0^+ and 1^+ States of *B* and B_s Mesons

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Based on

- **0^+ and 1^+ States of *B* and B_s Mesons,**
  Phys. Lett. B606 (2005) 329 (hep-ph/0411034).
- **Spinor Operator Giving Both Angular Momentum and Parity,**
  hep-ph/0408326.
- **Spectroscopy of heavy mesons expanded in $1/m_Q$,**
  by T. M. and T. M., PRD56, 5646 (1997).

Results/Conclusions

- Numerical calculations of 0^+ and 1^+ states both for D/D_s and B/B_s heavy mesons by using a potential model respecting Heavy Quark Symmetry (Good agreement with experiments within 1% accuracy)
- Masses of 0+ and 1+ states seems to be SU(3) symmetric

  (Explain this "Recovery of SU(3) flavor symmetry for 0+ and 1+ states" using our model, and predict SU(3) symmetry of heavy baryons like cc{u,d,s} and bb{u,d,s})
- Behavior of mass gap, $\Delta M(m_q) = M_X(1^+) - M_X(1^-) = M_X(0^+) - M_X(0^-)$

  is opposite to that of Bardeen et al.

  (monotonous decreasing in light quark mass m_q)
- One quantum number, *K*, can express both "total angular momentum" and "parity" of heavy mesons

I. Discovery of 0^+ and 1^+ states

- Discovery of D_{sJ}(2317), D_{sJ}(2460) by BaBar, CLEO and Bell in 2003

  D_0^{*0} (2308), $D_1^{'0}$ (2427), by Bell in 2004

- 0^+ and 1^+ states of $c\bar{s} / c\{\bar{u}, \bar{d}\}$, respectively

- D_{sJ}(2317), D_{sJ}(2460) : narrow decay width (4.6 Mev and 5.5 MeV)
  - Due to DK threshold $m_D + m_K > m\,(0^+)$ =2317
    - lhs = m (0^-) (= m_D) + m_K = 1865 + 498 = 2363
  - Isospin violation : $I(D(0^+)) = I(D(0^-)) = 0$, $I(\pi) = 1$
  - Likewise (D^*K threshold) m_{D^*} (=2007) + m_K = 2505 > $m\,(1^+)$ =2457

Exciting excited states

- D_0^{*0} (2308), $D_1^{'0}$ (2427) : wide decay width (276 and 384 MeV)
  - Due to $D\,\pi$ threshold $m_D + m_\pi < m\,(0^+) = 2308$
    - lhs = m (0^-) (= m_D) + m_π = 1865 + 135 = 2000
  - Isospin allowed : I(D(0^+)) = I(D(0^-)) =1/2, I(π) = 1
  - Likewise ($D^*\,\pi$ threshold) m_{D*} (=2007) + m_π = 2142 < m (1^+) = 2427
- Mistery because it seems no potential model succeeds in explaining these masses, D_{sJ} (2317), D_{sJ} (2460),

  D_0^{*0} (2308), and $D_1^{'0}$ (2427).

Exciting excited states (continued)

D_{sJ} (2317), D_{sJ} (2460) : BaBar, PRL90, 242001 (2003)
Belle, PRL91, 262002 (2003)
CLEO, PRD68, 032002 (2003)

