Decays of $D^*_0(2317)$ and $D_{s1}(2460)$ mesons

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Overview of the talk

- Focus on $D_{s0}^{*}(2317) = DK$ and $D_{s1}(2460) = D^{*}K$ mesons
- Observed in $B$-decays by BaBar, CLEO Coll. and confirmed by Belle Coll.
- Extension to bottom states $B_{s0}^{*}(5725) = B\bar{K}$ and $B_{s1}(5778) = B^{*}\bar{K}$ mesons
- Talk is based on the papers
  
  Faessler, Gutsche, Lyubovitskij, Ma
  PR D76 (2007) 014005
  Faessler, Gutsche, Kovalenko, Lyubovitskij
  PR D76 (2007) 014003
  Faessler, Gutsche, Lyubovitskij, Ma

Plan

- Introduction
- Approach
- Results: strong and em decays.
- Summary
Introduction

• Hadronic molecules (HM) - weakly bound states of hadrons

• Familiar examples: Nuclei and Hypernuclei

Complexity of hadronic mass spectra
Mass slightly below threshold of h.p. \( m_H < m_{H_1} + m_{H_2} \)
Voloshin, Okun, De Rujula, Georgi, Glashow, Weinstein, Isgur, Barnes

• Meson-meson molecules

\( a_0(980), \ f_0(980) = K\bar{K} \)
\( D_{s0}^*(2317) = DK, \quad D_{s1}(2460) = D^*K \)
\( B_{s0}^*(5725) = B\bar{K}, \quad B_{s1}(5778) = B^*\bar{K} \)
\( X(3872) = D^0\bar{D}^{*0} + \text{c.c.} \)
\( Y(4260) = D\bar{D}_1 - \text{c.c.} \)
\( \psi(4415) = D_s^*\bar{D}_{s0}(2317) + \text{c.c.} \)

• Meson-baryon molecules

\( \Lambda(1405) = N\bar{K} \quad \Lambda_c^+(2940) = D^*N \)
Introduction

Experimental and theoretical status of $D_{s0}^*(2317)$ and $D_{s1}(2460)$

- Discovered
  $D_{s0}^*(2317)$ by BABAR at SLAC (2003)
  $D_{s1}(2460)$ by CLEO at CESR (2003)

- Both confirmed by Belle at KEKB (2004)

- Basic properties

<table>
<thead>
<tr>
<th>State</th>
<th>$I(J^P)$</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{s0}^*(2317)\pm$</td>
<td>0(0$^+$)</td>
<td>2317.8 ± 0.6</td>
<td>&lt; 3.8</td>
</tr>
<tr>
<td>$D_{s1}(2460)\pm$</td>
<td>0(1$^+$)</td>
<td>2459.6 ± 0.6</td>
<td>&lt; 3.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strong decay (MeV)</th>
<th>EM decay (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma(D_{s0}^* \rightarrow D_s\pi^0) &lt; 0.25$ (th)</td>
<td>$\Gamma(D_{s0}^* \rightarrow D_s^*\gamma) &lt; 0.035$ (th)</td>
</tr>
<tr>
<td>$\Gamma(D_{s1} \rightarrow D_s\pi^0) &lt; 2$ (exp); &lt; 0.25 (th)</td>
<td>$\Gamma(D_{s1} \rightarrow D_s\gamma) &lt; 0.77$ (exp); &lt; 0.1 (th)</td>
</tr>
</tbody>
</table>
Introduction

• Theoretical approaches:
  quark models, effective Lagrangian approaches, QCD sum rules, lattice, · · ·

Bari, Beijing, Coimbra, Darmstadt, Durham, Valencia, Tübingen, · · ·

• Structure:  $q\bar{q}, \ (q\bar{q})^2, \ q\bar{q} + (q\bar{q})^2, \ DD^\dagger, \ 2M$

• Strong decays:  $D_{s0}^* \to D_s\pi^0$ and $D_{s1} \to D_s^*\pi^0$

  via $\eta - \pi^0$ mixing  $\implies \Gamma \sim \varepsilon^2 \sim (m_d - m_u)^2$

