Degeneracy of doubly heavy baryons from heavy quark symmetry

Masayasu Harada (Nagoya Univ.)

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Based on

- Yong-Liang Ma, Masayasu Harada, "Doubly heavy baryons with chiral partner structure", Physics Letters B 748, 463-466 (2015)
- Yong-Liang Ma, Masayasu Harada, "Degeneracy of doubly heavy baryons from heavy quark symmetry", Physics Letters B 754, 125-128 (2016).

1. Introduction

- Doubly Heavy Baryons (DHB)
  - ccq, bbq, bcq : q = u, d, s ; c = charm, b = bottom
- Ξ_{cc} (SELEX 2002,2005)
  - * state in PDG
  - mass = 3518.9 ± 0.9 MeV
- We expect more in future experiments
  - LHCb, BESIII, Belle II, …, J-PARC ?
- It is interesting to study DHBs theoretically.

Main Conclusions

- Yong-Liang Ma, Masayasu Harada, "Doubly heavy baryons with chiral partner structure", Physics Letters B 748, 463-466 (2015)
- Yong-Liang Ma, Masayasu Harada, "Degeneracy of doubly heavy baryons from heavy quark symmetry", Physics Letters B 754, 125-128 (2016).

- Mass degeneracy of DHBs including c and b
  - c and b in S-wave, spin of the light cloud = j_l

  → mass of an HQ singlet with $j = j_l$

  = mass of a HQ multiplet with $j = (j_l+1), j_l, \ldots, |j_l-1|$
- Study of chiral partner structure of DHBs
  - Predictions of mass spectra based on the chiral partner structure
  - Generalized Goldberger-Treiman relations for mass differences and decay widths

Outline

1. Introduction
2. Mass degeneracy of DHBs
3. Hadronic decays of DHBs based on chiral partner structure
4. Summary

2. Mass degeneracy of DHBs

Mass splitting of (cb) diquarks with spin=0,1

- An estimation based on a simple quark model with a spin-spin interaction   cf: A.P.Monteiro, M.Bhat, K.B.V.Kumar, arXiv:1601.05874 (Bc meson in a quark model)

$$\Delta M \equiv M(^3S_1) - M(^1S_0) = \frac{32\pi\alpha_s |\psi(0)|^2}{9 m_c m_b}$$

$\psi(0)$: wave function at origin

- Hydrogen-like wave function by Color-Coulomb force

$$|\psi(0)|^2 = 2\left(m\frac{4}{3}\alpha_s\right)^3 \quad ; \qquad m = \frac{m_c m_b}{m_c + m_b}$$

- an estimation in a quark model for B_c meson gives α_s = 0.3
  - a naïve use of the MS-bar running coupling at $\mu=m_b$ gives α_s = 0.3

ΔM = 55 MeV

- a naïve expectation of the mass of (cb) diquark ~ m_c+m_b ~5.5 GeV

Diquark mass in the heavy quark limit

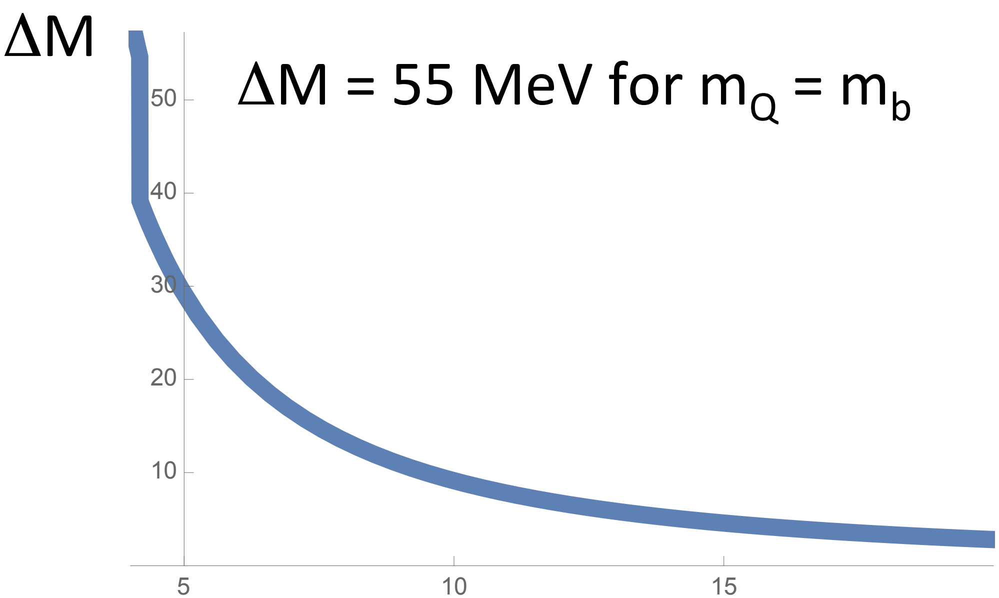
- A diquark made of *Q* and *Q'* with m_Q and $m_{Q'}$