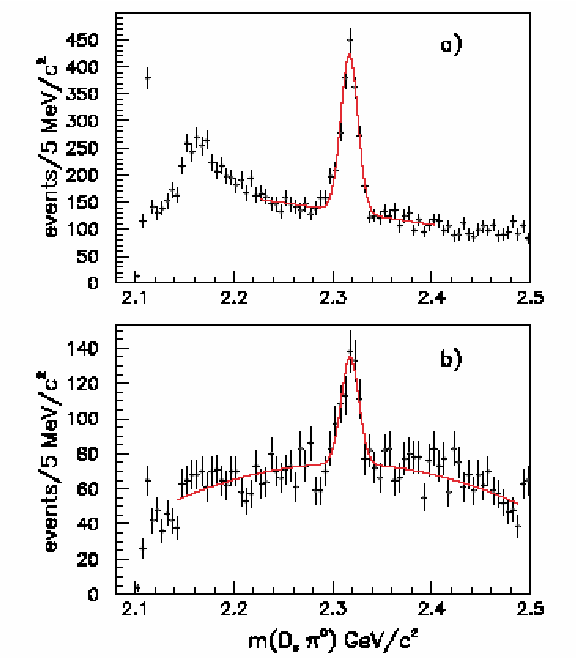
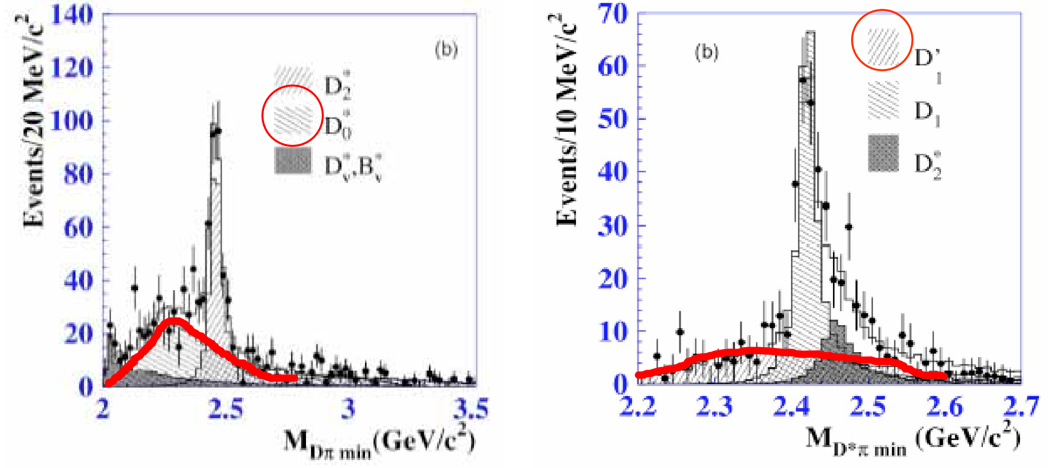
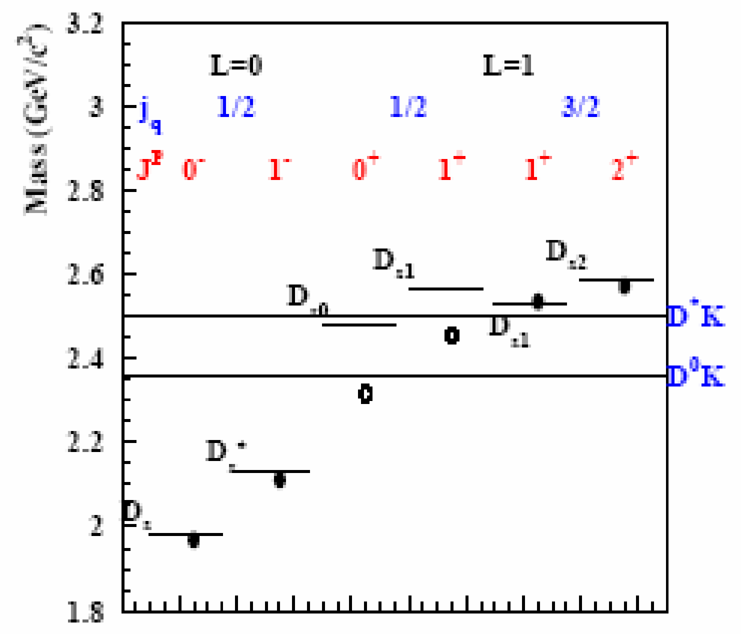


FIG. 2 (color online). The $D_s^+\pi^0$ mass distribution for (a) the decay $D_s^+ \to K^+K^-\pi^+$ and (b) the decay $D_s^+ \to K^+K^-\pi^+\pi^0$. The fits to the mass distributions as described in the text are indicated by the curves.