• Additional mechanism in molecular picture $D_{s0}^* = (DK)$ and $D_{s1} = (D^*K)$

due to presence of $u$ and $d$ quarks in $D^{(*)}$ and $K^{(*)}$

$\Gamma \sim \varepsilon^2 \sim \left( M_{H^+}^2 - M_{H^0}^2 \right)^2$ where $H = K, K^*, D, D^*$
$\eta - \pi^0$ mixing mechanism

$\tan 2\varepsilon = \frac{\sqrt{3} m_d - m_u}{\frac{m_s - m}{2}}$

$= D_{s0}^{*+} \, \eta \, D_s^+ + D_{s0}^{*+} \, K^0 \, D_s^+ + D_{s0}^{*+} \, K^{*0} \, D_s^+ \sim O(\varepsilon)$
Introduction

Direct mechanism

\[ \tan 2\varepsilon = \frac{\sqrt{3} m_d - m_u}{2 m_s - \hat{m}} \]

\[ = D_{s0}^+ \xrightarrow{\tau_3 \cos \varepsilon} K^* \xrightarrow{\pi^0} K \xrightarrow{\tau_3} K^+ \xrightarrow{\pi^0} D_s^+ = O(\varepsilon) \]
Approach

- **Our aim:** Bound state structure of HM using QFT approach based on compositeness condition $Z_M = 0$

Weinberg, PR 130 (1963) 776; Salam, NC 25 (1962) 224; Hayashi et al., FP 15 (1967) 625;
Efimov, Ivanov, The Quark Confinement Model of Hadrons, IOP Publishing, 1993;
Ivanov, Locher, Lyubovitskij, FBS 21 (1996) 131;
Ivanov, Lyubovitskij, Körner, Kroll, PR D56 (1997) , 348;
Faessler, Gutsche, Holstein, Lyubovitskij, Nicmorus, Pumsa-ard, PR D74 (2006) 074010;
Faessler, Gutsche, Lyubovitskij, Ma, PR D76 (2007) 014005

\[ Z_{M}^{1/2} = \langle M_0 | M \rangle \]

\[ Z_M = |\langle M_0 | M \rangle|^2 \]

\[ g_M = Z_M^{1/2} g_{M_0} \]

\[ Z_M = 1 - g_M^2 \Pi'(m_M^2) = 0 \]

$g_M$ is finite, $g_{M_0} \to \infty$
Approach

Molecular structure of $D_{s0}(0^+)$ and $D_{s1}(1^+)$ states

$$|D_{s0}^+\rangle = |D^+ K^0\rangle + |D^0 K^+\rangle$$
$$|D_{s1}^+\rangle = |D^{*+} K^0\rangle + |D^{*0} K^+\rangle$$

Couplings of molecules with constituents

$$\mathcal{L}_{D_{s0}^{*}}(x) = g_{D_{s0}^{*}} D_{s0}^{*-}(x) \int dy \Phi(y^2) D(x + w_{KD} y) K(x - w_{DK} y) + \text{H.c.}$$

$$\mathcal{L}_{D_{s1}}(x) = g_{D_{s1}} D_{s1}^{\mu-}(x) \int dy \Phi(y^2) D_{\mu}^*(x + w_{KD^{*}} y) K(x - w_{D^{*}K} y) + \text{H.c.}$$

$$D = \begin{pmatrix} D^0 \\ D^+ \end{pmatrix}, \quad D^* = \begin{pmatrix} D^{*0} \\ D^{*+} \end{pmatrix}, \quad K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}, \quad w_{ij} = \frac{m_i}{m_i + m_j}$$

Results: $g_{D_{s0}^{*}} = 10.58 \pm 0.68 \text{ GeV}$, $g_{D_{s1}} = 10.9 \pm 0.72 \text{ GeV}$.

Gaussian v.f. $\tilde{\Phi}(p_E^2) = \exp(-p_E^2/\Lambda^2)$ and $\Lambda = 1 - 2$ GeV.
**Approach**

