$D_{s1}(2536)^+$ decays and the properties of P-wave charmed-strange mesons

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5-th International Conference on Quarks and Nuclear Physics
Beijing, September 2009

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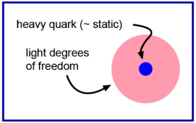
Contents

1.- D_s P-wave mesons. Theoretical and experimental situation

1.1.- Heavy Quark Symmetry

- Meson properties are characterized by the dynamics of the light quark:

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



- P-wave mesons can be grouped into two doublets:

$$j_q = 1/2 \longrightarrow J^P = 0^+ \ , \ 1^+$$
$$j_q = 3/2 \longrightarrow J^P = 1^+ \ , \ 2^+$$

- Properties
  - doublets are degenerated
  - Strong decays of the $D_{sJ}(j_q = 1/2)$ proceed only through S-waves $\Rightarrow$ Broad states
  - Strong decays of the $D_{sJ}(j_q = 3/2)$ proceed only through D-waves $\Rightarrow$ Narrow states

1.2.- Experimental situation

- Spectroscopy of D_s mesons

PDG08 data		
D_{sJ} P-wave mesons	J^P	mass (MeV)
$D_{s0}^*(2317)$	0^+	2318.0 ± 1.0
$D_{s1}(2460)$	1^+	2459.6 ± 0.9
$D_{s1}(2536)$	1^+	2535.12 ± 0.25
$D_{s2}(2573)$	2^+	2572.6 ± 0.9

- New data related with the $D_{s1}(2536)^+$ meson

$\Gamma_T = 1.03 \pm 0.05 \pm 0.12\,\text{MeV}$	arXiv:hep-ex/0607084
$\frac{\Gamma(D_{s1}(2536)^+ \to D^+\pi^-K^+)}{\Gamma(D_{s1}(2536)^+ \to D^{*+}K^0)} = (3.27 \pm 0.18 \pm 0.37)\%$	Phys. Rev. D **77**, 032001 (2008)
$\frac{\Gamma_S(D_{s1}(2536)^+ \to D^{*+}K^0)}{\Gamma(D_{s1}(2536)^+ \to D^{*+}K^0)} = 0.72 \pm 0.05 \pm 0.01$	Phys. Rev. D **77**, 032001 (2008)

→ *We will use a model without heavy quark approximations*

2.- Model Hamiltonian and D_s P-wave mesons

2.1.- Most important ingredients / J. Phys. G: Nucl. Part. Phys. **31**, 481 (2005)

- Spontaneous chiral symmetry breaking (Goldstone-Bosons exchange):

$$L = \bar{\psi}\left(i\gamma^\mu\partial_\mu - MU^{\gamma_5}\right)\psi \rightarrow \quad U^{\gamma_5} = 1 + \frac{i}{f_\pi}\gamma^5\lambda^a\pi^a - \frac{1}{2f_\pi^2}\pi^a\pi^a + \ldots$$

$$M(q^2) = m_q F\left(q^2\right) = m_q\left[\frac{\Lambda^2}{\Lambda^2+q^2}\right]^{1/2}$$

- QCD perturbative effects (One gluon exchange):

$$L = i\sqrt{4\pi\alpha_s}\,\bar{\psi}\gamma_\mu G^\mu\lambda^c\psi$$

- Confinement (screened potential):

$$V_{CON}^{C}(\vec{r}_{ij}) = \left[-a_c(1-e^{-\mu_c r_{ij}}) + \Delta\right](\vec{\lambda}_i^c\cdot\vec{\lambda}_j^c)$$

$$\begin{cases} V_{CON}^{C}(\vec{r}_{ij}) = \left(-a_c\mu_c r_{ij} + \Delta\right)(\vec{\lambda}_i^c\cdot\vec{\lambda}_j^c) & r_{ij}\rightarrow 0 \\ V_{CON}^{C}(\vec{r}_{ij}) = (-a_c + \Delta)(\vec{\lambda}_i^c\cdot\vec{\lambda}_j^c) & r_{ij}\rightarrow\infty \end{cases}$$

2.2.- Some remarks about the potential model and D_s P-wave meson predictions

J^P	State	QM	Experimental data
0^+	$D^*_{s0}(2317)$	2511	2317.4 ± 0.9
1^+	$D_{s_1}(2460)$	2593	2459.3 ± 1.3
1^+	$D_{s_1}(2536)$	2554	2535.3 ± 0.6
2^+	$D_{s_2}(2573)$	2592	2572.4 ± 1.5

$$V^{SO}_{OGE}(\vec{r}_{ij}) = -\frac{1}{16}\frac{\alpha_s}{m_i^2 m_j^2}(\vec{\lambda}^c_i \cdot \vec{\lambda}^c_j)\left[\frac{1}{r_{ij}^3} - \frac{e^{-r_{ij}/r_g(\mu)}}{r_{ij}^3}\left(1+\frac{r_{ij}}{r_g(\mu)}\right)\right] \times$$
$$\times \left[((m_i+m_j)^2 + 2m_i m_j)(\vec{S}_+ \cdot \vec{L}) + (m_j^2 - m_i^2)(\vec{S}_- \cdot \vec{L})\right]$$

$$V^{SO}_{CON}(\vec{r}_{ij}) = -\left(\vec{\lambda}^c_i \cdot \vec{\lambda}^c_j\right)\frac{a_c \mu_c e^{-\mu_c r_{ij}}}{4 m_i^2 m_j^2 r_{ij}}\left[((m_i^2+m_j^2)(1-2a_s)\right.$$
$$\left.+4m_i m_j(1-a_s))(\vec{S}_+ \cdot \vec{L}) + (m_j^2 - m_i^2)(1-2a_s)(\vec{S}_- \cdot \vec{L})\right]$$