D_0^{*0} (2308), $D_1^{'0}$ (2427) :
Belle, PRD69 (2004) 112002

DK/D^*K threshold (for potential model)

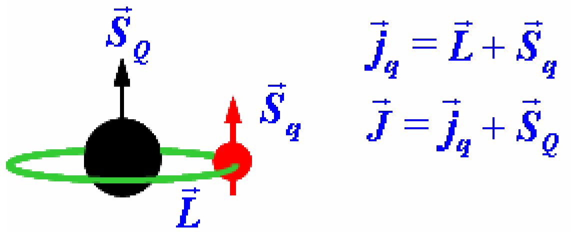


(K. Abe, Talk at PENTAQUARK04, July 20-23, 2004.)

- ● **already observed**
- ○ **newly observed**
- — **prediction by conventional potential model** **(Godfrey et al., PRD43, 1679 (1991))**

II. Potential Description of Narrow/Wide States of D & B

- Heavy-light system: $Q_\alpha \bar{q}_\beta$



- Godfrey, Isgur, and Kokoski (PRD 1985; 1991)

$$H = H_{\text{free}} + H_{\text{int}}$$

$$H_{\text{free}} = (p^2 + m_q^2)^{1/2} + (p^2 + m_Q^2)^{1/2} \quad \text{:Klein-Goldon}$$

$$H_{\text{int}} = H_{\text{conf+Coulomb}} + H_{\text{tensor}} + H_{\text{spin-orbit}}$$

  - Kinetic terms are Klein-Gordon (not spinors)
  - No negative energy states both for q and Q

II. Potential Description (continued)

- Ebert, Galkin, and Faustov (PRD 1998)
  - q Dirac spinor; Q neglected at the lowest order in $1/m_Q$
  - Potential and Energy expanded in $1/m_Q$ corrections
  - But wave functions are not expanded in $1/m_Q$

- Potential models seem to fail in reproducing experimental results

III. Alternative approaches

- Chiral Effective Theory with Heavy Quark Symmetry

(Bardeen et al., PRD68 (2003) 054024)

- mass difference

$$\text{Parity doublets}: \mathcal{H} = (0^-, 1^-), \mathcal{H}' = (0^+, 1^+)$$

$$L_{mass} = \frac{g_\pi}{4}\left[\mathrm{Tr}\left(\bar{\mathcal{H}}'\tilde{\sigma}\mathcal{H}'\right) - \mathrm{Tr}\left(\bar{\mathcal{H}}\tilde{\sigma}\mathcal{H}\right)\right]$$

$$\langle\tilde{\sigma}\rangle = f_\pi I_3$$

- (modified) Goldberger-Treiman relation

$$\Delta M(m_q) = M_X(1^+) - M_X(1^-) = M_X(0^+) - M_X(0^-) = g_\pi f_\pi$$

$$\Delta M(m_c) = 349, \Delta M(\infty) = 338 \text{ for } D_s$$

Is this true or coincident?
Only mass difference.

Alternative approaches (continued)

- DK molecule
  - Barnes, Close and Lipkin, PRD68 (2003) 054006; Bicudo NPA748 (2005) 537.
- Four quark states $c\bar{s}q\bar{q}$
  - Terasaki, PRD68 (2003) 01150.

- Bardeen et al.'s model is most liked by many people.
  - Simple! but absolute values are not calculable!

