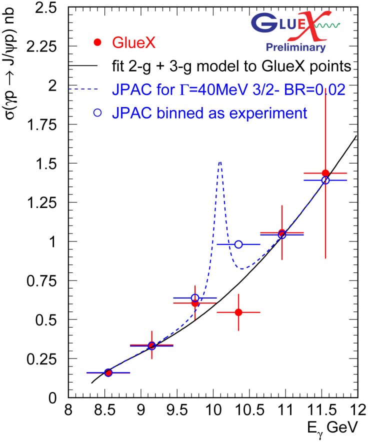
- $P_c(4312)$ — $\Sigma_c(2455)\bar{D}$, $|E_{\rm binding}| \approx 5 - 10\,$MeV, $J^P = \frac{1}{2}^-$
- $P_c(4440)$ — $\Sigma_c(2455)\bar{D}^*$, $J^P = \frac{1}{2}^-$
- $P_c(4457)$ — $\Sigma_c(2455)\bar{D}^*$, $J^P = \frac{3}{2}^-$
- $P_c(4557) - P_c(4440)$ splitting due to spin-spin interaction of Σ_c and $\bar{D}^*$
- Big question: what about $P_c \to \Lambda_c\bar{D}^{(*)}$? Not forbidden by any law of nature.

P_c as baryocharmonium. (Charmonium embedded in an excited baryon.)

- $P_c(4312)$ — $\chi_{c0}N$, $J^P = \frac{1}{2}^+$
- $P_c(4440)$, $P_c(4457)$ — $\psi(2S)N$, $J^P = \frac{1}{2}^-, \frac{3}{2}^-$

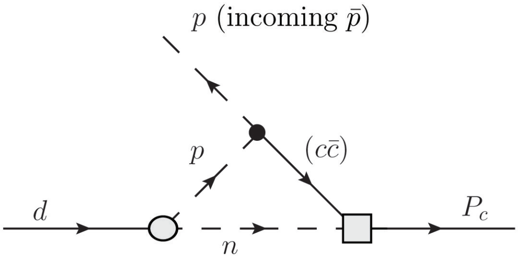
Additional sources of P_c: $\gamma + p \rightarrow P_c$, $\bar{p} + d \rightarrow P_c$





The upper limit on $Br(P_c \rightarrow J/\psi + p)$ depends on the J^P of P_c. So far unclear, likely at the level of few %

Hidden-charm pentaquarks in $\bar{p} + d \to P_c$



Simultaneously for d at rest and p at rest $\bar{p} + d \to Pc$ and $\bar{p} + p \to (c\bar{c})$:
$M_{P_c} = M_0$

$$M_0^2 = 2m^2_{(c\bar{c})} + m_N^2$$

$M_0 = 4.48\,\mathrm{GeV}$ for $(c\bar{c}) = J/\psi$ and $M_0 = 4.33\,\mathrm{GeV}$ for $(c\bar{c}) = \eta_c$.
Compare with $P_c(4450)$.
No need to consider short distance structure in deuteron.
BW max cross section: $\sigma(\bar{p} + d) \to P_c \approx Br[P_c \to \bar{p} + d] \times 2 \times 10^{-27}\mathrm{cm}^2$
$Br[P_c \to \bar{p} + d] \approx 0.5 \times 10^{-6}\, Br[P_c \to (c\bar{c}) + n]\, \Gamma[(c\bar{c}) \to p\bar{p}]/(1\mathrm{keV})$
$\sim 10^{-7}\, Br(P_c \to J/\psi + n)$ for J/ψ, $\sim 2.5 \times 10^{-5}\, Br(P_c \to \eta_c + n)$ for η_c

Conclusions

- It looks like we (somewhat) understand charmonium and bottomonium below open flavor threshold. The atomic physics of quarkonium.
- What happens above the threshold — mostly puzzles.
- Molecules, hadroquarkonium, . . . — Hadronic chemistry.
- Hybrids — $c\bar{c}$ plus gluonic excitations. Nowhere to be seen . . .
- Some are likely molecules, some - hadroquarkonium. No 'one size fits all solution'.
- Other sources of XYZ...P
  - Additional possibilities in $\bar{p} + p \to X,\ Y,\ Z$ (neutral)
  - More possibilities (charged states) if $\bar{p}n$ could be studied using deuterium target.
  - Formation in $\gamma + p \to P_c$ ongoing at JLAB.
  - Pentaquarks can possibly be studied in $\bar{p} + d \to Pc$.