Masses and Decays of 2P family of charm mesons

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Introduction

In the last decade, charmed meson spectroscopy has seen great success in experimental sector. Experiments like LHCb and Babar are providing many new states which are being added to charm spectroscopy. Recently states like D(3000) and D*(3000) [1] as predicted by LHCb are added to p-wave charm family for radial quantum number n=2. And the strange charm state $D_s(3040)$ [2] as predicted by Babar is added to strange family for n=2 p-wave states. This assignments are done by studying their properties like decay channels, coupling constants, masses etc. Decays can be strong, radiative, semileptonic. These properties are studied by various models like heavy quark effective theory (HQET), QCD sum rules, 3P0 model, QCD lattice. These three known states does not complete the P wave family for charm mesons for radial quantum number 2. In this paper, we tried to predict the masses of the rest of the other five unknown p wave states. Along with their masses, we also analyse their strong decays in terms of their strong coupling constants. For this work, we choose the theory based on the heavy quark flavour and spin symmetry which is popularly known as Heavy Quark Effective theory.

Framework:

In the infinite heavy quark mass limit, the system of heavy-light $Q\bar{q}$ can be classified in doublets defined as n L s_l J_P where n is radial quantum number, $s_l = s_q + l$ is the total angular momentum of light degree of freedom and $J = s_l + s_Q$ is the total momentum of the system. For n = 1, L=0 (S wave), doublet corresponds to s_l =1/2 consisting of two states having spin-parity J_P (0^- , 1^-) represented by (P, P*). Similarly for L=2 (P-wave) there are two doublets, one for s_l =1/2 and second one for s_l =3/2 representing J^P states as (0^+,1^+) and (1^+ ,2^+) respectively. Symbolically these states are notated as (P_0*,P'$_1$) and (P_1,P_2*) respectively. For n=2, these states are replaced by a tilde (~) on them e.g. $\tilde{P}, \widetilde{P^*}$. The negative parity ground doublet is represented by H_a field where a=1,2,3 for u,d,s. Similarly the excited positive parity doublets are represented by S_a and T_a fields. The properties of hadrons with a heavy quark coupled with light degrees of freedom can be explained on the basis of symmetries occurring in heavy-light quark system. Our model HQET is mainly based on two symmetries, first being the chiral symmetry for light quarks u, d, s in the zero mass limit and the other being the heavy quark spin and flavour symmetry for heavy quarks c and b in the infinite mass limit. Heavy light mesons can be studied by implementing both the chiral symmetry and heavy quark spin and flavour symmetry in the form of an effective Lagrangian [3]. These lagrangian are then used to drive the strong interactions for these heavy-light states. Strong interactions are very important to study the heavy hadrons in the non-perturbative regime and are studied by their decay to light- pseudo scalar mesons. Masses are predicted on the basis of the fact that effect of the strange quark is to shift the mass of a given state by the same amount in the fundamental and in the n = 2 radial excitation doublet [3], i.e.

$$M_{D_s} - M_{D^0} = M_{\tilde{D}_s} - M_{\tilde{D}^0} \quad (1)$$

Using the known masses of the fundamental P wave, the masses for radial quantum number n = 2 can be calculated. These calculated masses are then justified by studying their strong decay widths. Decay channels DK, D*K, Ds Ƞ, Ds* Ƞ and to other states, for complete 2P charm strange and non-strange family are analysed and coupling constants are calculated. Decay widths are calculated using formulas [4], some of which, for n=2, are formulated as follow:

$$\Gamma\left(\tilde{1}^{+} \rightarrow 1^{-}\right) = \frac{C_P g_{SH}^2 M_f \left(p_f^2 + m_p^2\right) p_f}{2\pi f_\pi^2 M_i}$$

$$\Gamma\left(\tilde{0}^{+} \rightarrow 0\right) = \frac{C_P g_{SH}^2 M_f \left(p_f^2 + m_p^2\right) p_f}{2\pi f_\pi^2 M_i}$$

$$\Gamma\left(\tilde{2}^{+} \rightarrow 1^{-}\right) = \frac{C_P 2 g_{TH}^2 M_f p_f^5}{5\pi f_\pi^2 \Lambda^2 M_i}$$

