Heavy meson molecules in heavy quark limit

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HADRONS IN NUCLEAR MEDIUM II, 10/25/2014

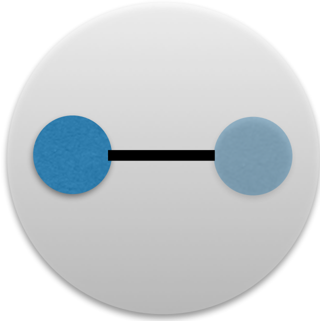
Outline

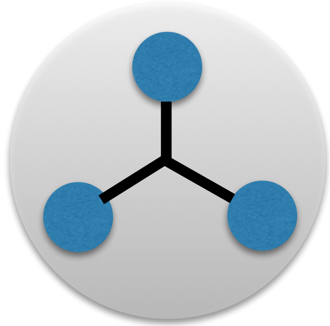
- Introduction/Motivation
- Heavy quark spin symmetry
- Spin structures of heavy meson molecules
- Spin degeneracy of heavy meson molecules
- Summary

Exotic Hadrons

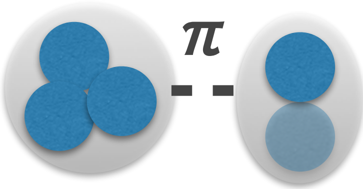
We know

meson and baryons

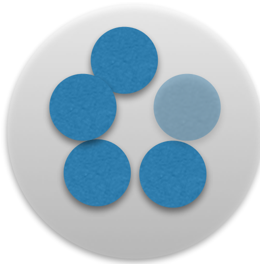




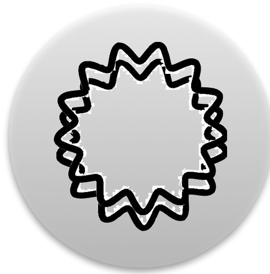
QCD also allows



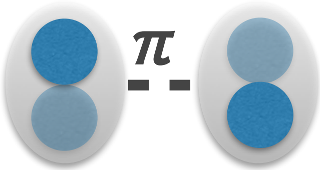
Molecules($\bar{D}N$, BN)



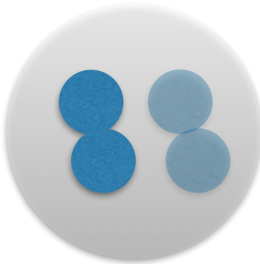
Penta quark



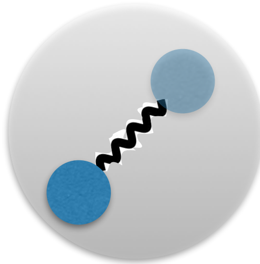
glueball



Molecules($D\bar{D}$, $B\bar{B}$)