**Effective Lagrangian**

\[ \mathcal{L} = \mathcal{L}_{\text{free}} + \mathcal{L}_{\text{int}} \]

\[
\mathcal{L}_{\text{str}} = -\frac{g_{D^* D \pi}}{2\sqrt{2}} D^{* \dagger}_{\mu} \hat{\pi}_D i \partial^\mu D + \frac{g_{K^* K \pi}}{\sqrt{2}} K^{* \dagger}_{\mu} \hat{\pi}_K i \partial^\mu K
\]
\[+ g_{D^* D_s K} D^*_{\mu} K i \partial^\mu D_s - g_{D^* D_s K} D^*_{s, \mu} D i \partial^\mu K
\]
\[ - ig_{K^* D_s^* D^*} \left[ D^*_{s, \mu \nu} D^*_{\mu} K^*_{\nu} + D^*_{\mu \nu} K^*_{\mu} D^*_{s, \nu} + K^*_{\mu \nu} D^*_{s, \mu} D^*_{\nu} \right]
\]
\[+ \mathcal{L}_{D_s^* 0} + \mathcal{L}_{D_s 1} + \text{H.c.} \]

where

\[ \hat{\pi}_D = \pi_1 \tau_1 + \pi_2 \tau_2 + \pi_3 (\tau_3 \cos \varepsilon + I \sin \varepsilon / \sqrt{3}) \]
\[ \hat{\pi}_K = \pi_1 \tau_1 + \pi_2 \tau_2 + \pi_3 (\tau_3 \cos \varepsilon + I \sin \varepsilon \sqrt{3}) \]

\[ \tan 2\varepsilon = \frac{\sqrt{3}}{2} \frac{m_d - m_u}{m_s - \hat{m}} \simeq 0.02, \quad \hat{m} = \frac{1}{2} (m_u + m_d) \]

\[ g_{D^* D \pi} = 17.9, \quad g_{K^* K \pi} = 4.61 \quad \text{Data} \]
\[ g_{D^* D_s K} = g_{K^* D_s D} = 2.02 \quad \text{LC QCD SR/Estimate} \]
\[ g_{D^* D_s K} = g_{D_s^* D^* K^*} = 1.84 \quad \text{LC QCD SR/Estimate} \]
$\mathcal{L}_{em}$ is generated using minimal substitution:

$$\partial^\mu M^{(*)\pm} \rightarrow (\partial^\mu \mp ieA^\mu) M^{(*)\pm}$$

$\mathcal{L}_{D^*_{s0}}$ and $\mathcal{L}_{D_{s1}}$ should be gauged:

$$H^{\pm}(y) \rightarrow \tilde{H}^{\pm}(y) = e^{-ie\int_x^y dz_\mu A^\mu(z)} H^{\pm}(y), \quad \frac{\partial}{\partial y_\nu} \int_x^y dz_\mu A^\mu(z) \approx A^\nu(y)$$
Strong decay $D_{s0}^* \rightarrow D_s \pi^0$
Approach

Strong decay $D_{s1} \rightarrow D_s^* \pi^0$

(a) $D_{s1}^{+} \rightarrow D^{*+} D^{+} \pi^{0}$

(b) $D_{s1}^{+} \rightarrow D^{*0} D^{0} \pi^{0}$

(c) $D_{s1}^{+} \rightarrow K^{0} K^{*+} \pi^{0}$

(d) $D_{s1}^{+} \rightarrow D^{*0} K^{0} K^{0} \pi^{0}$
Approach

Radiative decay $D_{s0}^* \rightarrow D_s^* \gamma$

(a) $\gamma$ $D_{s0}^* \rightarrow D^+ D_s^+$ $K^0$
(b) $\gamma$ $D_{s0}^* \rightarrow D^+ D_s^+$ $D^0$
(c) $\gamma$ $D_{s0}^* \rightarrow D^+ D_s^+$ $K^0$
(d) $\gamma$ $D_{s0}^* \rightarrow D^+ D_s^+$ $D^0$
(e) $\gamma$ $D_{s0}^* \rightarrow D^+ D_s^+$ $K^0$
(f) $\gamma$ $D_{s0}^* \rightarrow D^+ D_s^+$ $D^0$
(g) $\gamma$ $D_{s0}^* \rightarrow D^+ D_s^+$ $K^0$
(h) $\gamma$ $D_{s0}^* \rightarrow D^+ D_s^+$ $D^0$
Approach

