Contribution ID : 121

XVII INTERNATIONAL CONFERENCE ON HADRON SPECTROSCOPY AND STRUCTURE
September 25th-29th 2017 Salamanca

Pionic transitions of excited charmed mesons in the covariant oscillator quark model

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1 Introduction

Charmed meson spectroscopy since 2010

Spectroscopy of charmed mesons has been made a remarkable progress by recent development of high energy collider experiment [1]. Since 2010, candidates for the highly excited states have been successively observed by the BABAR and LHCb collaborations.

Table 1: Charmed mesons observed in recent experiments.

Resonance	J^P	Channel	Mass (MeV)	Width (MeV)	Experiment
$D_J(2550)^0$		$D^{*+}\pi-$	$2539.4\pm4.5\pm6.8$	$130\pm12\pm13$	BABAR[2]
$D_J(2580)^0$		$D^{*+}\pi-$	$2579.5\pm3.4\pm3.5$	$177.5\pm17.8\pm46.0$	LHCb[3]
$D^*_J(2600)^0$		$D^{+}\pi-$	$2608.7\pm2.4\pm2.5$	$93\pm6\pm13$	BABAR[2]
$D^*_J(2650)^0$		$D^{*+}\pi^-$	$2649.2\pm3.5\pm3.5$	$140.2\pm17.1\pm18.6$	LHCb[3]
$D^*_1(2680)^0$	1^-	$D^{+}\pi^-$	$2681.1\pm5.6\pm4.9\pm13.1$	$186.7\pm8.5\pm8.6\pm8.2$	LHCb[6]
$D(2750)^0$		$D^{*+}\pi^-$	$2752.4\pm1.7\pm2.7$	$71\pm6\pm11$	BABAR[2]
$D_J(2740)^0$		$D^{*+}\pi^-$	$2737.0\pm3.5\pm11.2$	$73.2\pm13.4\pm25.0$	LHCb[3]
$D^*_J(2760)^0$		$D^{*+}\pi^-$	$2761.1\pm5.1\pm6.5$	$74.4\pm3.4\pm37.0$	LHCb[3]
		$D^{+}\pi^-$	$2760.1\pm1.1\pm3.7$	$74.4\pm3.4\pm19.1$	LHCb[3]
		$D^{+}\pi^-$	$2763.3\pm2.3\pm2.3$	$60.9\pm5.1\pm3.6$	BABAR[2]
$D^*_J(2760)^+$		$D^0\pi^+$	$2771.7\pm1.7\pm3.8$	$66.7\pm6.6\pm10.5$	LHCb[3]
$D^*_1(2760)^0$	1^-	$D^{+}\pi^-$	$2781\pm18\pm11\pm6$	$177\pm32\pm20\pm7$	LHCb[4]
$D^*_3(2760)^-$	3^-	$\bar{D}^0\pi^-$	$2798\pm7\pm1\pm7$	$105\pm18\pm6\pm23$	LHCb[5]
			$2802\pm11\pm10\pm3$	$154\pm27\pm13\pm9$	LHCb[5]
$D^*_3(2760)^0$	3^-	$D^{+}\pi^-$	$2775.5\pm4.5\pm4.5\pm4.7$	$95.3\pm9.6\pm7.9\pm33.1$	LHCb[6]
$D_J(3000)^0$		$D^{*+}\pi^-$	2971.8 ± 8.7	188.1 ± 44.8	LHCb[3]
$D^*_J(3000)^0$		$D^{+}\pi^-$	3008.1 ± 4.0	110.5 ± 11.5	LHCb[3]
	2^+	$D^{+}\pi^-$	$3214\pm29\pm33\pm36$	$186\pm38\pm34\pm63$	LHCb[6]

Purpose of this work

- The study of the hadronic decay is the most suitable way to probe the nature of hadrons since decay widths strongly depend on their internal structure. (→ L-S/S_Q-j_q, role of FF, relativistic effect, …)
- Although several theoretical studies have been done, spectroscopic assignments for these states still remain to be completely elucidated.
- In this work we employ the Covariant Oscillator Quark Model (COQM) to calculate the strong decay widths of charmed mesons.
- In order to evaluate the transitions rates, we use the effective coupling vertex [18] in the elementary emission model with suitable modification in conformity with our scheme.
- We have paid a particular attention about the relativistic effect of our model and discuss the impact to the decay widths. Obtained results are compared with the experimental data and other quark models.