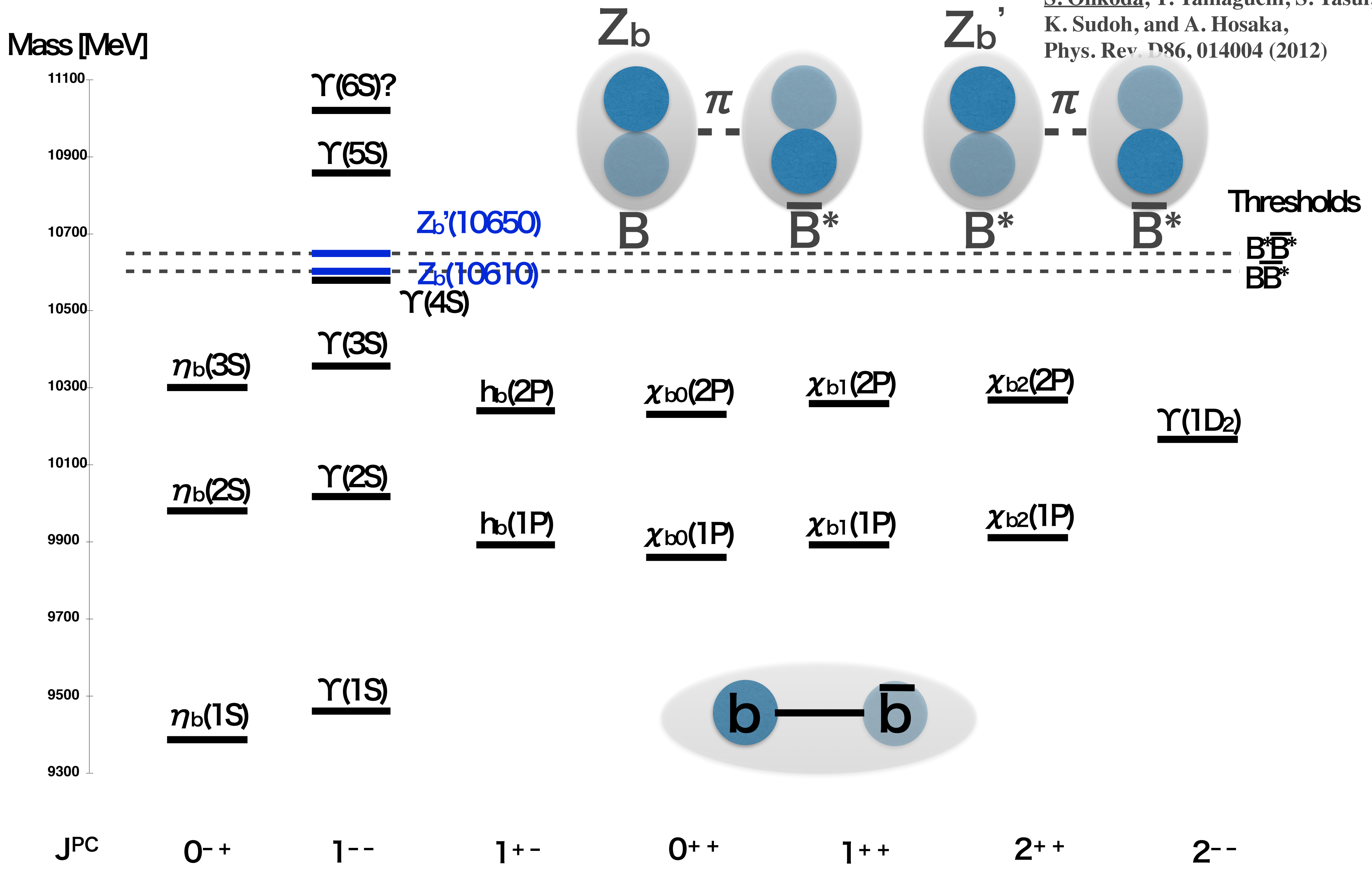
Tetra quark



hybrid

Bottomonium

S. Ohkoda, Y. Yamaguchi, S. Yasui, K. Sudoh, and A. Hosaka, Phys. Rev. D86, 014004 (2012)



$Z_b(10610)$ and $Z_b(10650)$

A. Bondar, et al,
PRD84 054010 (2011)

S. Ohkoda, Y. Yamaguchi, S. Yasui,
K. Sudoh, and A. Hosaka,
Phys. Rev. D86, 014004 (2012)

Exotic quantum numbers

- ✔ $I^G(J^P)=1^+(1^+)$
- ✔ $\Upsilon(5S) \to Z_b^+ \pi^- \to \Upsilon(1,2,3S)\pi^+\pi^-$
- ✔ Z_b's are "genuine" exotic states

Exotic masses

- ✔ Z_b's are twin resonances with small mass splittings, ~ 45 MeV
- ✔ Z_b's are very close to the respective thresholds, $B\bar{B}^*$ and $B^*\bar{B}^*$

Exotic decays

- ✔ The decays of $\Upsilon(5S) \to Z_b \pi \to h_b(mP)\pi\pi$ are not suppressed although it needs spin flip

Z_b are $B^{(*)}\bar{B}^{(*)}$ molecules ?

Heavy quark symmetry

Heavy quark symmetry

- In heavy quark limit, spin-spin interactions are suppressed
  —— Heavy quark spin symmetry

M. B. Wise, PRD45, 2188 (1992)

$$Q_v(x) = e^{im_Q v\cdot x}\frac{1+\not{v}}{2}Q(x)$$

$$\mathcal{L}_{\rm HQ} = \bar{Q}(i\not{D} - m_{\rm Q})Q$$

$$\mathcal{L}_{\rm HQET} = \bar{Q}_v v\cdot iDQ_v + \bar{Q}_v\frac{(iD_\perp)^2}{2m_Q}Q_v - c(\mu)g_s\bar{Q}_v\frac{\sigma_{\mu\nu}G^{\mu\nu}}{4m_Q}Q_v + \mathcal{O}(1/m_Q^2)$$

- New conserved quantity appears in heavy quark limit
  —— light spin degree of freedom

M. B. Voloshin, PRD85, 034024 (2012)

S. Ohkoda, Y. Yamaguchi, S. Yasui and A. Hosaka, PRD86, 117502 (2012).

Y. Yasui, K. Sudoh, Y. Yamaguchi, S. Ohkoda, A. Hosaka and T. Hyodo, Phys. Lett. B727 185-189 (2013).

$S_l = J - S_H$

S_l : Light spin

J : Total angular momentum

S_H : Heavy quark spin

Spin structures

- Heavy hadrons are classified with spin structures, $(S_H \otimes S_l)_J$.