Radiative decay $D_{s1} \rightarrow D_s \gamma$

(a) $\gamma$ 

(b) $\gamma$

(c) $\gamma$

(d) $\gamma$

(e) $\gamma$

(f) $\gamma$

(g) $\gamma$

(h) $\gamma$
Matrix elements and decay width

Matrix elements

\[ D_{s0}^+(p) \rightarrow D_s(p') \pi^0(q) \quad M = G_{D_{s0}D_s} \]
\[ D_{s1}^+(p) \rightarrow D_s^*(p') \pi^0(q) \quad M^{\mu\nu} = g^{\mu\nu} G_{D_{s1}^*D_s^*} - \nu' \nu F_{D_{s1}^*D_s^*} \]
\[ D_{s0}^*(p) \rightarrow D_s^*(p') \gamma(q) \quad M^{\mu\nu} = e G_{D_{s0}^*D_s^*} (g_{\mu\nu} p' q - p'_{\mu} q_{\nu}) \]
\[ D_{s1}^+(p) \rightarrow D_s(p') \gamma(q) \quad M^{\mu\nu} = e G_{D_{s1}D_s^*} (g_{\mu\nu} p q - q_{\mu} p_{\nu}) \]

Decay widths

\[ \Gamma(D_{s0}^* \rightarrow D_s \pi) = \frac{G_{D_{s0}D_s}^2}{8 \pi m_{D_{s0}}^2} P^* \]
\[ \Gamma(D_{s1} \rightarrow D_s^* \pi^0) = \frac{G_{D_{s1}D_s}^2}{12 \pi m_{D_{s1}}^2} P^* \left\{ 1 + \frac{w^2}{2} \left( 1 + \frac{F_{D_{s1}D_s^*} m_{D_{s1}}^2}{G_{D_{s1}D_s^*} m_{D_{s1}}^2} \frac{w^2 - 1}{w} \right)^2 \right\}, \quad w = \nu \nu' \]
\[ \Gamma(D_{s0}^* \rightarrow D_s^* \gamma) = \alpha G_{D_{s0}D_s^*}^2 P^* 3 \]
\[ \Gamma(D_{s1} \rightarrow D_s \gamma) = \frac{\alpha}{3} G_{D_{s1}D_s}^2 P^* 3 \]
## Results

### Table 1. Strong decay widths in keV

<table>
<thead>
<tr>
<th>Approach</th>
<th>$\Gamma(D_{s0} \rightarrow D_s\pi^0)$</th>
<th>$\Gamma(D_{s1} \rightarrow D_{s}^*\pi^0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nielsen 2005</td>
<td>6 ± 2</td>
<td>7 ± 1</td>
</tr>
<tr>
<td>Colangelo 2003</td>
<td>7 ± 1</td>
<td>10</td>
</tr>
<tr>
<td>Guo 2006</td>
<td>8.69</td>
<td>11.41</td>
</tr>
<tr>
<td>Godfrey 2003</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Fayyazuddin 2003</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>Bardeen 2003</td>
<td>21.5</td>
<td>21.5</td>
</tr>
<tr>
<td>Lu 2006</td>
<td>32</td>
<td>35</td>
</tr>
<tr>
<td>Wei 2005</td>
<td>39 ± 5</td>
<td>43 ± 8</td>
</tr>
<tr>
<td>Cheng 2003</td>
<td>10 − 100</td>
<td></td>
</tr>
<tr>
<td>Ishida 2003</td>
<td>155 ± 70</td>
<td>155 ± 70</td>
</tr>
<tr>
<td>Azimov 2004</td>
<td>129 ± 43</td>
<td>187 ± 73</td>
</tr>
<tr>
<td>Lutz 2007</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>Our results</td>
<td>46.7 − 75</td>
<td>50.1 − 79.2</td>
</tr>
</tbody>
</table>
## Results