$$\Delta M \equiv M(^3S_1) - M(^1S_0) \simeq \alpha_s^4 \pi \left(\frac{32}{9}\right)^2 \frac{(m_Q m_{Q'})^2}{(m_Q + m_{Q'})^3}$$

  – Take $m_Q \to \infty$ limit for fixed $m_{Q'} = m_c = 1.275$ GeV.

- Suppression of the mass difference in the heavy quark limit by $(m_c/m_Q) \to 0$

- Numerical estimation by using the MS-bar running coupling at $\mu = m_Q$



- In the following analysis, I will neglect the mass difference.
- The effects may generate some corrections of order of 55MeV or 1% in (cb) system.

Effective Lagrangian for the diquarks

- 2 diquarks made from Q and Q' quarks are in the S-wave
  - neglecting the mass difference

$$M\left(\bar{\Phi}^{(QQ')}\right) = M\left(\bar{\Phi}^{(QQ')}_{\mu}\right)$$

$$\bar{\Phi}^{(QQ')} \ : \ \text{spin} = 0 \ ; \quad \bar{\Phi}^{(QQ')}_{\mu} \ : \ \text{spin} = 1$$

- Effective Lagrangian for the diquarks
  - 2 diquarks have the same interaction with the gluon which combines them to a light degree of freedom (``Brown muck'') to form two types of heavy baryons.

$$\begin{aligned}\mathcal{L}^{\Phi}_{\text{eff}} =& \bar{\Phi}^{(QQ')} i\, v_{\nu}(\partial^{\nu} + igG^{\nu})\bar{\Phi}^{(QQ')\dagger} \\ &+ \bar{\Phi}^{(QQ')\mu} i\, v_{\nu}(\partial^{\nu} + igG^{\nu})\bar{\Phi}^{(QQ')\dagger}_{\mu}\end{aligned}$$

v_{ν} : velocity of diquarks

G^{ν} : Gluon field

Mass degeneracy of DHBs in the ground state

$$M(D_{\mathbf{Q}}) = M(D^{\mu}_{\mathbf{Q}})$$

$$D_{\mathbf{Q}} \equiv \bar{\Phi}^{(cb)} q \quad : \text{ HQ singlet } j^P = \frac{1}{2}^+$$

$$D^{\mu}_{\mathbf{Q}} \equiv \bar{\Phi}^{(cb)\mu} q \; : \text{ HQ doublet } j^P = \left(\frac{1}{2}^+, \frac{3}{2}^+\right)$$

– 2 $j^P=1/2^+$ states cannot mix due to the difficulty of the heavy quark spin flipping.

- In the heavy quark limit, the ground states of the DHBs with different heavy quarks form a heavy quark singlet and a heavy quark doublet which are classified by the total spin of the heavy diquark included in them and the DHBs in these two sets have the same mass.

Mass degeneracy of DHBs in excited states

HQ singlet $j^P = j_l^P$

HQ multiplet $j^P = ((j_l+1)^P, \cdots, (|j_l - 1|)^P)$

j_l^P : spin-parity of the light cloud

- Examples in the 1st orbital excitation

J_Q	l	j_l^P	j^P	Mass relation
0	0	$\frac{1}{2}^+$	$\frac{1}{2}^+$	degenerate
1	0	$\frac{1}{2}^+$	$(\frac{3}{2}^+, \frac{1}{2}^+)$	
0	1	$\frac{1}{2}^-$	$\frac{1}{2}^-$	degenerate
1	1	$\frac{1}{2}^-$	$(\frac{3}{2}^-, \frac{1}{2}^-)$	
0	1	$\frac{3}{2}^-$	$\frac{3}{2}^-$	degenerate
1	1	$\frac{3}{2}^-$	$(\frac{5}{2}^-, \frac{3}{2}^-, \frac{1}{2}^-)$	