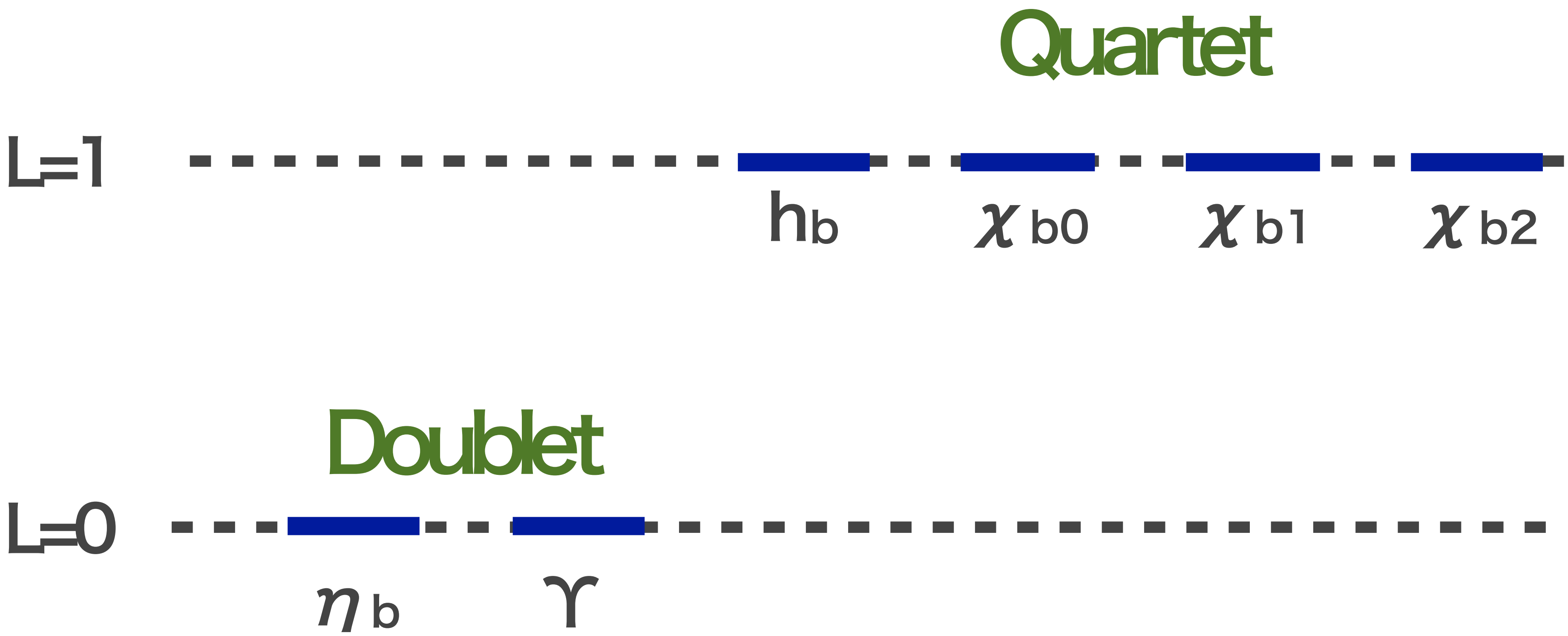
	J^{PC}		$b\bar{b}(^{2S+1}L_J)$		$(S_H \otimes S_l)_J$
η_b :	0^{-+}	:	$^1S_0$	→	$(0_H \otimes 0_l)_J$
Υ :	1^{--}	:	$^3S_1$	→	$(1_H \otimes 0_l)_J$
h_b :	1^{+-}	:	$^1P_1$	→	$(0_H \otimes 1_l)_J$
χ_{bJ} :	1^{++}	:	^3P_J	→	$(1_H \otimes 1_l)_J$

- Spin selection rule

$\Upsilon \to \Upsilon\pi\pi$ $\qquad$ $\Upsilon \to \chi_{bJ}\omega$

$\Upsilon \not\to h_b\pi\pi$ $\qquad$ $\Upsilon \not\to \eta_b\omega$

Spin degeneracy of heavy quarkonium

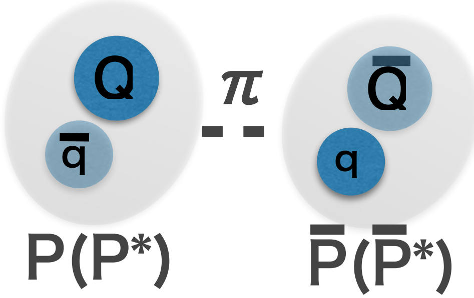


J^{PC}	0^{-+}	1^{--}	1^{+-}	0^{++}	1^{++}	2^{++}
$(S_H \otimes S_l)_J$	$(0_H \otimes 0_l)_0$	$(1_H \otimes 0_l)_1$	$(0_H \otimes 1_l)_1$	$(1_H \otimes 1_l)_{0,1,2}$		

Spin structures in heavy meson molecules

Purpose

◎We study $P^{(*)}\bar{P}^{(*)}$ molecules in the HQ limit



✔This study clarify the $1/m_Q$ effects in charm/bottom region

✔This study shows the spin partners

✔Spin selection rules provide the information about the properties of decays and productions

This study

✔We focus on $I^G(J^P)=1^+(1^+)$, which corresponds to Z_b channel

✔What are the spin partners for Z_b?

