Strong decays of excited 1D ~~and 2S~~ charmed(-strange) mesons in the covariant oscillator quark model

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Outline

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   and purpose of this work

2. Covariant oscillator quark model

3. Numerical results

4. Summary and future works

1. Recent experiments and purpose of this work

(D_n level below 2.5 GeV) n=u, d

✓ Thanks to the recent development of high energy collider experiment, the spectroscopy of the HL mesons has been made a remarkable progress.

✓ For D_n meson, the 1S and 1P levels have been well established.

1S

states	J^P	n_r, $^{2S+1}L_J$	observed modes
$D(1865)^0$, $D(1870)^\pm$	0^-	1, $^1S_0$	—
$D^*(2007)^0$, $D^*(2010)^\pm$	1^-	1, $^3S_1$	D π

1P

states	J^P	n_r, $^{2S+1}L_J$	observed modes
$D_0^*(2400)^0$, $D_0^*(2400)^\pm$	0^+	1, $^3P_0$	D π
$D_1(2430)^0$	1^+	1, $^{j=1/2}P_1$	D* π
$D_1(2420)^0$, $D_1(2420)^\pm$	1^+	1, $^{j=3/2}P_1$	D* π
$D_2^*(2460)^0$, $D_2^*(2460)^\pm$	2^+	1, $^3P_2$	D π, D* π

K.A. Olive *et al*. (Particle Data Group), Chin. Phys. C38, 090001 (2014)

✓ The mass spectra of these states are consistent described very well in the various quark potential model.

Often-quoted theoretical predictions in a relativised quark potential model

S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985).