3. Hadronic decays of DHBs based on chiral partner structure

Chiral partner structure of DHBs

$D_{\mathbf{Q}}$: HQ singlet $j^P = \frac{1}{2}^+$

$D^\mu_{\mathbf{Q}}$: HQ doublet $j^P = \left(\frac{1}{2}^+, \frac{3}{2}^+\right)$

$N_{\mathbf{Q}}$: HQ singlet $j^P = \frac{1}{2}^-$

$N^\mu_{\mathbf{Q}}$: HQ doublet $j^P = \left(\frac{1}{2}^-, \frac{3}{2}^-\right)$

Chiral partners

- Generalized Goldberger-Treiman relation

$$\Delta M = M(N_{\mathbf{Q}}) - M(D_{\mathbf{Q}}) = g_\pi f_\pi$$

g_π : $N_{\mathbf{Q}}$-$D_{\mathbf{Q}}$-π coupling

  – This determines several decay widths in terms of mass differences.

Numerical estimate of decay widths

- Inputs
  - $m_{\Xi_{bc}} = m_{\Xi'_{bc}} = 6.80 \pm 0.05$ GeV (non-relativistic QCD)
  - $m_{\Omega_{bc}} = m_{\Omega'_{bc}} = 6.89 \pm 0.07$ GeV

V.V. Kiselev, A.I. Onishchenko, Nucl. Phys. B 581 (2000) 432
V.V. Kiselev, A.E. Kovalsky, Phys. Rev. D 64 (2001) 014002,

  - $m_{\Xi^*_{bc}} - m_{\Xi_{bc}} = m_{\Xi'^*_{bc}} - m_{\Xi'_{bc}} = m_{D(0^+)} - m_{D(0^-)} = 430$ MeV
  - $m_{\Omega^*_{bc}} - m_{\Omega_{bc}} = m_{\Omega'^*_{bc}} - m_{\Omega'_{bc}} = m_{D_s(0^+)} - m_{D_s(0^-)} = 350$ MeV

- Predictions

Spectrum	Prediction (MeV)	Decay channel	Partial width (MeV)
$m_{\Xi^*_{bc}}$	7230 ± 50	$\Xi^{*+}_{bc} \to \Xi^+_{bc} + \pi^0$	340
$m_{\Xi^\mu_{bc}}$	$6860 \pm 50 \pm 20$	$\Xi^{*+}_{bc} \to \Xi^0_{bc} + \pi^+$	680
$m_{\Xi'^\mu_{bc}}$	$7290 \pm 50 \pm 20$	$\Xi'^{+\mu}_{bc} \to \Xi^{+\mu}_{bc} + \pi^0$	340
$m_{\Xi'^*_{bc}}$	7230 ± 50	$\Xi'^{+\mu}_{bc} \to \Xi^{0\mu}_{bc} + \pi^+$	680
$m_{\Omega^*_{bc}}$	7240 ± 70	$\Xi'^{*+}_{bc} \to \Xi'^+_{bc} + \pi^0$	340
$m_{\Omega^\mu_{bc}}$	$6950 \pm 70 \pm 20$	$\Omega^*_{bc} \to \Omega_{bc} + \pi^0$	18×10^{-3}
$m_{\Omega'^\mu_{bc}}$	$7300 \pm 70 \pm 20$	$\Omega'^\mu_{bc} \to \Omega^\mu_{bc} + \pi^0$	20×10^{-3}
$m_{\Omega'^*_{bc}}$	7240 ± 70	$\Omega'^*_{bc} \to \Omega'_{bc} + \pi^0$	18×10^{-3}

These are about a few 100 MeV. This is an indication of the chiral partner structure.