Spin structures

$S_l = S_{q\bar{q}} + L \; (\neq 0^{+-}, 1^{-+}, 2^{+-}, J<2)$

$I^G(J^P) = 1^+(1^+) : Z_b$

$$\begin{pmatrix} |\frac{1}{\sqrt{2}}(P\bar{P}^* - P^*\bar{P})(^3S_1)\rangle \\ |\frac{1}{\sqrt{2}}(P\bar{P}^* - P^*\bar{P})(^3D_1)\rangle \\ |P^*\bar{P}^*(^3S_1)\rangle \\ |P^*\bar{P}^*(^3D_1)\rangle \end{pmatrix} = U_{1+-} \begin{pmatrix} |0_H, 1_l[1_q, 0_L]; 1\rangle \\ |0_H, 1_l[1_q, 2_L]; 1\rangle \\ |1_H, 0_l[0_q, 0_L]; 1\rangle \\ |1_H, 2_l[0_q, 2_L]; 1\rangle \end{pmatrix}$$

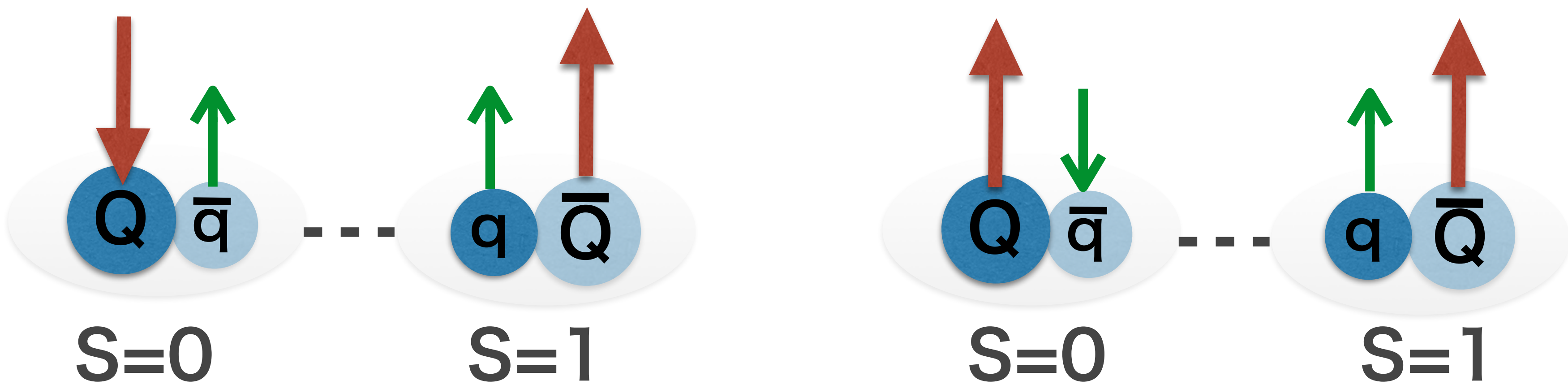
$(S_H \otimes S_l)_J$

$(0_H \otimes 1_l)_1$

$(1_H \otimes 0_l)_1$

$(1_H \otimes 2_l)_1$

$$|\frac{1}{\sqrt{2}}(P\bar{P}^* - P^*\bar{P})(^3S_1)\rangle = \frac{1}{\sqrt{2}}|0_H \otimes 1_l\rangle_1 + \frac{1}{\sqrt{2}}|1_H \otimes 0_l\rangle_1$$



Spin partners

J^{PC}	$(S_H^{P_1C_1} \otimes S_l^{P_2C_2})_{J^{PC}}$	Spin partners
	$(0_H^{-+} \otimes 1_l^{--})_{1^{+-}}$	quartet ! $(1_H^{--} \otimes 1_l^{--})_{0^{++}}, (1_H^{--} \otimes 1_l^{--})_{1^{++}}, (1_H^{--} \otimes 1_l^{--})_{2^{++}}$
1^{+-}	$(1_H^{--} \otimes 0_l^{-+})_{1^{+-}}$	$(0_H^{-+} \otimes 0_l^{-+})_{0^{++}}$ doublet !
	$(1_H^{--} \otimes 2_l^{-+})_{1^{+-}}$	$(0_H^{-+} \otimes 2_l^{-+})_{2^{++}} (1_H^{--} \otimes 2_l^{-+})_{2^{+-}}, (1_H^{--} \otimes 2_l^{-+})_{3^{+-}}$

- ✔ The appearance of spin degeneracies is **depend on dynamics**
- ✔ We need some sort of the **effective model**