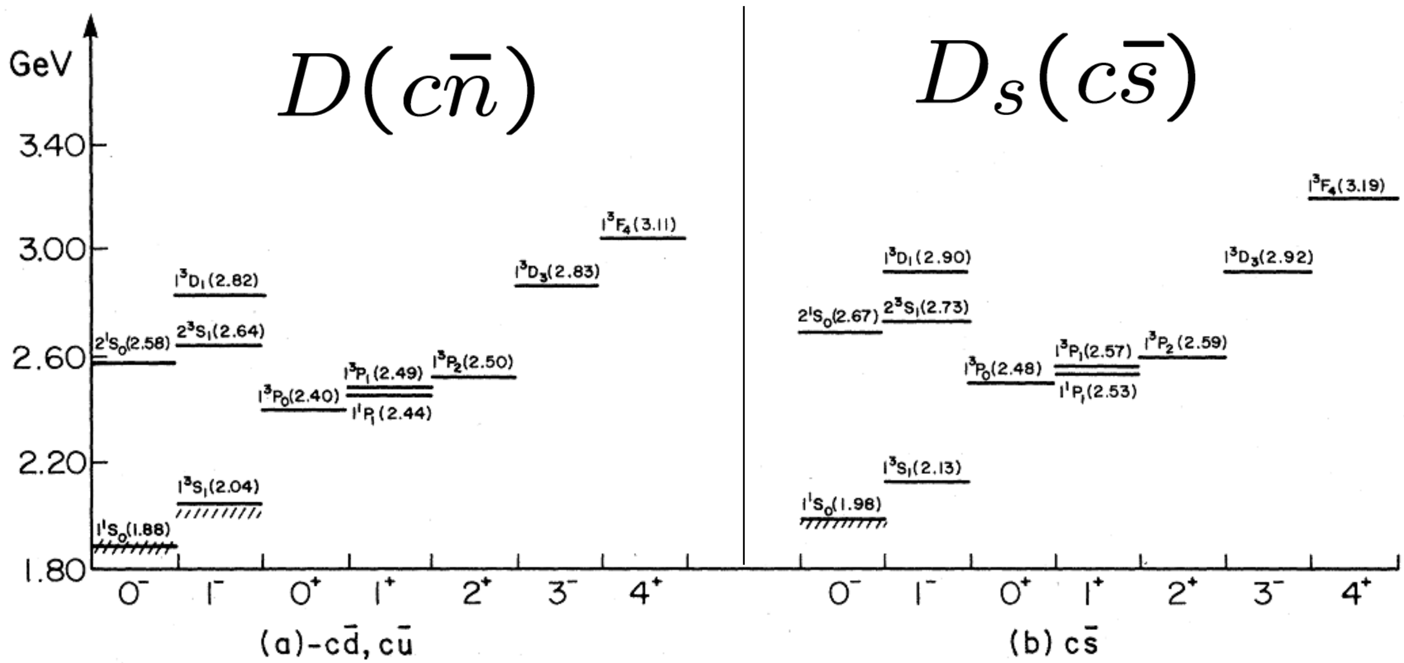


FIG. 7. The charmed mesons ($-c\bar{d}, c\bar{u}, c\bar{s}$). The legend is as for Fig. 3. Significant spectroscopic mixing in these sectors:

(D_s level below 2.6 GeV)

- ✓ Also, 1S and 1P levels have been established and it can be seen that the simple mass shift $M_{cs} - M_{cn} \sim 100$ MeV, except for 2317(0^+), 2460(1^+).
- ✓ Considerably low mass of D_s(2317/2460) has triggered a strongly renewed interest about the nature of hadrons.

1S

states	J^P	n_r, $^{2S+1}L_J$	observed modes
$D_s(1968)^\pm$	0^-	1, $^1S_0$	—
$D_s^*(2112)^\pm$	1^-	1, $^3S_1$	$D_s\ \pi_{\text{(Isospin Viol)}}$

1P

states	J^P	n_r, $^{2S+1}L_J$	observed modes
$D_s^*(2317)^\pm$	0^+	1, $^3P_0$	$D_s\ \pi_{\text{(Isospin Viol)}}$
$D_{s1}(2460)^\pm$	1^+	1, $^{j=1/2}P_1$	$D_s^*\ \pi_{\text{(Isospin Viol)}}$
$D_{s1}(2536)^\pm$	1^+	1, $^{j=3/2}P_1$	D^* K
$D_{s2}^*(2573)^\pm$	2^+	1, $^3P_2$	D K, D^* K

K.A. Olive *et al*. (Particle Data Group), Chin. Phys. C38, 090001 (2014)

- ✓ Concerning D_s(2317/ 2460), it is commonly recognized that the couple channel effect is important. Here, we do not discuss this matter. At least, we have no doubt that the theoretical evaluation of coupling with genuine quark component has primarily importance.

See, for theoretical review;
E. S. Swanson, Phys. Rep. 429, 243 (2006).
Colangelo, F. De Fazio, F. Giannuzzi, and S. Nicotri, Phys. Rev. D 86, 054024 (2012).

- ✓ Subsequently, our next interest necessarily moves higher 1D and 2S state. Concerning these states, important experimental progress have been made in the last few years.

- ✓ According to the latest experimental results by LHCb collaboration, studying inclusive $p\,p \to D_J / D_{sJ}\,X$ process and Dalitz plot analyses of B / B_s decays, it has revealed that there exist two different states with $J^P=1^-$ and 3^- at the same mass region 2800 MeV for $c\bar{n}$ and 2860 MeV for $c\bar{s}$ states.

R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. D91, 092002 (2015).
R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. D92, 032002 (2015).

R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. 113, 162001 (2014)

summarized at : A. Palano, arXiv:1509.03511v1

(D_n levels from 2.5 to 2.9 GeV)

- ✓ Considering latest data together with the previous results by BABAR, Belle and LHCb collaborations through 2006〜2015, we can make a plausible assignment for 1D and 2S states.
- ✓ In the latest result by LHCb, spin-parity of the states at 2760 are determined to 1^- and 3^-. Since spin-3 state have no other choice but to assign it to 1 $^3D_3$, and considering that 1- state having very close mass to it, is is likely to be also same multiplet.