IV. Predicted Power of Our model (semi-relativistic potential model)

- Heavy and light quarks are Dirac
- Expanding energy (=mass), wave functions, and Hamiltonian in $1/m_Q$ consistently

$$H\psi_l = E^l \psi_l$$

$$H = H_{\mathrm{FWT}} - m_Q = m_Q H_{-1} + H_0 + \frac{1}{m_Q} H_1 + \frac{1}{m_Q^2} H_2 + \cdots$$

$$E^l = E_0{}^l + \frac{1}{m_Q} E_1{}^l + \frac{1}{m_Q^2} E_2{}^l + \cdots$$

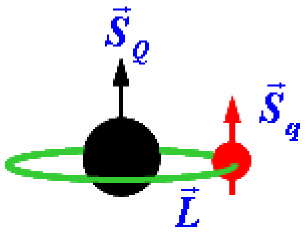
$$\psi_l = \psi_{l0} + \frac{1}{m_Q} \psi_{l1} + \frac{1}{m_Q^2} \psi_{l2} + \cdots$$

Spinor Operator K

- Relation among total ($\vec{J}$), partial ($\vec{j}_q$), and angular momentum ($\vec{L}$):

$$\vec{J} = \vec{j}_q + \frac{1}{2}\vec{\Sigma}_Q, \quad \vec{j}_q = \vec{L} + \frac{1}{2}\vec{\Sigma}_q$$

$$K = -\beta_q\left(\vec{\Sigma}_q \cdot \vec{L} + 1\right), \quad K\Psi^k_{jm} = k\Psi^k_{jm}$$



$$\vec{j}_q = \vec{L} + \vec{S}_q$$
$$\vec{J} = \vec{j}_q + \vec{S}_Q$$

- Relation between K and j_q (k : quantum number of spinor operator K)

$$K^2 = (\Sigma_q)_i(\Sigma_q)_j L_i L_j + 2\vec{\Sigma}_q \cdot \vec{L} + 1 = \vec{L}^2 + \vec{\Sigma}_q \cdot \vec{L} + 1$$
$$= \vec{j}_q^{\,2} + \frac{1}{4}$$
$$\therefore k = \pm(j_q + \frac{1}{2}) \longrightarrow k = \pm j \quad \text{or} \quad \pm(j+1)$$

or

$$\sqrt{\vec{j}_q^{\,2} + \frac{1}{4}} = K = -\beta_q\left(\vec{\Sigma}_q \cdot \vec{L} + 1\right)$$

Same operator can be defined in the case of a single Dirac particle in a central potential.
cf.) J.J.Sakurai, "Advanced Quantum Mechanics"

State Classification

- The parity of heavy meson
  - The parity P' of ψ_0^a is determined by the upper component of .

$$P' = \begin{cases} (-1)^j & \text{for} \quad \Psi_{jm}^{-(j+1)} \text{ and } \Psi_{jm}^{j} \\ (-1)^{j+1} & \text{for} \quad \Psi_{jm}^{j+1} \text{ and } \Psi_{jm}^{-j} \end{cases}$$

  - The parity P of heavy meson

$$P = -P' = \frac{k}{|k|}(-1)^{|k|+1}$$

Degeneracy is automatically resolved due to $1/m_Q$ corrections

Intrinsic parity of $\bar{q}$

J^P	0^-	1^-	0^+	1^+	1^+	2^+
k	-1	-1	1	1	-2	-2
$j_q^{P_q}$	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{1}{2}^+$	$\frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{3}{2}^+$
${}^{2s+1}L_J$	${}^1S_0$	${}^3S_1$	${}^3P_0$	${}^3P_1, {}^1P_1$	${}^1P_1, {}^3P_1$	${}^3P_2$
Ψ_j^k	Ψ_0^{-1}	Ψ_1^{-1}	Ψ_0^{1}	Ψ_1^{1}	Ψ_1^{-2}	Ψ_2^{-2}

Comparison of Mass Spectra (1)

	J^P	$D(0^-)$	$D(1^-)$	$D(0^+)$	$D(1^+)$
D	observed	1867	2008	2308	2427
	predicted	1867	2009	2285	2423

	J^P	$D_s(0^-)$	$D_s(1^-)$	$D_s(0^+)$	$D_s(1^+)$
D_s	observed	1969	2112	2317	2457
	predicted	1969	2112	2330	2472

