$D_{s_1}(2536)^+$ decays and the structure of P-wave charmed strange mesons[*]

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Abstract We calculate the $D_{s_1}(2536)^+$ decays into D^*K channels, including the decay $D_{s_1}(2536)^+ \to D^+\pi^-K^+$ through a virtual D^{*0} in a constituent quark model. Widths and S/D amplitudes ratio are in agreement with the recent Belle and BABAR data, being the results sensitive to $^1P_1$ and $^3P_1$ mixture.

Key words meson spectra, meson decays, non relativistic quark models, multiquarks

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1 Introduction

The D_s P-wave mesons have been revealed as an excellent system to test low momentum QCD. From a theoretical point of view, the combination of a heavy and a light quark allows to make predictions based on the assumption of heavy quark symmetry (HQS). More relevant are, however, the unexpected properties shown by the experiments. In particular the low masses of the $D_{s_0}^*(2317)$ and $D_{s_1}(2460)$ states [1, 2] represents a challenge for model builders.

Recently new data related with the $D_{s_1}(2536)$ meson has appeared. BABAR collaboration has performed a high precision measurement of the $D_{s_1}(2536)$ decay width obtaining a value of $1.03\pm0.05\pm0.12$ MeV [3]. Furthermore, Belle collaboration has reported the first observation of the $D_{s_1}(2536)^+ \to D^+\pi^-K^+$ decay measuring the branching fraction [4]

$$\frac{D_{s_1}(2536)^+ \to D^+\pi^-K^+}{D_{s_1}(2536)^+ \to D^{*+}K^0} = (3.27\pm0.18\pm0.37)\%. \quad (1)$$

They also measured the ratio of the D and S wave amplitudes in the $D_{s_1}(2536)^+ \to D^{*+}K^0$ decay finding a value of $0.72\pm0.05\pm0.01$. These results contradict the predictions of HQS because in this limit the $D_{s_1}(2536)$ decays can only occur through D-waves.

In this work we will use the constituent quark model of Ref. [5] together with the $^3P_0$ model [6] to study the reaction rates of the $D_{s_1}(2536)^+ \to D^+\pi^-K^+$ decay as well as the angular decomposition of the $D_{s_1}(2536)^+ \to D^{*+}K^0$ in order to gain insight into the structure of the P-wave charm strange mesons [7].

2 P-wave mesons and $D_{s_1}(2536)^+$ decays

For the low-lying positive parity excitations any quark model predicts four states $^1P_1$, $^3P_0$, $^3P_1$ and $^3P_2$ in terms of the JLS basis. The mixing between $^1P_1$ and $^3P_1$ states is induced by the antisymmetric term of the spin-orbit interaction. However even this mixing is unable to reproduce the experimental data as one can see in Table 1 where the results for the low-lying positive parity excitations $^1P_1$, $^3P_0$, $^3P_1$ and $^3P_2$ calculated in our model are shown.

The small experimental mass of the $D_{s_0}^*(2317)$ has been attributed to several mechanisms. The existence of tetraquark structures with $J^P = 0^+$ and $J^P = 1^+$ is used in Ref. [8] to explain the $D_{s_0}^*(2317)$ and the $D_{s_1}(2460)$ as mixed states of $c\bar{s}$ states and the

tetraquark.

Table 1.   Masses (in MeV) of the low-lying positive parity $c\bar{s}$ states in the quark model (QM).

J^P	state	QM	experimental data
0^+	$D_{s_0}^*(2317)$	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

We will work in a similar approach but using the HQS limit as a guide to select dominant couplings. The $^3P_0$ model assumes that the $n\bar{n}$ pair created is in a $J^{PC} = 0^{++}$ state, therefore the D_s states will only couple with the tetraquark component which has spin $1/2$ for the three light quarks. In the HQS limit the heavy quark is an spectator and the angular momentum of the light quarks has to be conserved so that the tetraquark will only couple to the $c\bar{s}$ $j_q = 1/2$ state.

This choice has several advantages: it has the correct heavy quark limit, it may reproduce the narrow width of the $D_{s_1}(2536)^+$ state and it is in agreement with the experimental situation which tells us that the prediction of the heavy quark limit is reasonable for the $j_q = 3/2$ state but not for the $j_q = 1/2$ one.

The reaction $D_{s_1}(2536)^+ \to D^+\pi^-K^+$ 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 usual $D_{s_1}(2536) \to D^*K$. The D^{*0} meson can only decay into $D^+\pi^-$ virtually since $M_{D^{*0}} < M_{D^+} + M_{\pi^-}$.

Then to describe this decay we need to modify the $^3P_0$ amplitude taking into account that it is not an stable particle but a resonance with a width that allows the decay to take place. Following Ref. [9], the width for the decay $A \to (B_1B_2)C$ is given in this case by

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

$$k_{\max} = \frac{\sqrt{[M_A^2 - (M_{B_1} + M_{B_2} + M_C)^2][M_A^2 - (M_{B_1} + M_{B_2} - M_C)^2]}}{2M_A}, \tag{3}$$

where $k_{\max}$ is the maximum relative momentum for the BC system allowed by the three body decay $A \to (B_1B_2)C$.