2S

states	J^P	$n_{r,}$ $^{2S+1}L_J$	observed modes
$D_J(2580)^0$?	0^-	2, $^1S_0$	$D^*\pi$
$D_J^*(2650)^0$?	1^-	2, $^3S_1$	$D\pi$, $D^*\pi$

1D

states	J^P	$n_{r,}$ $^{2S+1}L_J$	observed modes
$D_1^*(2760)^0$, $D_1^*(2760)^\pm$	1^-	1, $^3D_1$	$D\pi$, $D^*\pi$
$D_J(2740)^0$?	2^-	1, $^{j=3/2}D_2$	$D^*\pi$
	2^-	1, $^{j=5/2}D_2$	$D^*\pi$
$D_3^*(2760)^0$, $D_3^*(2760)^\pm$	3^-	1, $^3D_3$	$D\pi$, $D^*\pi$

(D_s levels from 2.5 to 2.9 GeV)

✓ Same consideration hold for D_s meson system. In the latest result by LHCb, spin-parity of the states at 2860 are determined to 1^- and 3^-. Since spin-3 state is inevitably assigned to 1 $^3D_3$, and thus 1- state is likely to be also same multiplet.

2S

states	J^P	$n_{r,}$ $^{2S+1}P_J$	modes
—	0-	2, $^1S_0$	-
$D_{s1}^*(2700)^\pm$	1-	2, $^3S_1$	D* K, D*K

1D

states	J^P	$n_{r,}$ $^{2S+1}P_J$	modes
$D_{s1}^*(2860)^\pm$	1-	1, $^3D_1$	D K, D* K
—	2-	1, $^{j=3/2}D_2$	D* K
—	2	1, $^{j=5/2}D_2$	D* K
$D_{s3}(2740)^\pm$	3-	1, $^3D_3$	D K, D* K

General

✓ From theoretical point of view, the spectroscopy of HL meson provides a special opportunity for understanding of the structure of the hadron.

→ Concerned with the key symmetry of QCD
- Heavy quark symmetry for heavy-quark
- Chiral symmetry for light-quark

✓ The study of the decay is the most suitable way to probe the nature of hadrons since decay widths strongly depend on their internal structure.

→ good subject to study the spectroscopic classifications

✓ light-meson emission proceeds through a single light-quark transition

→ probe the WF since, for example, the pseudo-scalar(NG boson) interactions are determined by low energy theorem.

Purpose of this work

✓ In this talk, we treat the both charmed and charmed-strange mesons in parallel, and study their strong decays up to orbitally excited 1D states and 2S within the framework of **the Covariant Oscillator Quark Model (COQM).**

✓ Especially, we shall pay a particular attention to relativistic effect offered by the COQM.

Here note that the word `Relativistic' has two different kinds of meaning in treating the hadronic decays.

a) For quark motion (in the case of large internal velocity):
→ Non-negligible even at the rest frame of hadrons
e.g. Godfrey-Isgur (1985), ``relativized Q.M."

b) For Center of Mass (CM) motion :
→ Relevant to the transition with large mass differences

Here our interest is rather the latter case !

✓ We carefully examined such the effect and will discuss their impact.

An approach adopted in this work:

2. Covariant Oscillator Quark Model

Key ingredient of the COQM

✓ The COQM is one of the possible covariant extension of conventional non-relativistic quark model retaining the various success, principally restricted to the static problem.

(Note)

The COQM has a long history of development. (e.g. Feynman, Kislinger and Ravndal (1971), Y. S. Kim et al. (1973) , Namiki et al. (1970) , Ishida et al. (1971))
See for review, S. Ishida and M.Oda, in proc. of int. symp. on “Extended Objects and Bound Systems.” ed. by O. Hara, S. Ishida and S. Naka, World Scientific, Karuizawa, Japan, March 1992.
Especially it had been widely applied to investigate the radiative decays of LL and HH mesons with considerable success. See, for the recent application: T.M., Kenji Yamada, Masuho Oda, Shin Ishida, arXiv:1310.7507.

✓ 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.

✓ Most important property is that the excited states are on the linear Regge trajectory in terms of squared masses.

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

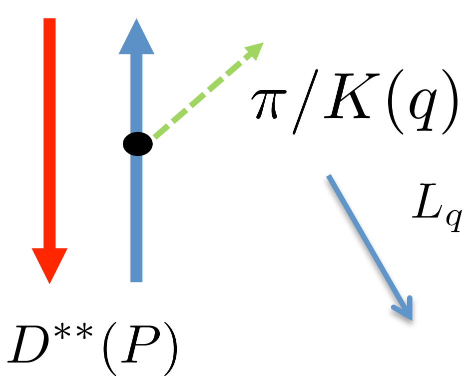
✓ Electromagnetic current is conserved even for the transitions and it is possible to introduce a quark-pion coupling in conformity with PCAC relation.