Spin degeneracy with one pion exchange potential model

OPEP model

- Interactions for $B^{(*)}$ and π

$$\mathcal{L}_I = ig\,\mathrm{Tr}[H_b \gamma_\mu \gamma_5 A^\mu_{ba} H_a]$$

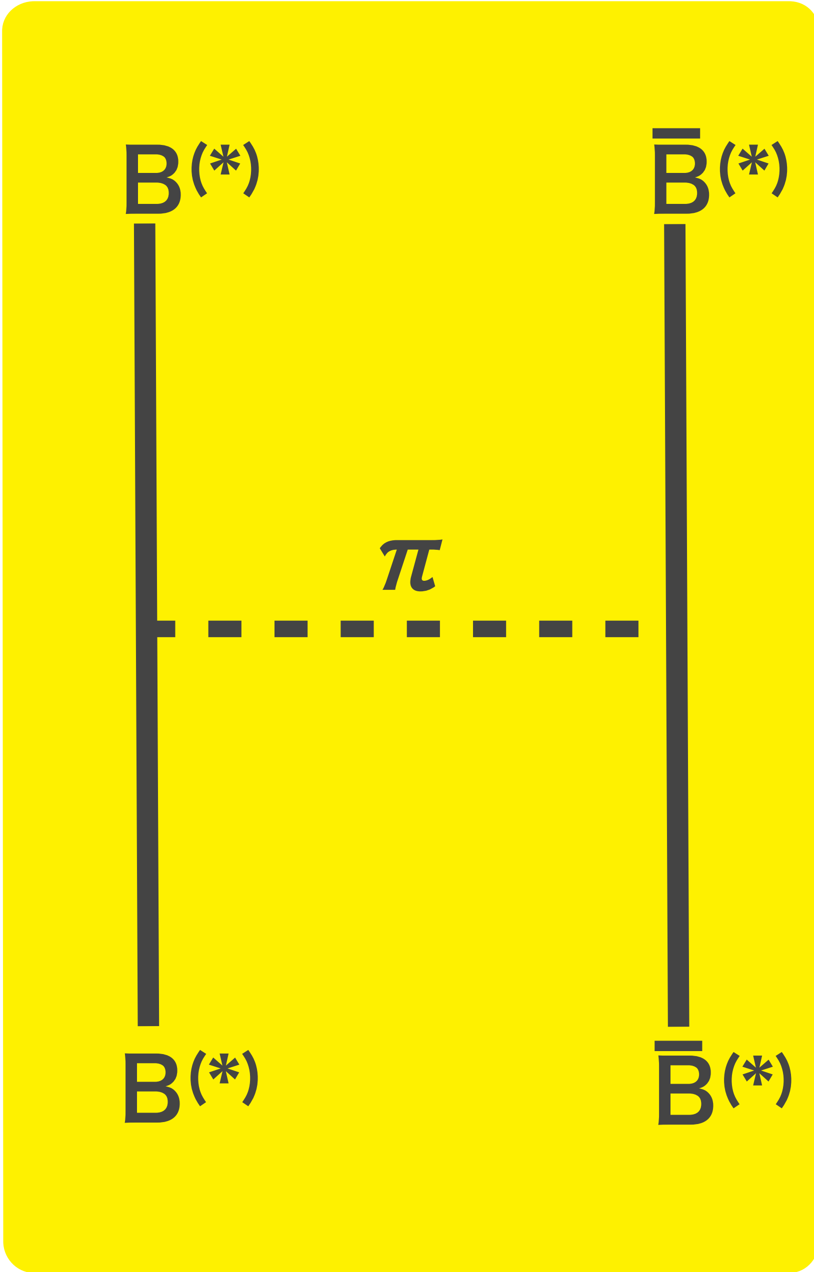
$$H_a = \left(\frac{1+\not{v}}{2}\right)[M^\mu_a \gamma_\mu - M_a \gamma_5]$$

- Coupled channels for Z_b

$$\frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})(^3S_1),\ \frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})(^3D_1),$$

$$B^*\bar{B}^*(^3S_1),\ B^*\bar{B}^*(^3D_1)$$

- We obtain the Hamiltonians of $B^{(*)}\bar{B}^{(*)}$ states



OPEP model

✔Hamiltonian

S. Ohkoda, Y. Yamaguchi, S. Yasui,
K. Sudoh, and A. Hosaka,
Phys. Rev. D86, 014004 (2012)

1+(1+-): $\frac{1}{\sqrt{2}}(\mathrm{B\bar{B}^*} - \mathrm{B^*\bar{B}})(^3S_1)$, $\frac{1}{\sqrt{2}}(\mathrm{B\bar{B}^*} - \mathrm{B^*\bar{B}})(^3D_1)$, $\mathrm{B^*\bar{B}^*}(^3S_1)$, $\mathrm{B^*\bar{B}^*}(^3D_1)$

$$H_{1^{+-}} = \begin{pmatrix} K_0 + C_I & -\sqrt{2}T_I & -2C_I & -\sqrt{2}T_I \\ -\sqrt{2}T_I & K_2 + C_I + T_I & -\sqrt{2}T_I & -2C_I + T_I \\ -2C_I & -\sqrt{2}T_I & K_0 + C_I & -\sqrt{2}T_I \\ -\sqrt{2}T_I & -2C_I + T_I & -\sqrt{2}T_I & K_2 + C_I + T_I \end{pmatrix}$$

