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).

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(π) = 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 : $I(D(0^+)) = I(D(0^-)) = 1/2$, $I(\pi) = 1$
  - 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).

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

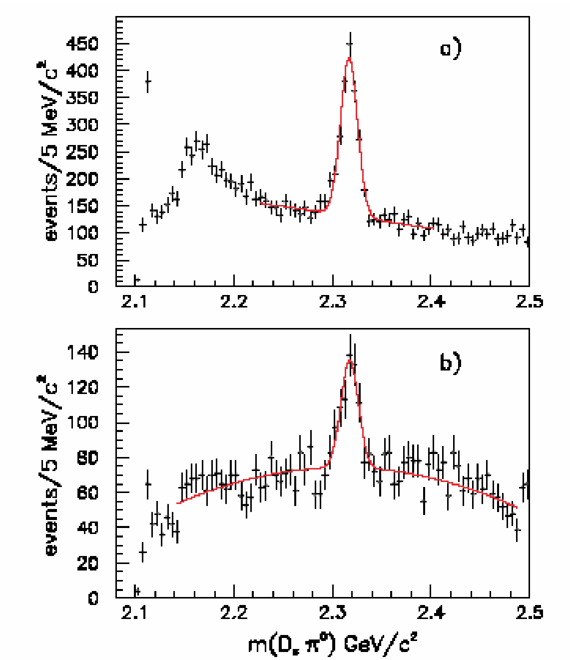
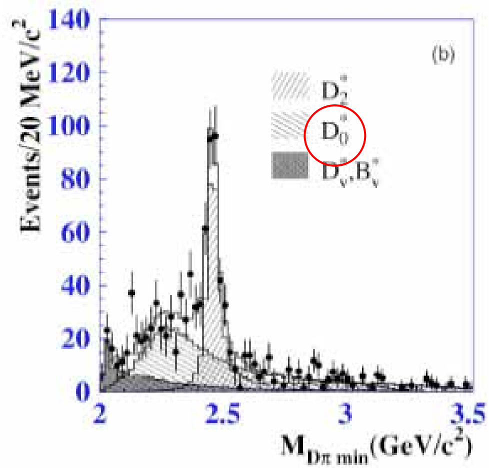
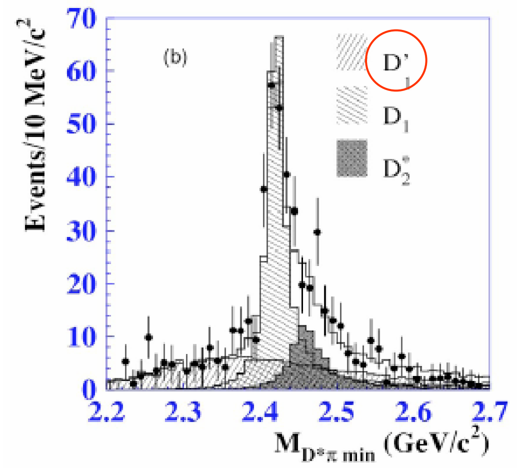


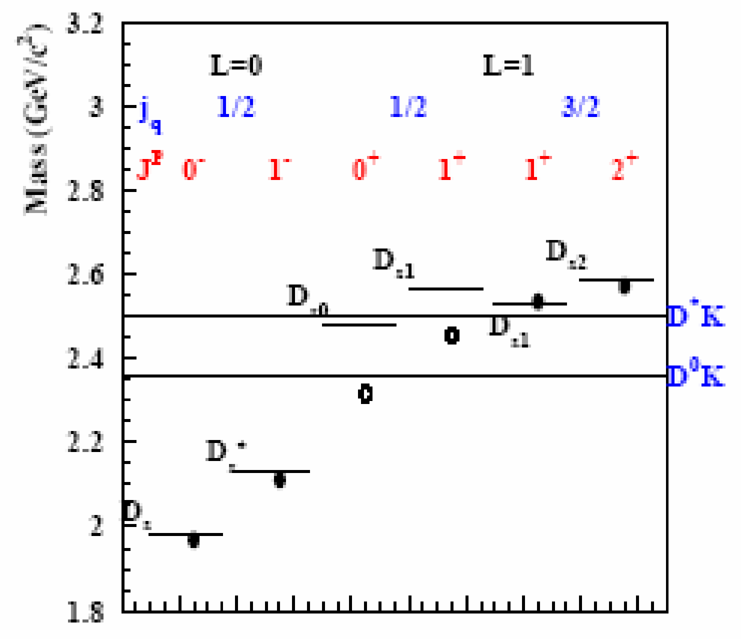
FIG. 2 (color online). The $D_s^+\pi^0$ mass distribution for (a) the decay $D_s^+ \to K^+K^-\pi^+$ and (b) the decay $D_s^+ \to K^+K^-\pi^+\pi^0$. The fits to the mass distributions as described in the text are indicated by the curves.