2 Covariant Oscillator Quark Model

- The COQM [7-12] is one of the possible covariant extension of conventional non-relativistic quark model.
- The remarkable features of the COQM is that hadrons are treated in a manifestly covariant way. Covariant formulation allows us to deal with retardation effects.
- Excited states are on the linear Regge trajectory in terms of squared masses.

$$M_n{}^2 = M_0{}^2 + n\Omega \qquad \text{Here, } n = L + 2n_r$$

- It is possible to introduce a quark-pion coupling in conformity with the low energy theorem.

basic KG Eq. : $\left(-\frac{\partial^2}{\partial X_\mu \partial X^\mu} - \mathcal{M}^2(x)\right)\Psi(X,x)_\alpha{}^\beta = 0,\quad \mathcal{M}(x)^2 = \lambda\left(\frac{1}{2\mu}\frac{\partial^2}{\partial x_\mu x^\mu} - \frac{1}{2}Kx_\mu x^\mu\right) + \text{const.}$

($\lambda = 2\,(m_1+m_2),\quad \mu = \frac{m_1 m_2}{m_1+m_2}$)

bi-local WF : $\Psi(x_1^\mu, x_2^\mu)_\alpha{}^\beta = \Psi(X^\mu, x^\mu)_\alpha{}^\beta = \sqrt{\frac{2M}{2P_0V}}e^{\mp iP_\mu X^\mu}\Phi(v,x)_\alpha{}^{\beta(\pm)}$

boosted LS coupling scheme : $\Phi(v,x)_\alpha^{(\pm)\beta} = f(v,x)^{\mu\nu\cdots} \otimes \left(W_\alpha^{(\pm)\beta}(v)\right)_{\mu\nu\cdots}$

– Spin part W: Bargmann-Wigner spinor

– Space-time part f: Definite-type 4 dimensional SHO

satisfying definite metric-type subsidiary condition ($P^\mu a_\mu^\dagger f(v,x)^{(nL)} = 0,\ a_\mu^\dagger = \frac{1}{\sqrt{2\beta^2}}(\beta^2 x_\mu - \partial_{x\mu})$) [11]

$$f_{\rm G}(v,x) = \frac{\beta^2}{\pi}\exp\left(-\frac{\beta^2}{2}\left(-g_{\mu\nu}+2v_\mu v_\mu\right)x^\mu x^\nu\right) \xrightarrow{\boldsymbol{v}=0} \left(\frac{\beta^2}{\pi}\right)\exp\left(-\frac{\beta^2}{2}\left(t^2+\boldsymbol{x}^2\right)\right) \quad \text{with the HO parameter } \beta^2 = \sqrt{\mu K}.$$

$$\rightarrow\ \text{FF} \sim \int d^4x\ f_{\rm G}(v_F,x) f_{\rm G}(v_I,x) e^{i\frac{m_2}{m_1+m_2}q_\mu x^\mu} = \frac{1}{\omega}\exp\left(\frac{1}{4\beta^2}\left(\frac{m_2}{m_1+m_2}\right)^2\left(q^2 - \frac{2(v_I q)(v_F q)}{\omega}\right)\right)$$

$$\overset{\boldsymbol{P}_I=0}{=} \frac{M_F}{(P_F)_0}\exp\left(-\frac{1}{4\beta^2}\left(\frac{m_2}{m_1+m_2}\right)^2\left(\boldsymbol{q}^2 + q_0^2 + 2\frac{q_0}{(P_F)_0}\boldsymbol{q}^2\right)\right).$$

pseudo-scalar coupling [12] :

$$\partial_1^\mu\Psi \to \partial_1^\mu\Psi - i\frac{g_A}{f_{\rm ps}}\gamma_5\partial_1^\mu\phi_{\rm ps} \ \rightarrow\ S_{fi} = \langle f|\int d^4x_1\int d^4x_2\langle\bar{\Psi}(x_1,x_2)\frac{-i}{2m_1}\frac{g_A}{f_{\rm ps}}\gamma_5\sigma_{\mu\nu}(\overrightarrow{\partial_1^\nu} - \overleftarrow{\partial_1^\nu})\Psi(x_1,x_2)\rangle\partial_1^\mu\phi_{\rm ps}|i\rangle$$

3 Results and Discussions

Parameters

In this work, we take the following values of parameters:

$$f_\pi = 0.130\ \text{GeV}, f_K = f_\eta = 0.156\ \text{GeV}\ g_A = 0.75,$$

$$\beta = 0.43\ \text{GeV}, m_1 = \frac{m_\rho}{2} = 0.387\ \text{GeV},\ m_2 = \frac{m_{J/\psi}}{2} = 1.55\ \text{GeV}$$

Numerical results in comparison with other quark-model predictions are shown in Tab. 2 and 3.