✓ In the COQM, internal WF of relevant ($q\bar{c}$) mesons are described as boosted LS-coupling from.

$$\Phi(x,P)_{\alpha}^{(\pm)\beta} \sim \left(W(v)_{\alpha}^{(\pm)\beta}\right)^{\mu_1\mu_2\cdots} \times f_{\mu_1\mu_2\cdots}(v,x)$$

- Spin part consists of the direct product of respective Dirac spinor with the velocity of hadrons.
- Space-time part is taken as 4dim. SHO function, with suitable constraint.

✓ Concerning effective quark pion/ kaon coupling, we assume



$$L_q = -\frac{g_A}{\sqrt{2}f}\frac{1}{2m_q}\bar{q}[\gamma_5(\overrightarrow{\partial_\mu} + \overleftarrow{\partial_\mu}) - i\gamma_5\sigma_{\mu\nu}(\overrightarrow{\partial^\nu} - \overleftarrow{\partial^\nu})]q\partial^\mu\phi_{ps}$$

$$T = \frac{g_A}{\sqrt{2}f_\pi}\int d^4x\langle\bar{\Psi}^{(-)}(P',x)\gamma_5 q^\mu\sigma_{\mu\nu}\left(P^\nu + P'^\nu + \frac{i\lambda}{2m_s}\overleftrightarrow{\partial_x}^\nu\right)\phi_{ps}(q)\Psi^{(+)}(P,x)\rangle \exp[i\frac{2m_c}{\lambda}q\cdot x]$$

Damping effect of the form factor (NRQM v.s. COQM)

NRQM : $$F_1^{\mathrm{NRQM}} = \exp\left(-\frac{q^2}{4\beta^2}(\frac{m_2}{m_1+m_2})^2\right)$$

COQM : $$F_1^{\mathrm{COQM}} = \frac{1}{\omega}\exp\left(-\frac{1}{4\beta^2}(\frac{m_2}{m_1+m_2})^2\frac{2v_{I\mu}q_\mu v_{F\nu}q_\nu}{\omega}\right)$$

$$\to \frac{1}{\omega}\exp\left(-\frac{q^2}{4\beta^2}(\frac{m_2}{m_1+m_2})^2(2+\frac{2\omega_3}{\omega})\right)$$

at rest frame of initial particle

comes from space integral and time integral

boost effect

✓ In the transition with large momentum transfer, it will be expected the appearance of the dumping effect which comes from the degree of freedom of the Lorentz boost and relative-time .

3. Numerical Results

Fixing the model parameters

Model Parameters

1) Coupling strength for quark-NG boson: $g_A = 0.60$ from $\Gamma(D^{*+} \to D\pi)$

2) Quark mass ratio: $\frac{m_{u,d}}{m_c} = \frac{M_\rho}{M_{J\psi}} = 0.25$, $\frac{m_s}{m_c} = \frac{M_\phi}{M_{J\psi}} = 0.33$

3) Harmonic Oscillator Mass:

$M_1 = 2.46\text{GeV}, M_2 = 2.76\text{GeV}$ for D_n
$M_1 = 2.53\text{GeV}, M_2 = 2.86\text{GeV}$ for D_s

Note that they are related with Regge Slope parameter as

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

All meson mass are taken from PDG 2014 or LHCb 2014/2015 (for 1D states)

Numerical Results (1) cn^{bar} 1S, 1P

— comparison with experiment —

Initial States	Final states	Decay width (/MeV): Our Results	Decay width (/MeV): Sum of PW	Decay width (/MeV): Experiment (PDG2014/LHCb2015)
$D^*(2010)^\pm$	$D\pi$	83.4×10^{-3} (input→g_A)		$(83.4\pm1.8)\times10^{-3}$
$D_0^*(2360)^0$	$D\pi$	281		267±40 /255 ± 26
$D_1(2430)^0$	$D^*\pi$	185		384^{+107}_{-75} -74
$D_1(2420)^0$	$D^*\pi$	15		27.4 ± 2.5
$D_2^*(2460)^0$	$D\pi$	36	50	49.0±1.3 /46.0 ± 3.4 etc.
	$D^*\pi$	14		