Ξcc and Ωcc

- Inputs
  - $m_{\Xi_{cc}} = 3.52$ GeV (PDG)
  - $m_{\Omega_{cc}} = 3.678$ GeV
  - $m_{\Xi^*_{cc}} - m_{\Xi_{cc}} = m_{D(0^+)} - m_{D(0^-)} = 430$ MeV
  - $m_{\Omega^*_{cc}} - m_{\Omega_{cc}} = m_{D_s(0^+)} - m_{D_s(0^-)} = 350$ MeV

K.A. Olive, et al., Particle Data Group Collaboration, Chin. Phys. C 38 (2014).
Z.F. Sun, Z.W. Liu, X. Liu, S.L. Zhu, Phys. Rev. D 91(9) (2015) 094030.

- Predictions

Spectrum	Prediction (MeV)	Decay channel	Partial width (MeV)
$m_{\Xi^*_{cc}}$	3950	$\Xi^{*++}_{cc} \to \Xi^{++}_{cc} + \pi^0$	331
$m_{\Xi^\mu_{cc}}$	3625	$\Xi^{*++}_{cc} \to \Xi^{+}_{cc} + \pi^+$	662
$m_{\Xi'^\mu_{cc}}$	4055	$\Xi'^{++}_{cc} \to \Xi^{++\mu}_{cc} + \pi^0$	332
$m_{\Omega^*_{cc}}$	4028	$\Xi'^{++}_{cc} \to \Xi^{+\mu}_{cc} + \pi^+$	663
$m_{\Omega^\mu_{cc}}$	3783	$\Omega^{*+}_{cc} \to \Omega^{+}_{cc} + \pi^0$	20×10^{-3}
$m_{\Omega'^\mu_{cc}}$	4133	$\Omega'^{+\mu}_{cc} \to \Omega^{+\mu}_{cc} + \pi^0$	20×10^{-3}

These are about a few 100 MeV. This is an indication of the chiral partner structure.

Ξbb and Ωbb

- Inputs
  - $m_{\Xi_{bb}} = 10150$ MeV
  - $m_{\Omega_{cc}} = 10308$ MeV
  - $m_{\Xi^*_{bb}} - m_{\Xi_{bb}} = m_{D(0^+)} - m_{D(0^-)} = 430$ MeV
  - $m_{\Omega^*_{bb}} - m_{\Omega_{bb}} = m_{D_s(0^+)} - m_{D_s(0^-)} = 350$ MeV

M. Karliner, J.L. Rosner, Phys. Rev. D 90(9) (2014) 094007.
Z.S. Brown, W. Detmold, S. Meinel, K. Orginos, Phys. Rev. D 90(9) (2014) 094507.

- Predictions

Spectrum	Prediction (MeV)	Decay channel	Partial width (MeV)
$m_{\Xi^*_{bb}}$	10,580	$\Xi^{*0}_{bb} \to \Xi^{0}_{bb} + \pi^0$	343
$m_{\Xi^{\mu}_{bb}}$	10,184	$\Xi^{*0}_{bb} \to \Xi^{-}_{bb} + \pi^+$	686
$m_{\Xi'^{\mu}_{bb}}$	10,614	$\Xi'^{0}_{bb} \to \Xi^{0\mu}_{bb} + \pi^0$	343
$m_{\Omega^*_{bb}}$	10,658	$\Xi'^{0}_{bb} \to \Xi^{-\mu}_{b} + \pi^+$	686
$m_{\Omega^{\mu}_{bb}}$	10,342	$\Omega^{*-}_{bb} \to \Omega^{-}_{bb} + \pi^0$	20×10^{-3}
$m_{\Omega'^{\mu}_{bb}}$	10,692	$\Omega'^{-\mu}_{bb} \to \Omega^{-\mu}_{bb} + \pi^0$	20×10^{-3}

These are about a few 100 MeV. This is an indication of the chiral partner structure.

4. Summary

- (Approximate) Mass degeneracy of DHBs including c and b
  - c and b in S-wave, spin of the light cloud = j_l

  → mass of an HQ singlet with $j = j_l$

  = mass of a HQ multiplet with $j = (j_l+1), j_l, \ldots, |j_l-1|$
- Estimated mass difference is about 50 MeV, which is about 1% of the mass of DHBs.
- Study of chiral partner structure of DHBs
  - Predictions of mass spectra based on the chiral partner structure
  - Generalized Goldberger-Treiman relations for mass differences and decay widths
  - Decay widths of chiral partners are about a few 100 MeV, which is an indication of chiral partner structure.

END