**Table 2.** Radiative decay widths in keV

<table>
<thead>
<tr>
<th>Approach</th>
<th>$\Gamma(D_{s0}^* \rightarrow D_{s}^*\gamma)$</th>
<th>$\Gamma(D_{s1} \rightarrow D_{s}\gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fayyazuddin 2003</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Oset 2007</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>Colangelo 2003</td>
<td>0.85 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>Close 2005</td>
<td>1</td>
<td>$\leq 7.3$</td>
</tr>
<tr>
<td>Lu 2006</td>
<td>$\approx 1.1$</td>
<td>0.6 – 2.9</td>
</tr>
<tr>
<td>Wang 2006</td>
<td>1.3 – 9.9</td>
<td>5.5 – 31.2</td>
</tr>
<tr>
<td>Azimov 2004</td>
<td>$\leq 1.4$</td>
<td>$\approx 2$</td>
</tr>
<tr>
<td>Bardeen 2003</td>
<td>1.74</td>
<td>5.08</td>
</tr>
<tr>
<td>Godfrey 2003</td>
<td>1.9</td>
<td>6.2</td>
</tr>
<tr>
<td>Colangelo 2005</td>
<td>4 – 6</td>
<td>19 – 29</td>
</tr>
<tr>
<td>Lutz 2007</td>
<td>$&lt; 7$</td>
<td>$\approx 43.6$</td>
</tr>
<tr>
<td>Ishida 2003</td>
<td>21</td>
<td>93</td>
</tr>
<tr>
<td>Hayashigakai 2005</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Our results</td>
<td>0.47 – 0.63</td>
<td>2.37 – 3.73</td>
</tr>
</tbody>
</table>
## Results

Table 3. Ratios $R_{D^*_{s0}} = \frac{\Gamma(D_{s0}^{*} \rightarrow D_s^* \gamma)}{\Gamma(D_{s0}^{*} \rightarrow D_s \pi)}$ and $R_{D_{s1}} = \frac{\Gamma(D_{s1} \rightarrow D_s \gamma)}{\Gamma(D_{s1} \rightarrow D_s^* \pi)}$

<table>
<thead>
<tr>
<th>Approach</th>
<th>$R_{D^*_{s0}}$</th>
<th>$R_{D_{s1}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fayyazuddin 2003</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Azimov 2004</td>
<td>$\leq 0.02$</td>
<td>0.01 - 0.02</td>
</tr>
<tr>
<td>Lutz 2007</td>
<td>$&lt; 0.05$</td>
<td>$\approx 0.31$</td>
</tr>
<tr>
<td>Bardeen 2003</td>
<td>0.08</td>
<td>0.24</td>
</tr>
<tr>
<td>Colangelo 2003</td>
<td>0.11 – 0.14</td>
<td></td>
</tr>
<tr>
<td>Godfrey 2003</td>
<td>0.19</td>
<td>0.62</td>
</tr>
<tr>
<td>Ishida 2003</td>
<td>0.09 - 0.25</td>
<td>0.41 - 1.09</td>
</tr>
<tr>
<td>PDG 2007</td>
<td>$\leq 0.059$</td>
<td>0.44 ± 0.09</td>
</tr>
<tr>
<td>Our results</td>
<td>$\approx 0.01$</td>
<td>$\approx 0.05$</td>
</tr>
</tbody>
</table>
Table 4. Decay widths of $B_{s0}^*(5725)$ and $B_{s1}(5778)$ in keV

<table>
<thead>
<tr>
<th>Approach</th>
<th>$\Gamma(B_{s0}^* \to B_s \pi^0)$</th>
<th>$\Gamma(B_{s1} \to B_{s1}^* \pi^0)$</th>
<th>$\Gamma(B_{s0}^* \to B_{s1}^* \gamma)$</th>
<th>$\Gamma(B_{s1} \to B_{s1} \gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guo 2006</td>
<td>7.92</td>
<td>10.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Our results</td>
<td>52.9 – 87.1</td>
<td>53.5 – 87.3</td>
<td>1.54 – 2.04</td>
<td>1.04 – 1.22</td>
</tr>
</tbody>
</table>
Summary

• Quantum field approach for HM PR D76 (2007) 014003, 014005
  Only one model parameter: scale $\Lambda$ in HM wave function

• Predictions for strong and radiative decay properties:
  effective couplings and decay widths

• Other applications: PR D76 (2007) 014003
  Leptonic decay constants $f_{D^{*}_{s0}} = 67.1$ MeV and $f_{D_{s1}} = 144.5$ MeV
  Two-body decays $B \rightarrow D^{(*)} D^{*}_{s0} (D_{s1})$

• In progress:
  radiative decays $D_{s1} \rightarrow D^{*}_{s} \gamma$ and $D_{s1} \rightarrow D^{*}_{s0} \gamma$

• Extension:
  Light molecules $a_{0}, f_{0}$
  Heavy molecules $X(3872), Y(4260), \psi(4415), \Lambda_{c}^{+}(2940), \ldots$