C : Center force

T : Tensor force

1-(1++): $\frac{1}{\sqrt{2}}\left(\mathrm{B\bar{B}^*} + \mathrm{B^*\bar{B}}\right)\left(^3S_1\right)$, $\frac{1}{\sqrt{2}}\left(\mathrm{B\bar{B}^*} + \mathrm{B^*\bar{B}}\right)\left(^3D_1\right)$, $\mathrm{B^*\bar{B}^*}(^5D_1)$

$$H_{1^{++}} = \begin{pmatrix} K_0 - C_I & \sqrt{2}T_I & -\sqrt{6}T_I \\ \sqrt{2}T_I & K_2 - C_I - T_I & -\sqrt{3}T_I \\ -\sqrt{6}T_I & -\sqrt{3}T_I & K_2 - C_I + T_I \end{pmatrix}$$

OPEP model in HQ limit

✔ Potential model

S. Ohkoda, Y. Yamaguchi, S. Yasui, K. Sudoh, and A. Hosaka, Phys. Rev. D86, 014004 (2012)

$H^{HQ}_{J^{PC}}$: Hamiltonian in HQ basis

$$H^{HQ}_{1^{+-}} = U^{-1}_{1^{+-}} H_{1^{+-}} U_{1^{+-}}$$

$$= \left(\begin{array}{cc|c|c} K_0 - C & -2\sqrt{2}T & 0 & 0 \\ -2\sqrt{2}T & K_2 - C + 2T & 0 & 0 \\ \hline 0 & 0 & K_0 + 3C & 0 \\ \hline 0 & 0 & 0 & K_2 + 3C \end{array}\right)$$

$(0_H \otimes 1_l)_1$

$(1_H \otimes 0_l)_1$

$(1_H \otimes 2_l)_1$

$$= \left(\begin{array}{c|c|c} H^{(0,1)}_{1^{+-}} & 0 & 0 \\ \hline 0 & H^{(1,0)}_{1^{+-}} & 0 \\ \hline 0 & 0 & H^{(1,2)}_{1^{+-}} \end{array}\right)$$

➜ Diagonalized Hamiltonian : $H^{(S_Q,S_l)}_{J^{PC}}$

$$H^{HQ}_{1^{++}} = \left(\begin{array}{cc|c} K_0 - C & -2\sqrt{2}T & 0 \\ -2\sqrt{2}T & K_2 - C + 2T & 0 \\ \hline 0 & 0 & K_2 - C - 2T \end{array}\right)$$

$$= \left(\begin{array}{c|c} H^{(1,1)}_{1^{++}} & 0 \\ \hline 0 & H^{(1,2)}_{1^{++}} \end{array}\right)$$

$$H^{(0,1)}_{1^{+-}} = H^{(1,1)}_{0^{++}} = H^{(1,1)}_{1^{++}} = H^{(1,1)}_{2^{++}}$$

Meson molecules in HQ limit

Mass spectrum

- HQS quartet : $H^{(0,1)}_{1+-} = H^{(1,1)}_{0++} = H^{(1,1)}_{1++} = H^{(1,1)}_{2++}$
- They are lowest bound state of $P^{(*)}\bar{P}^{(*)}$ states

Wave functions

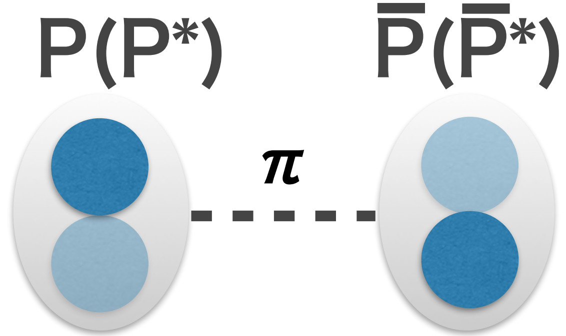
- Spin structures restrict the wave functions
- Ex) $1^+(1^{+-})$: $f(P\bar{P}^*(^3S_1)) : f(P^*\bar{P}^*(^3S_1))$
  $1 : 1.$

Decay properties

- Spin selection rules lead the decay properties
- Ex) $\Gamma(Z_b^0 \to \chi_{b0}\gamma) : \Gamma(Z_b^0 \to \chi_{b1}\gamma) : \Gamma(Z_b^0 \to \chi_{b2}\gamma)$
  $1 : 3 : 5$

  $\Gamma(H^{(1,1)}_{1++} \to \chi_{b0}\pi) : \Gamma(H^{(1,1)}_{1++} \to \chi_{b1}\pi) : \Gamma(H^{(1,1)}_{1++} \to \chi_{b2}\pi)$
  $4 : 3 : 5$