Table 2: Calculated widths for $L=0$ and $L=1$ states. (in MeV)

State	${}^{2S+1}L_J$	Channel	Exp.[1]	This work	ZZ:2008[13]	GM:2016[17]	CS:2005[15]
$D^*(2010)^+$	${}^3S_1$	$D\ \pi$	$(83.4\pm1.8)\cdot10^{-3}$	$117\cdot10^{-3}$	$112\cdot10^{-3}$	$125\cdot10^{-3}$	$52\cdot10^{-3}$
$D_1^{'}(2420)^+$	${}^{j_q=\frac{3}{2}}P_1$	$D^*\ \pi$	25±6	21	22	9.92	22
$D_0^*(2400)^+$	${}^3P_0$	$D\ \pi$	230±17	264	248	154	283
$D_1(2430)^0$	${}^{j_q=\frac{1}{2}}P_1$	$D^*\ \pi$	384^{+130}_{-110}	234	220	161	272
$D_2^*(2460)$	${}^3P_2$	$D\ \pi$	-	30	39	15.3	35
		$D^*\ \pi$	-	19	19	6.98	20
		total	46.7±1.2	49	59	23	55

Table 3: Calculated widths for $L=2$ states. (in MeV)

State	${}^{2S+1}L_J$	Channel	Exp.[4, 5]	This work	Z:2010[14]	SCLM:2015[15]	GM:2016[17]	CS:2005[15]
$D_1^*(2760)$	${}^3D_1$	$D\ \pi$	-	89	156.8	76.13	53.6	73
		$D\ \eta$	-	11	43.2	9.01	10.1	16
		$D_s\ K$	-	12	45.8	11.66	22.8	55
		$D^*\ \pi$	-	45	64.9	35.16	29.3	45
		$D^*\ \eta$	-	4.2	12.9	2.68	4.0	9
		$D_s^*\ K$	-	12	10.3	2.92	7.4	23
		$D_1(2430)\ \pi$	-	Very preliminary	29.4	0.56	2.1	0.2
		$D_1'(2420)\ \pi$	-		187.1	211.72	76.4	189
		$D_2^*(2460)\ \pi$	-		2.7	0.007	0.6	7
		$D\ \rho$	-	-	0.2	26.34	19.8	74
		$D\ \omega$	-	-	0.05	8.87	6.3	16
		total	$177\pm32\pm20\pm7$	>173	553.3	385.06	234	523
$D_2'(2750)$	${}^{j_q=\frac{5}{2}}D_2$	$D^*\ \pi$	-	22.5				
		total	71 ± 6	>23.3				
$D_2(\sim 2750)$	${}^{j_q=\frac{3}{2}}D_2$	$D^*\ \pi$	-	131				
		total	-	>170				
$D_3^*(2760)$	${}^3D_3$	$D\ \pi$	-	18.6	32.5	8.47	20.1	53
		$D\ \eta$	-	1.42	2.6	0.31	1.24	4
		$D_s\ K$	-	1.79	2.1	0.17	1.1	4
		$D^*\ \pi$	-	16.5	20.6	7.05	15.5	55
		$D^*\ \eta$	-	0.60	0.7	0.11	-	3
		$D_s^*\ K$	-	0.481	0.3	0.04	-	2
		$D_1'(2420)\ \pi$	-	Very preliminary	1.7	0.21	-	2
		$D_1(2430)\ \pi$	-		5.2	0.26	-	3
		$D_2^*(2460)\ \pi$	-		1.7	0.63	0.9	6
		$D\ \rho$	-	-	0.4	0.61	1.30	15
		$D\ \omega$	-	-	0.1	0.21	-	4
		total	$105\pm18\pm6\pm23$ $154\pm27\pm13\pm9$	$\gtrsim 40$	67.9	18.07	51	277

* We have used $v_I \approx v_F$ approximation to compute respective amplitudes.

Discussions and comments

- Concerning the 1P states, our model successfully reproduces experiments as well as other models.
- Calculated widths for 1D-states are relatively narrow than them by other models since our relativistic form-factor the strongly suppresses the rates.
- The results for D_1*(2760) is larger than present data. This indicates that state mixing between 1D-2S are required.
- While the total width for D_3*(2760) is slightly smaller than experiment, obtained results are totally not contradict with present data. We expect that forthcoming precise experiments will make these predictions to verify.

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