	J^P	$B(0^-)$	$B(1^-)$	$B(0^+)$	$B(1^+)$
B	observed	5279	5325	–	–
	predicted	5275	5307	5595	5627

	J^P	$B_s(0^-)$	$B_s(1^-)$	$B_s(0^+)$	$B_s(1^+)$
B_s	observed	5369	–	–	–
	predicted	5391	5424	5627	5660

Refined calculations

Good agreement within 1% accuracy

Predicted values

Comparison of Mass Spectra (2)

by T.M. and T.M., PRD56 (1997) 5646 (8 years ago!!)

D

J^P	$D(0^-)$	$D(1^-)$	$D(0^+)$	$D(1^+)$
observed	1867	2008	2308	2427
predicted	1867	2008	2304	2449

D_s

J^P	$D_s(0^-)$	$D_s(1^-)$	$D_s(0^+)$	$D_s(1^+)$
observed	1969	2112	2317	2457
predicted	1966	2125	2339	2487

Good agreement within 1% accuracy

B

J^P	$B(0^-)$	$B(1^-)$	$B(0^+)$	$B(1^+)$
observed	5279	5325	–	–
predicted	5281	5323	5697	5740

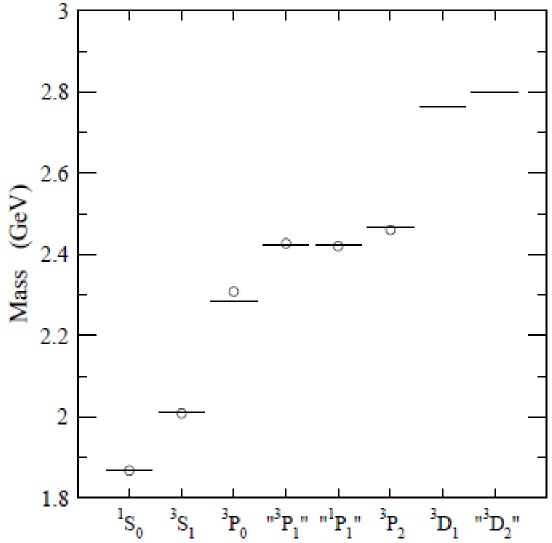
B_s

J^P	$B_s(0^-)$	$B_s(1^-)$	$B_s(0^+)$	$B_s(1^+)$
observed	5369	–	–	–
predicted	5393	5440	5716	5760