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

DK/D^*K threshold

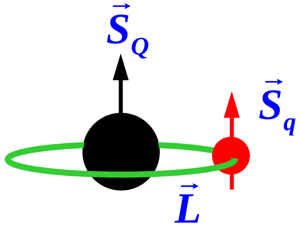


K. Abe, Talk at PENTAQUARK04, July 20-23, 2004.

- ● **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: $Q_\alpha \bar{q}_\beta$



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

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

- 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 of q and Q

II. Potential Description（2）

- 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 approach

- Chiral Effective Theory with Heavy Quark Symmetry

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

- mass difference

Parity doublets : $H=(0^-,1^-)$, $H'=(0^+,1^+)$

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

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

- (modified) Goldberger-Treiman relation

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

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

Is this true or coincident?
Only mass difference.

III. Other alternative approaches

- 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

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

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

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

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

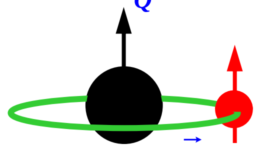
$$\psi_l = \psi_{l0} + \frac{1}{m_Q}\psi_{l1} + \frac{1}{m_Q^2}\psi_{l2} + \cdots$$

V. Spinor Operator K

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

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

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



- 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

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

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

VI. State Classification

- The parity of heavy meson
  - The parity *P'* of ψ_0^a is determined by the upper component of y_{jm}^k.

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

  - 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}

VII. Comparison of Mass Spectra

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

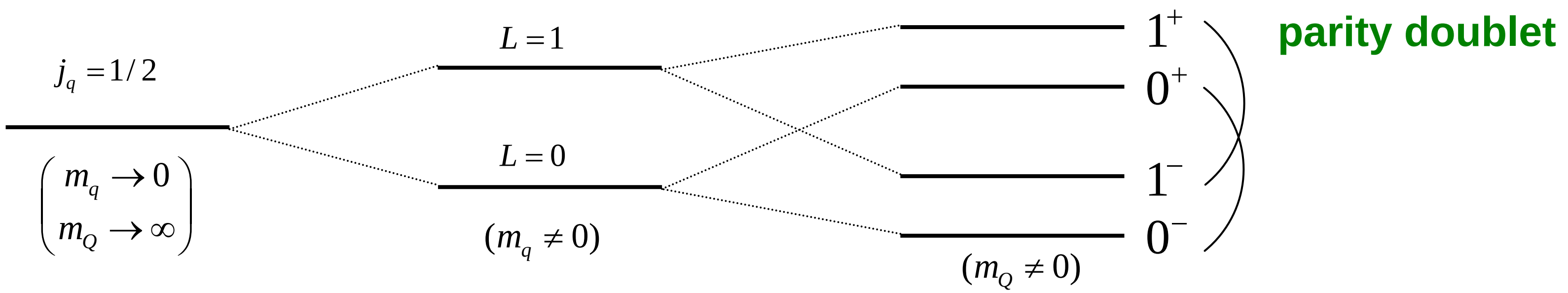
B_s

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

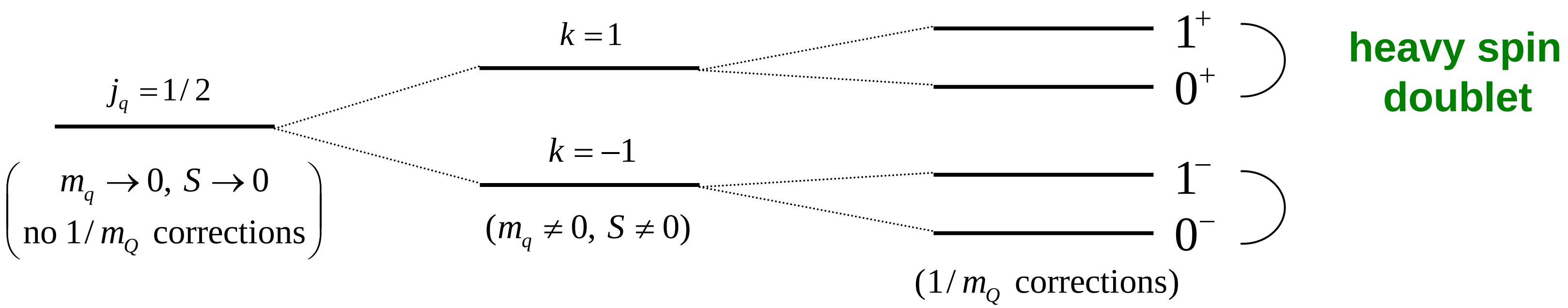
Predicted values

VIII. Structure of Mass Level

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



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



IX. 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. $\because D(1^+) \to D(1^-) + \pi$

X. 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. $\because D_s(1^+) \to D_s(1^-) + \pi$

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

VII. Summary

- We treated $Q\bar{q}$ system in a semi-relativistic approach.
  - Hamiltonian 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.
- Mass gap between parity doublets, $(0^-, 0^+)$ and $(1^-, 1^+)$, is approximate in our model.
- SELEX $D_{sJ}(2632)$ might be radial excitation.
- Open a new way to calculate heavy mesons/baryons. Lots more coming.