What is the mechanism that explains the small mass of $D^*_{s0}(2317)$ and $D_{s1}(2460)$?

2.3.- Tetraquark structure as a posible way

- J. Vijande, F. Fernandez and A. Valcarce, Phys. Rev. D **73** 034002 (2006)
  - Suggest the coupling between the $c\bar{s}$ states and the tetraquark structure to explain the low masses of $D_{s0}^*(2317)$ and $D_{s1}(2460)$ mesons
  - Calculate tetraquarks $c\bar{s}n\bar{n}$ with $J^P = 0^+$ and 1^+ that have to be coupled with the $c\bar{s}$ states
  - $J^P = 1^+$ case
    - Coupling between ${}^1P_1$ and the tetraquark to explain $D_{s1}(2460)$
    - The $D_{s1}(2536)$ meson is a ${}^3P_1$ theoretical state
    - Its width should be larger than the experimental data
- J. Segovia, D. R. Entem and F. Fernandez, Accepted in Phys. Rev. D (2009)
  - Working in HQS limit
    - Three different spin states for tetraquark: $|0\,1/2\rangle$, $|1\,1/2\rangle$ and $|1\,3/2\rangle$. The first index denotes the spin of the $n\bar{n}$ pair and the second the coupling with the $\bar{s}$ spin
  - ${}^3P_0$ model to select the dominant couplings
    - $n\bar{n}$ pair created is in $J = 0$
    - The coupling between D_s states and $|0\,1/2\rangle$ tetraquark component is dominant

2.3.- Tetraquark structure as a posible way (Continuation)

- Efective coupling between $c\bar{s}$ states and the tetraquark:

$$M = \begin{pmatrix} M_{^3P_1} & C_{SO} & \sqrt{\frac{2}{3}}C_S \\ C_{SO} & M_{^1P_1} & \sqrt{\frac{1}{3}}C_S \\ \sqrt{\frac{2}{3}}C_S & \sqrt{\frac{1}{3}}C_S & M_{c\bar{s}n\bar{n}} \end{pmatrix}$$

$M_{^3P_1}$	2571.5 MeV
$M_{^1P_1}$	2576.0 MeV
$M_{c\bar{s}n\bar{n}}$	2841 MeV
C_{SO}	19.6 MeV
C_S	224 MeV

- The physical states are given by the three eigenvalues of the previous matrix:

$M(MeV)$	$S(^3P_1)$	$P(^3P_1)$	$S(^1P_1)$	$P(^1P_1)$	$S(c\bar{s}n\bar{n})$	$P(c\bar{s}n\bar{n})$
2459	-	55.7	-	18.8	+	25.5
2557	+	27.7	-	72.1	+	0.2
2973	+	16.6	+	9.1	+	74.3

- The doublets D_{sJ} with $j_q = 1/2,\ 3/2$ from HQS

$$|1/2, 0^+\rangle = |^3P_0\rangle \qquad |3/2, 1^+\rangle = \sqrt{\frac{1}{3}}|^3P_1\rangle - \sqrt{\frac{2}{3}}|^1P_1\rangle$$

$$|1/2, 1^+\rangle = \sqrt{\frac{2}{3}}|^3P_1\rangle + \sqrt{\frac{1}{3}}|^1P_1\rangle \qquad |3/2, 2^+\rangle = |^3P_2\rangle$$

3.- The $D_{s1}(2536)^+$ decays

3.1.- $^3P_0$ model

- *Bibliograhy*
  - *L. Micu, Nucl. Phys. B* **10**, *521 (1969)*
  - *A. Le Yaouanc, L. Olivier, O. Pene, and J.C. Raynal, Phys. Rev. D***8**, *2223 (1973)*
  - *R. Bonnaz, and B. Silvestre-Brac, Few-Body Syst.* **27**, *163 (1999)*

- Phenomenological transition operator:

$$T = -3\gamma \sum_{\mu} \int d^3p d^3p' \, \delta^{(3)}(p + p') \left[\mathcal{Y}_1 \left(\frac{p - p'}{2} \right) b^\dagger_\mu(p) d^\dagger_\nu(p') \right]^{C=1, I=0, S=1, J=0}$$