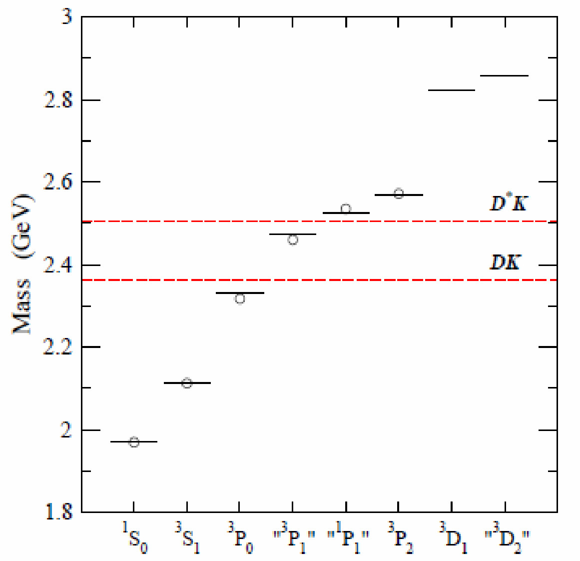
Predicted values

Mass Spectra

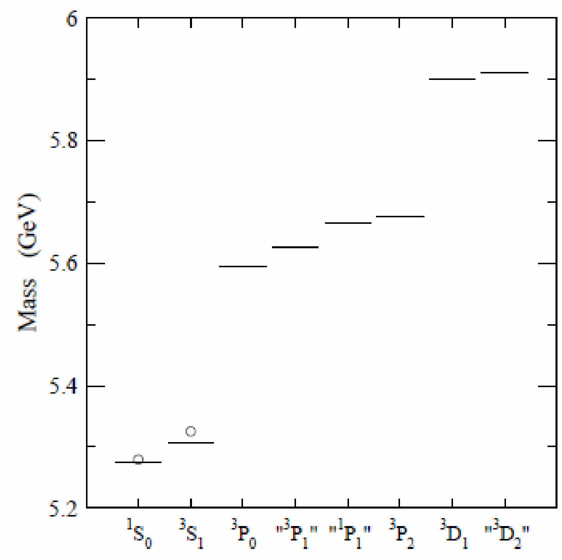
D



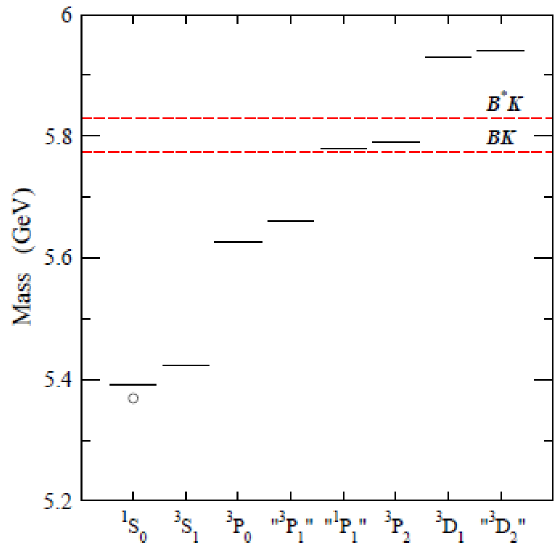
D_s



B

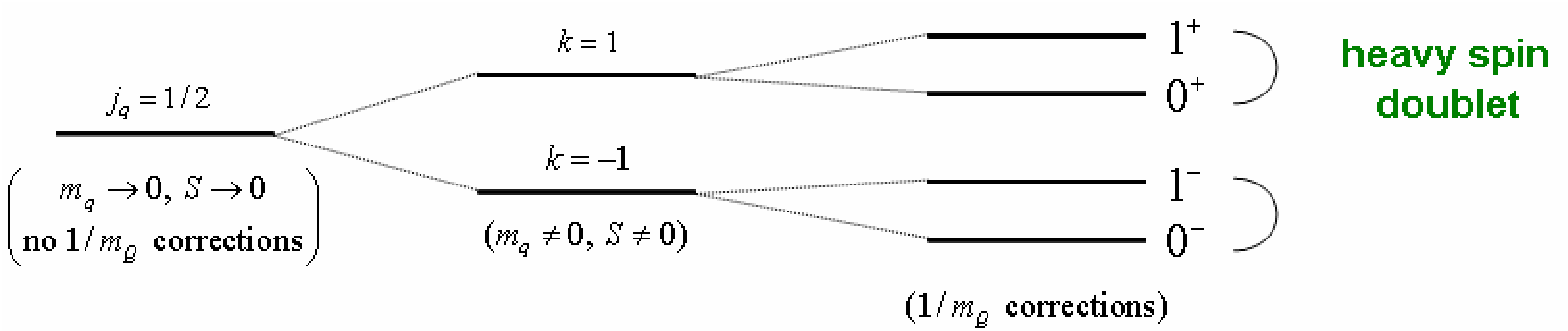


B_s

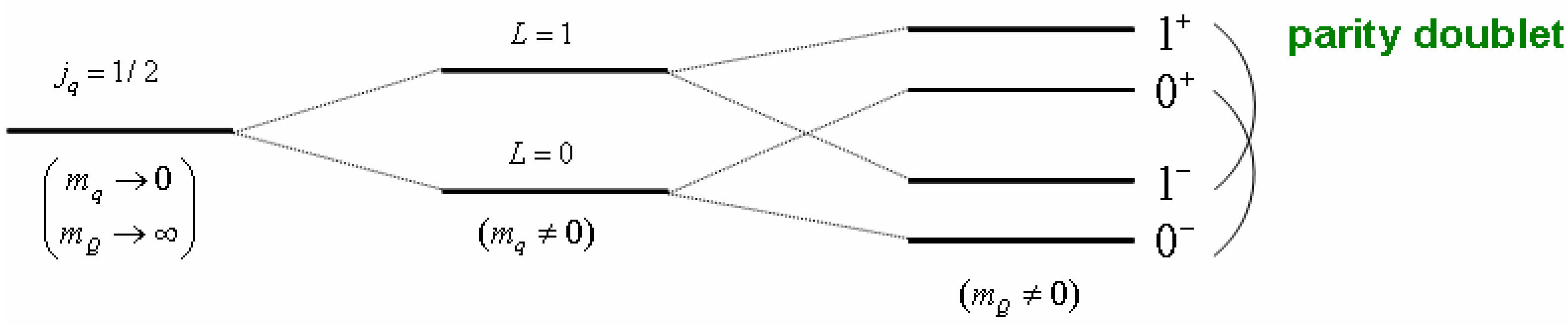


Structure of Mass Level

- Semi-relativistic model **(Our model, hep-ph/0408326, 0411034)**



- Bardeen et al. **(Bardeen et al., PRD68 (2003) 054024)**



Decay Modes of Higher B and B_s Mesons

- $B_s(1^-) \to B_s(0^-) + \gamma$

  Decay $B_s(1^-) \to B_s(0^-) + \gamma$ **is similar to** $B(1^-) \to B(0^-) + \gamma$ **: dominant decay mode**

- $B(0^+) \to B(0^-) + \pi$

  strong decay, not prohibited by isospin invariance

  Decay width is as broad as a few hundred MeV like $D(0^+) \to D(0^-) + \pi$ **.**

- $B(1^+) \to B(1^-) + \pi$

  Decay width is also broad, a few hundred MeV. $\because D(1^+) \to D(1^-) + \pi$

Decay Modes (continued)

- $B_s(0^+) \to B_s(0^-) + \pi$

  prohibited by isospin invariance, below BK **threshold**

  Decay width is expected narrow, a few MeV like $D_s(0^+) \to D_s(0^-) + \pi$ **.**

- $B_s(1^+) \to B_s(1^-) + \pi$

  Decay width is also narrow, a few MeV. $\because D_s(1^+) \to D_s(1^-) + \pi$

These higher states might be observed in Tevatron/LHC experiments.

X. Recovery of SU(3) Symmetry

- 0^- and 1^- are not symmetric

quarks	$c\bar{u}$	$c\bar{d}$	$c\bar{s}$
$D(0^-)$	D^0	D^+	D_s^+
observed	1864.6	1869.4	1968.3
predicted	1867	1867	1969
$D(1^-)$	D^{*0}	D^{*+}	D_s^{*+}
observed	2006.7	2010.0	2112.1
predicted	2009	2009	2112

Recovery of SU(3) Symmetry (continued)