$P^{(*)}\bar{P}^{(*)}$ states in HQ limit



Pion Extended

$P\bar{P}^*, P^*\bar{P}^*$

$P\bar{P}$

Quartet

	$h_b\pi$	$\chi_{b1}\pi$	$\chi_{b1,2}\pi$	$\chi_{b1,2}\pi$
$I^G(J^{PC})$	$1^+(1^{+-})$	$1^-(0^{++})$	$1^-(1^{++})$	$1^-(2^{++})$
$(S_H \otimes S_l)_J$	$(0_H \otimes 1_l)_1$		$(1_H \otimes 1_l)_{0,1,2}$	

$P^{(*)}\bar{P}^{(*)}$ states in HQ limit

$\Upsilon(5S)$ → $Z_b\pi$ → $\Upsilon(nS)\pi\pi$

$(1_H \otimes 0_l)_1$ $\quad$ $(1_H \otimes 0_l)_1$

→ $h_b(mP)\pi\pi$

$(0_H \otimes 1_l)_1$

$P\bar{P}^*, P^*\bar{P}^*$

$P\bar{P}$

Quartet

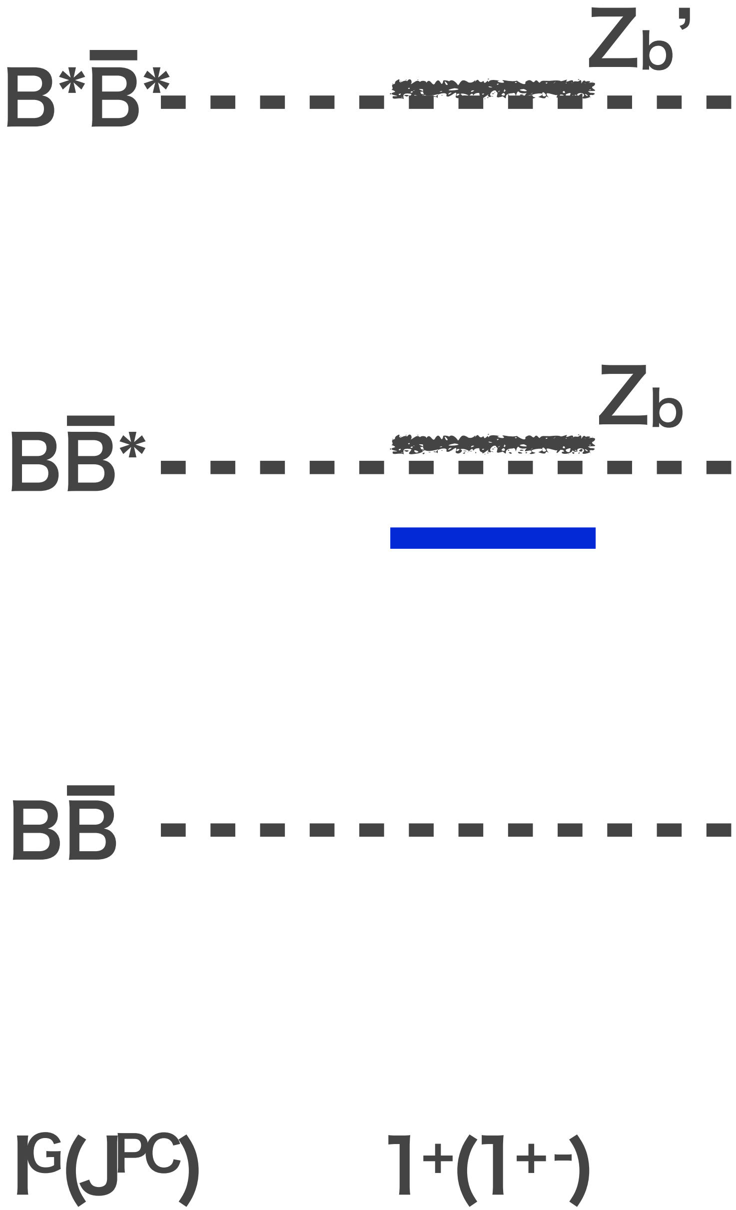
Z_b?

$h_b\pi$	$\chi_{b1}\pi$	$\chi_{b1,2}\pi$	$\chi_{b1,2}\pi$

$I^G(J^{PC})$	$1^+(1^{+-})$	$1^-(0^{++})$	$1^-(1^{++})$	$1^-(2^{++})$
$(S_H \otimes S_l)_J$	$(0_H \otimes 1_l)_1$		$(1_H \otimes 1_l)_{0,1,2}$	

$B^{(*)}\bar{B}^{(*)}$ states

S. Ohkoda, Y. Yamaguchi, S. Yasui,
K. Sudoh, and A. Hosaka,
Phys. Rev. D86, 014004 (2012)



Mixing ratio of each channel

$(S_H \otimes S_l)_J$	$(0_H \otimes 1_l)_1$	$(1_H \otimes 0_l)_1$	$(1_H \otimes 2_l)_1$
$P^{(*)}\bar{P}^{(*)}$	100%	0%	0%
$B^{(*)}\bar{B}^{(*)}$	84%	15%	1%
Decays	$h_b\pi$	$\Upsilon\pi$	$(\Upsilon\pi)_{D\text{-wave}}$