Numerical Results (2) cs^{bar} 1S, 1P

— comparison with experiment —

<table>
<tr><th rowspan="2">Initial States</th><th rowspan="2">Final states</th><th colspan="3">Decay width (/MeV)</th></tr>
<tr><th colspan="2">Our Results | Sum of PW</th><th>Experiment (PDG2014 / LHCb2015)</th></tr>
<tr><td>$D_{s1}(2536)$</td><td>D* K</td><td colspan="2">0.31</td><td>0.92 ± 0.03 ± 0.04</td></tr>
<tr><td rowspan="2">$D_{s2}{}^{*}(2573)$</td><td>D K</td><td>13</td><td rowspan="2">14</td><td rowspan="2">17 ± 4
/16.9 ± 0.5 ± 0.4 ± 0.4</td></tr>
<tr><td>D* K</td><td>1</td></tr>
</table>

Here we have omitted isospin violation modes.

Numerical Results (3) cn^{bar} 1D

— comparison with experiment —

Initial States	Final states	Decay width		
		Our Results	Sum of PW	Experiment (LHCb2015)
$D_1^*(2760)^0$	$D\pi$	in preparation		177±32
	$D^*\pi$			
$D_3^*(2760)^0$	$D\pi$	34	51	105±18±6±23 (Isobar) / 154±27±13±9 (K-matrix)
	$D^*\pi$	17		

It seems to disagree (?)

Numerical Results (4) cs^{bar} 1D

— comparison with experiment —

Initial States	Final states	Decay width: Our Results	Decay width: Sum of PW	Decay width: Experiment (LHCb2014)
$D_{s1}^*(2860)^0$	D K	in preparation		$159 \pm 23 \pm 27 \pm 72$
	D* K			
$D_{s3}^*(2860)^0$	D K	30	41	$53 \pm 7 \pm 4 \pm 6$
	D* K	11		

Numerical Result (5) cs^{bar} 1D

— comparison with other theory —

Initial States	Final states	Experiment: LHCb2014 (total width)	Theory: Present work	CS 2005	ZZ 2008	ZZ 2010	GJ 2014	GM 2014	SCLM 2015
$D_{s1}^*(2860)^0$	D K	159 ± 23 ± 27 ± 72	in preparation	120	-	-	93	94	62~76
	D* K			74	-	-	32	49	35~44
$D_{s3}^*(2860)^0$	D K	53 ± 7 ±4 ± 6	30	82	27	24	19	20	25~30
	D* K		11	67	11	20	8	12	14~24

✓ Compering with other results, it is not found a critical difference in the numerical value of the decay width.

References

F. E. Close and E. S. Swanson, Phys. Rev. D 72, 094004 (2005).	$^3P_0$ model
X.H. Zhong and Q. Zhao, Phys. Rev. D 78, 014029 (2008).	Chiral q−type effective model
X. H. Zhong and Q. Zhao, Phys. Rev. D 81, 014031 (2010).	Effective quark-meson coupling model
S. Godfrey and I.T. Jardine, Phys. Rev. D 89, 074023 (2014).	pseudo-scalar emission model
S. Godfrey and K. Moats, Phys.Rev.D90,117501(2014).	$^3P_0$ model
Q. T. Song, D. Y. Chen, X. Liu, and T. Matsuki, Eur. Phys. J. C 75, 30 (2015).	$^3P_0$ model

(note) Many other $^3P_0$ results exist.

4. Summary and future subjects

Summary

- ✓ In this work, treating in parallel both the D_n and D_s system, we have studied pionic / kaonic transitions from the ground to higher 1D excited states.
- ✓ Calculated partial width for $c\bar{n}$ and $c\bar{s}$ mesons well reproduce the experimental data except for recently reported $D_3^*(2760)$.
- ✓ Relativistic effect, especially the boosting effect of form factor caused by recoiling of final meson has certainly worked. However, it is not visible to the calculated results of partial width being compared with to the conventional non-relativistic quark model. One possible reason is such modification is absorbed in model parameters.

Future subject

- ✓ We will submit our results including all processes in the near future, please check it.

Thank you very much for your kind attention.