- 0^+ and 1^+ are symmetric

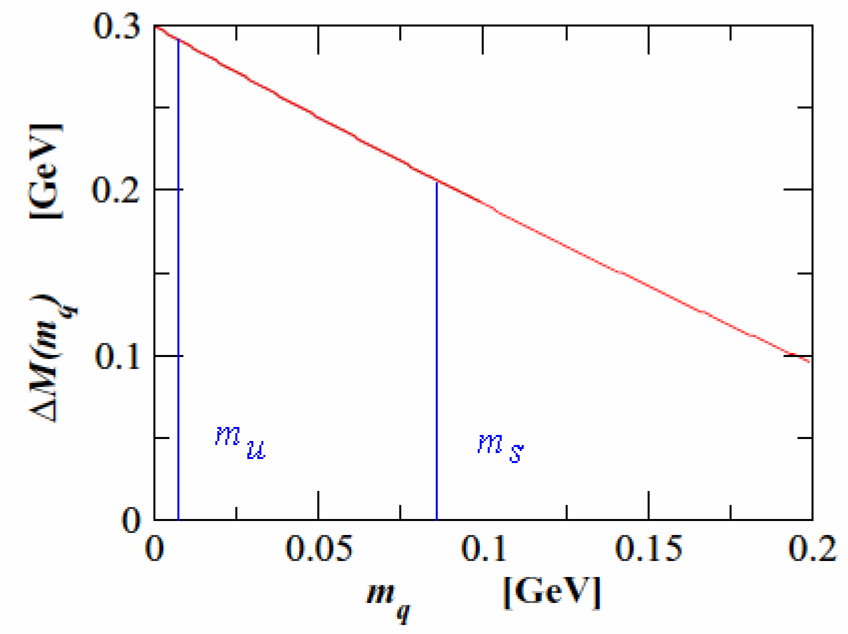
quarks	$c\bar{u}$	$c\bar{d}$	$c\bar{s}$
$D(0^+)$	D_0^{*0}	D_0^{*+}	D_{sJ}^+
observed	2308	–	2317
predicted	2285	2285	2330
$D(1^+)$	D^{*0}	D^{*+}	D_s^{*+}
observed	2422.2	2427 ± 5	2459.3
predicted	2423	2423	2472

Recovery of SU(3) Symmetry (continued)

- **Mass gap is** opposite tendency to that of Bardeen et. al.

  (monotonous decreasing in $\boldsymbol{m_q}$ while Bardeens' proportional to $\boldsymbol{m_q}$)

$$\Delta M(m_q) = M_X(1^+) - M_X(1^-) = M_X(0^+) - M_X(0^-)$$



Recovery of SU(3) Symmetry (continued)

k	$-1(L=0)$		$+1(L=1)$
J^P	$0^- \& 1^-$		$0^+ \& 1^+$
D	1782		2073
	$\downarrow$		$\wr\wr$
D_s	1902	$\rightarrow$	2102

Table for Degenerate masses

$$\Delta M(m_q) = M_X(1^+) - M_X(1^-) = M_X(0^+) - M_X(0^-)$$

$$\Delta M(m_u) = 291\,\mathrm{MeV}, \quad \Delta M(m_s) = 200\,\mathrm{MeV}$$

$$\Delta M(m_s) - \Delta M(m_u) = -91\,\mathrm{MeV} \quad \text{(vertidcal)}$$

$$M_D(m_s) - M_D(m_u) = 120\,\mathrm{MeV} \quad \text{(horizontal)}$$

The same is true for B/Bs mesons.

XI. Summary

- We treated $Q\bar{q}$ system in a semi-relativistic approach.
  - Hamiltonian, eigenvalues and wave functions are expanded in $1/m_Q$.
  - New operator K is introduced.

$$K \cdots \text{determines} \begin{cases} \text{total angular momentum of light quark degrees of freedom: } j_q \\ \text{parity of heavy meson: } P \end{cases}$$

- Predict 0^+ and 1^+ state masses of B and B_s mesons and their decay modes based on our success of prediction of D/D_s meson masses in our model .
  - Degeneracy between each heavy spin multiplet $(0^-, 1^-)$ and $(0^+, 1^+)$ is automatically derived.
  - We expect these states will be observed in Tevatron/LHC.
- We have used current quark masses (running mass) as input, i.e., quantum effects are important.
- Recovery of SU(3) symmetry in $(0^+, 1^+)$ multiples is explained in our model.
- SELEX $D_{sJ}(2632)$ might be radial excitation.
- Open a new way to calculate heavy mesons/baryons. Lots more coming.