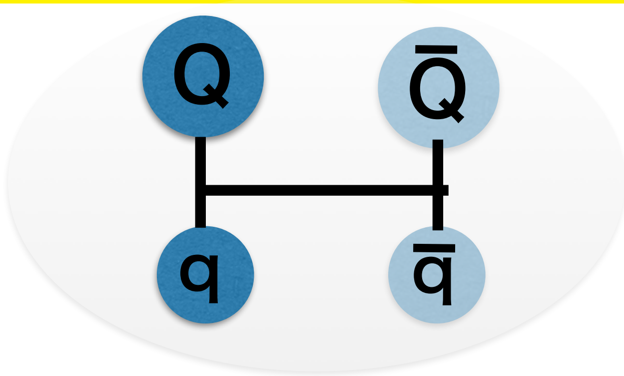
✓ HQS is broken in the bottom quark region

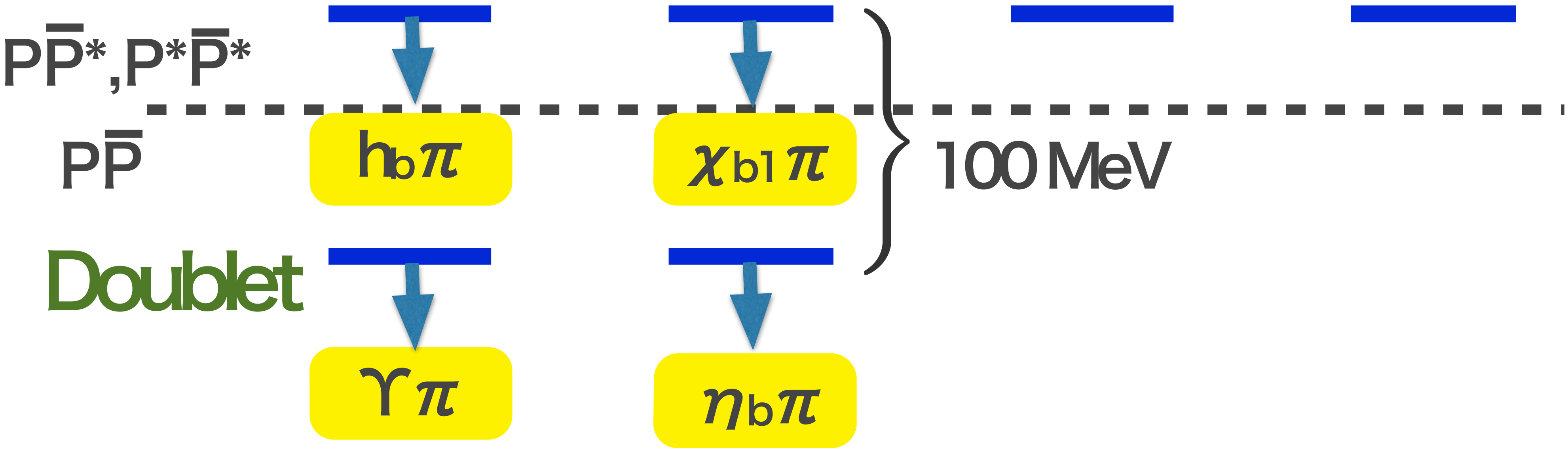
✓ $(1_H \otimes 0_l)_1$ component allows the decays, $Z_b \to \Upsilon(nS)\pi$.

Diquark-antidiquaks in HQ limit

L. Maiani et al,
Phys. Rev. D71, 014028 (2005)

Gluon
Compact





$I^G(J^{PC})$	$1^+(1^{+-})$	$1^-(0^{++})$	$1^-(1^{++})$	$1^-(2^{++})$
$(S_H \otimes S_l)_J$	$(0_H \otimes 1_l)_1$ $(1_H \otimes 0_l)_1$	$(1_H \otimes 1_l)_0$ $(0_H \otimes 0_l)_0$	$(1_H \otimes 1_l)_1$	$(1_H \otimes 1_l)_2$

Summary

- We investigate the $P^{(*)}\bar{P}^{(*)}$ states in HQ limit
- The spin degeneracy is related with the inner structures of the heavy hadrons
- We find a quartet in $H^{(0,1)}_{1+-} = H^{(1,1)}_{0++} = H^{(1,1)}_{1++} = H^{(1,1)}_{2++}$
- Spin partners of Z_b are possible to be observed in future experiments
- Spin structures give the decay properties

Y. Yasui, K. Sudoh, Y. Yamaguchi, S. Ohkoda, A. Hosaka and T. Hyodo,
Phys. Lett. B727 185-189 (2013).