- Defining the S-matrix as:

$$\langle f|S|i\rangle = I + i(2\pi)^4 \delta^4(p_f - p_i)\mathcal{M}$$

- So, the partial width is:

$$\Gamma = 2\pi \sum_{JL} \int dk \delta(E_i - E_f) \, |\mathcal{M}^{JL}_{A\to BC}(k)|^2$$
$$= 2\pi \frac{E_B E_C}{k_0 M_A} \sum_{JL} |\mathcal{M}^{JL}_{A\to BC}(k_0)|^2$$

3.2.- A particular case: the $D_{s1}(2536)^+ \longrightarrow D^+\pi^-K^+$

The reaction $D_{s1}(2536)^+ \longrightarrow D^+\pi^-K^+$ is characterized by the fact that the pair $D^+\pi^-$ in the final state is the only $D\pi$ combination that cannot come from a D^* resonance making this channel different from the other $D\pi K$ channels

$M_{D^{*0}} \sim 2007$ MeV
$M_{D^+} \sim 1870$ MeV
$M_{\pi^-} \sim 140$ MeV

S. Capstick and W. Roberts, Phys. Rev. D **49***, 4570 (1994)*

- To describe this decay we need to modify the intermediate D^* propagator

$$\frac{1}{M_A - E_B - E_C - i\epsilon} = \mathcal{P}\frac{1}{M_A - E_B - E_C} + i\pi\delta(M_A - E_B - E_C)$$

- ϵ is related with the total width of the unstable intermediate state. For finite width Γ_B

$$\frac{1}{M_A - E_B - E_C - i\frac{\Gamma_B}{2}} = \frac{M_A - E_B - E_C + i\frac{\Gamma_B}{2}}{(M_A - E_B - E_C)^2 + \frac{\Gamma_B^2}{4}}$$

- so the δ-function should be replaced by

$$\delta(M_A - E_B - E_C) \rightarrow \frac{\Gamma_B}{2\pi\left[(M_A - E_B - E_C)^2 + \frac{\Gamma_B^2}{4}\right]}$$

3.2.- A particular case: the $D_{s1}(2536)^+ \longrightarrow D^+\pi^-K^+$ (Continuation)

- For the decay $B \longrightarrow B_1 B_2$ we multiply by the branching

$$\mathcal{B}(B \longrightarrow B_1 B_2) = \frac{\Gamma_{B\rightarrow B_1 B_2}(k)}{\Gamma_B}$$

- Neglecting the momentum dependence of the total width of the B meson Γ_B, the width for the decay $A \longrightarrow (B_1 B_2)C$ is given by

$$\Gamma_{A\rightarrow(B_1B_2)C} = \sum_{JL}\int_0^{k_{max}} dk\, \frac{\Gamma_{B\rightarrow B_1 B_2}(k)}{\left[(M_A - E_B - E_C)^2 + \frac{\Gamma_B^2}{4}\right]} |\mathcal{M}^{JL}_{A\rightarrow BC}(k)|^2.$$

- k_{max} is the maximum relative momentum for the BC system allowed by the three body decay $A \longrightarrow (B_1 B_2)C$ and is given by

$$k_{max} = \frac{\sqrt{\left[M_A^2 - (M_{B_1} + M_{B_2} + M_C)^2\right]\left[M_A^2 - (M_{B_1} + M_{B_2} - M_C)^2\right]}}{2M_A}$$

4.- Results and Discussion

4.1.- Results

- We calculate the following physical observables:

$$\Gamma(D_{s1}(2536)^+) = \Gamma(D^{*0}K^+) + \Gamma(D^{*+}K^0)$$

$$R_1 = \frac{\Gamma(D_{s1}(2536)^+ \to D^{*0}K^+)}{\Gamma(D_{s1}(2536)^+ \to D^{*+}K^0)}$$

$$R_2 = \frac{\Gamma_S(D_{s1}(2536)^+ \to D^{*+}K^0)}{\Gamma(D_{s1}(2536)^+ \to D^{*+}K^0)}$$

$$R_3 = \frac{\Gamma(D_{s1}(2536)^+ \to D^+\pi^-K^+)}{\Gamma(D_{s1}(2536)^+ \to D^{*+}K^0)}$$

- Results for physical state and quark model states without coupling to tetraquark

$M(MeV)$	$\Gamma(MeV)$	R_1	R_2	$R_3(\%)$
2593	88	1.09	1.00	3.73
2554	5.2	1.11	0.97	3.75
2557	0.46	1.31	0.66	4.00
Exp.	1.03	1.27	0.72	3.27

As the DK decay is suppressed the total width would be mainly given by the D^*K channel and is in the order of the experimental value

4.2.- Summary

- We have calculated the $D_{s1}(2536)^+$ strong decays in a constituent quark model. These decays posses very demanding constrains to the D_{s1} wave function
- Inspired with Heavy Quark Symmetry, we propose a particular choice for the coupling between the $c\bar{s}$ states and a tetraquark structure which reproduces simultaneously its narrow width and the ratio of the S and D waves amplitudes in its decays
- The decay $D_{s1}(2536)^+ \to D^+\pi^-K^+$ through a virtual D^{*0} is also well reproduced within the model