3   Results and discussion

To couple $c\bar{s}$ states to tetraquark as discussed above we diagonalize the matrix

$$M = \begin{pmatrix} M_{^3P_1} & C_{SO} & \sqrt{\dfrac{2}{3}}C_S \\ C_{SO} & M_{^1P_1} & \sqrt{\dfrac{1}{3}}C_S \\ \sqrt{\dfrac{2}{3}}C_S & \sqrt{\dfrac{1}{3}}C_S & M_{c\bar{s}n\bar{n}} \end{pmatrix}, \tag{4}$$

where $M_{^3P_1} = 2571.5$ MeV and $M_{^1P_1} = 2576.0$ MeV are the masses of the $c\bar{s}$ pair obtained with our model and $M_{c\bar{s}n\bar{n}} = 2841$ MeV is the tetraquark mass calculated with the same model in Ref. [8], the $C_{SO} = 19.6$ MeV is the coupling induced by the antisymmetric spin-orbit interaction calculated within the model and C_S is the parameter that gives the coupling between the $j_q = 1/2$ component of the $^3P_1$ and $^1P_1$ states and the tetraquark. The value of the parameter $C_S = 224$ MeV is fitted to the mass of the $D_{s_1}(2460)$. We get the three eigenstates shown in Table 2. There we also show the probabilities of the three components for each state and the relative phases between different components.

Table 2.   Masses and probability distributions for the three eigenstates obtained from the coupling of the D_s and tetraquark states. The relative sign to the tetraquark component is also shown.

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

We now calculate the different decay widths for the $D_{s_1}(2536)^+$ state of Table 2. As expected the D^*K decay width is narrow $\Gamma = 0.46$ MeV. 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 $\Gamma_{\exp} = 1.03 \pm 0.05 \pm 0.12$ MeV measured by BABAR [3]. The $^3P_0$ γ strength parameter that we have taken from a previous study of strong decays in charmonium [10].

There are two other experimental data that does not depend on the γ parameter, namely the branching ratio [11]

$$R_1 = \frac{\Gamma(D_{s_1}(2536)^+ \to D^{*0}K^+)}{\Gamma(D_{s_1}(2536)^+ \to D^{*+}K^0)} = 1.27 \pm 0.21, \quad (5)$$

and the ratio of S-wave over the full width for the $D^{*+}K^0$ decay [4]

$$R_2 = \frac{\Gamma_S(D_{s_1}(2536)^+ \to D^{*+}K^0)}{\Gamma(D_{s_1}(2536)^+ \to D^{*+}K^0)} = 0.72 \pm 0.05 \pm 0.01. \quad (6)$$

The first branching ratio should be 1 if the isospin symmetry was exact. However the charge symmetry breaking in the phase space makes it different from this value. The effect is sizable since the $D_{s_1}(2536)^+$ is close to the D^*K threshold and for this reason it also depends on the details of the D_{s_1} wave function. We get for this ratio the value $R_1 = 1.31$ in good agreement with the experimental one.

In the HQS limit the branching ratio R_2 should be zero because the decay of $j_q = 3/2$ state would go only through D-wave. In our case we get a value of $R_2 = 0.66$ close to the experimental data. The fact that our result is smaller than the experimental one indicates that the probability of the $j_q = 3/2$ state is too high which is in agreement with the fact that we get a too narrow state.

Finally we calculate the branching ratio

$$R_3 = \frac{\Gamma(D_{s_1}(2536)^+ \to D^+\pi^-K^+)}{\Gamma(D_{s_1}(2536)^+ \to D^{*+}K^0)} =$$

$$(3.27 \pm 0.18 \pm 0.37)\%. \quad (7)$$

The reaction in the numerator goes through a virtual D^{*0} as explained previously and for that reason the branching is small. We get the value $R_3 = 4.00\%$.

All these results for the width and the ratios R_1, R_2 and R_3 are summarized in Table 3.

Table 3. Width and the 3 branching ratios defined in the text. The first row shows the experimental data and the second shows our results for the physical $D_{s_1}(2536)$ state given in Table 2.

M/MeV	Γ/MeV	R_1	R_2	$R_3(\%)$
Exp.	1.03	1.27	0.72	3.27
2557	0.46	1.31	0.66	4.00

4　Summary

As summary, we have calculated the $D_{s_1}(2536)$ decays in a constituent quark model using the $^3P_0$ model as decay mechanism. These decays posses very demanding constrains to the D_{s_1} wave function. When the $c\bar{s}$ $j_q = 1/2$ is coupled with the tetraquark state of mass 2841 MeV, the $D_{s_1}(2536)$ appears as a mixture of $^1P_1$ and $^3P_1$ states which is crucial to reproduce simultaneously its narrow width and the ratio of the S and D-wave amplitudes in its decays. Also the decay $D_{s_1}(2536)^+ \to D^+\pi^-K^+$ through a virtual D^{*0} is well reproduced within the model.

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