$$\Gamma\left(\tilde{1}^{+} \rightarrow 1^{-}\right) = \frac{C_P 2 g_{TH}^2 M_f p_f^5}{3\pi f_\pi^2 \Lambda^2 M_i}$$

$$\Gamma\left(\tilde{1}^{+} \rightarrow 1^{-}\right) = \frac{C_P 2 g_{XS}^2 M_f p_f^5}{3\pi f_\pi^2 \Lambda^2 M_i}$$

$$\Gamma\left(\tilde{0}^{+} \rightarrow 2^{-}\right) = \frac{C_P 4 g_{XS}^2 M_f p_f^5}{3\pi f_\pi^2 \Lambda^2 M_i}$$

In the above expressions of decay width, M_i, M_f stands for initial and final meson mass. All hadronic coupling constants are dependent on the radial quantum number. For n=1 they are notated as g_{SH}, g_{TH} etc, and for coupling between n=2 and n=1 they will be replaced by $\widetilde{g_{SH}}$, $\widetilde{g_{TH}}$ etc. and similarly for the coupling between initial and final states both belonging to n=2 ,they are written as $\widetilde{\widetilde{g_{SH}}}$, $\widetilde{\widetilde{g_{TH}}}$ etc.

Calculations:

States n J^P	Symbol	Masses (MeV)	
		Non-Strange	Strange
2 0^+	D_0^*	D(2949) [5]	D_s (2866)
2 1^+	D_1'	D(3010)	**D_s (3040)**[2]
2 1^+	D_1	**D(3000)**[1]	D_s (3116)
2 2^+	D_2^*	**D*(3000)**[1]	D_s (3113)

Table 1: Predicted and experimental masses of the 2P charm meson family. Bold states shows the masses which are experimentally known and the rest are predicted in HQET framework.

Masses of the n=2 p wave charm mesons are tabulated in Table 1. Using the experimentally known fundamental strange and non-strange charm masses [3], masses of the unknown members of the 2P charm meson family are predicted using equation (1). By this method we are able to predict the masses for all members except for state with $J^P = 0^-$. For this state we use the non-strange mass as predicted by [5], and then again use the same formulae to calculate the strange charm meson for this state. These masses are then justified by studying their strong decays through pseudo-scalar mesons. Decay widths of these states in terms of the strong coupling constants are tabulated in Table 2.

nJ^P	Decay widths (MeV)			
	Non-Strange		Strange	
	Decay channel	Decay width	Decay channel	Decay width
20^+	$D^0\pi^0$	$2046.64\tilde{g}_{SH}^2$	$D_s\pi^0$	$1398.02\tilde{g}_{SH}^2$
	$D^+\pi^-$	$4120.51\tilde{g}_{SH}^2$	$D_s\eta$	$1682.71\tilde{g}_{SH}^2$
	$D^0\eta$	$653.516\tilde{g}_{SH}^2$	D^0K^-	$3306.72\tilde{g}_{SH}^2$
	D_sK^-	$3258.44\tilde{g}_{SH}^2$	D^+K^0	$3270.48\tilde{g}_{SH}^2$
	$\tilde{D}^0\pi^0$	$200.488\tilde{\tilde{g}}_{SH}^2$	$\tilde{D}_s\pi^0$	$11.24\tilde{\tilde{g}}_{SH}^2$
21^+	$D^{*0}\pi^0$	$1829.62\tilde{g}_{SH}^2$	$D_s^*\pi^0$	$1584.20\tilde{g}_{SH}^2$
	$D^{*+}\pi^-$	$3635.6\tilde{g}_{SH}^2$	$D_s^*\eta$	$1921.07\tilde{g}_{SH}^2$
	$D^{*0}\eta$	$571.485\tilde{g}_{SH}^2$	$D^{*0}K^-$	$3754.99\tilde{g}_{SH}^2$
	$D_s^*K^-$	$2707.61\tilde{g}_{SH}^2$	$D^{*+}K^0$	$3725.99\tilde{g}_{SH}^2$
	$\tilde{D}^{*0}\pi^0$	$217.56\tilde{\tilde{g}}_{SH}^2$	$\tilde{D}_s^*\pi^0$	$129.29\tilde{\tilde{g}}_{SH}^2$
21^+	$D^{*0}\pi^0$	$1563.66\tilde{g}_{TH}^2$	$D_s^*\pi^0$	$1718.5\tilde{g}_{TH}^2$
	$D^{*+}\pi^-$	$3079.43\tilde{g}_{TH}^2$	$\tilde{D}_s^*\pi^0$	$36.28\tilde{\tilde{g}}_{TH}^2$
	$\tilde{D}^{*0}\pi^0$	$26.00\tilde{\tilde{g}}_{TH}^2$		
22^+	$D^{*0}\pi^0$	$938.196\tilde{g}_{TH}^2$	$D_s^*\pi^0$	$1018.46\tilde{g}_{TH}^2$
	$D^{*+}\pi^-$	$1847.66\tilde{g}_{TH}^2$	$D_s^*\eta$	$568.476\tilde{g}_{TH}^2$
	$D^{*0}\eta$	$128.54\tilde{g}_{TH}^2$	$D^{*0}K^-$	$1694.82\tilde{g}_{TH}^2$
	$D_s^*K^-$	$505.22\tilde{g}_{TH}^2$	$D^{*+}K^0$	$1654.28\tilde{g}_{TH}^2$
	$D^0\pi^0$	$993.05\tilde{g}_{TH}^2$	$\tilde{D}_s^*\pi^0$	$20.97\tilde{g}_{TH}^2$
	$D^+\pi^-$	$1953.59\tilde{g}_{TH}^2$	$D_s\eta$	$763.05\tilde{g}_{TH}^2$
	$D^0\eta$	$171.54\tilde{g}_{TH}^2$	D^0K^-	$1898.61\tilde{g}_{TH}^2$
	D_sK^-	$762.89\tilde{g}_{TH}^2$	D^+K^0	$1854.73\tilde{g}_{TH}^2$
	$\tilde{D}^{*0}\pi^0$	$15.60\tilde{\tilde{g}}_{TH}^2$	$\tilde{D}_s\pi^0$	$13.98\tilde{\tilde{g}}_{TH}^2$
	$\tilde{D}^0\pi^0$	$23.58\tilde{\tilde{g}}_{TH}^2$		

Table 2: Decay width of members of 2P charm meson family.

Conclusion:

Table 1, show the masses of three known states i.e. D(3000), D*(3000), D_s(3040). We calculated, the masses of other unknown p-wave states using the mass formulae given in equation 1 and using the n=1 charm states. We tabulated the masses of all 8 states in Table 1.Using these masses, their decay widths in terms of their couplings are calculated, which is shown in Table 2. Using the known experimental widths ($\Gamma(D(3000)) = 188.1MeV$, $\Gamma\big(D^*(3000)\big) = 110.5MeV$ and $\Gamma(D_s(3040)) = 239\ MeV$) and constraints on few coupling constants ($0.1 < \tilde{g}_{SH}^2 < 0.15,\ 0.1 < \tilde{g}_{TH}^2 < 0.22$) [3,4], we computed the other unknown couplings ($\tilde{\tilde{g}}_{SH}^2 = 0.4$, $\tilde{\tilde{g}}_{TH}^2 = 0.3$). Using these couplings, we predicted the decay widths of other charm states calculated. Their decay width comes out to be get$\Gamma\big(D_0^*(2949)\big) = 229.62\ MeV$, $\Gamma(D_{s0}^*(2866)) = 191.09\ MeV$, $\Gamma(\big(D_1'(3010)\big) = 206.19MeV$, $\Gamma(D_{s1}'(3040)) = 236.01MeV$, $\Gamma(D_1(3000)) = 188.06MeV$, $\Gamma\big(D_{s1}(3116)\big) = 72MeV$, $\Gamma\big(D_2^*(3000)\big) = 108.74MeV$ and $\Gamma\big(D_{s2}^*(3113)\big) = 139.26MeV$. Apart from decay to H fields, these states also decay to X and Y fields, but the value of decay width for these decay channels is very small, so it can be neglected. In this paper, we computed some hadronic coupling constants and predicted decay widths of some states, which are expected to be useful for experimentalists in future.

References:

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