The coupled channel system $D^*D^* - DD^*$ and decays of doubly charmed meson molecules

R. Molina[1], H. Nagahiro[2] and A. Hosaka[3]

[1]Department of Physics, Columbian College of Arts & Sciences, Corcoran Hall, 725 21st Street NW, Washington DC, [2]Department of Physics, Nara Women's University, Nara 630-8506, Japan, [3]Research Center for Nuclear Physics (RCNP), Mihogaoka 10-1, Ibaraki 567-0047, Japan

Contents

$D^* D^*$-$D^* D$ coupled channel system combining HQS and HGS

HQSS: light and heavy degrees of freedom are separated. QCD dynamics is invariant under rotations of the spin of the heavy quarks.

1. Clasify the states in the HQSS basis: $|S_{cc}, J_l, J, \alpha\rangle_{(j_{l,m}, j_{l,m'})}$

S_{cc}: spin of the cc subsystem,
J_l: Total spin of the light quark system,

$j_{l,m}$: total spin of the light quark in the meson m. We are working with lower states, $L's = 0$.

S_{cc}	J_l	J	$j_{l,m}$	$j_{l,m'}$
0	0	0	1/2	1/2
0	1	1	1/2	1/2
1	0	1	1/2	1/2
1	1	0	1/2	1/2
1	1	1	1/2	1/2
1	1	2	1/2	1/2

$${}_{(j_{l,m1}, j_{l,m2})}\langle S'_{cc}, J'_l, J' | H_{QCD} | S_{cc}, J_l, J\rangle_{(j'_{l,m1}, j'_{l,m2})} = \delta_{JJ'}\, \delta_{J_l J_{l'}}\, \delta_{S_{cc} S'_{cc}} \langle j_{l,m1} j_{l,m2} J_l | H_{QCD} | j'_{l,m1} j'_{l,m2} J_l\rangle.$$

2. Determine the LEC's:

$$\langle 1/2, 1/2, 1 | H_{QCD} | 1/2, 1/2, 1\rangle = \lambda$$
$$\langle 1/2, 1/2, 0 | H_{QCD} | 1/2, 1/2, 0\rangle = \mu$$

3. Identify the states with the particle channels, $|S_{cc}, J_l, J\rangle_{(j'_{l,m1}, j'_{l,m2})}$

$9 - j$ *symbols* $|l_1 s_1 j_1, l_2 s_2 j_2; JM\rangle$ $|D^* D^*, J = 1\rangle = \frac{1}{\sqrt{2}} |0, 1, 1\rangle_{(1/2,1/2)} + \frac{1}{\sqrt{2}} |1, 0, 1\rangle_{(1/2,1/2)},$

$|l_1 l_2 L, s_1 s_2 S; JM\rangle$ $|DD^*, J = 1\rangle = \frac{1}{2} |0, 1, 1\rangle - \frac{1}{2} |1, 0, 1\rangle + \frac{1}{\sqrt{2}} |1, 1, 1\rangle$

Therefore, we have in the HQSS basis, (Channels: DD^*, D^*D^*)

$$V(J=1) = \begin{pmatrix} \frac{3}{4}\lambda + \frac{1}{4}\mu & \frac{1}{2\sqrt{2}}\lambda - \frac{1}{2\sqrt{2}}\mu \\ \frac{1}{2\sqrt{2}}\lambda - \frac{1}{2\sqrt{2}}\mu & \frac{1}{2}\lambda + \frac{1}{2}\mu \end{pmatrix}$$

$$V(D^*D^* \to D^*D^*)_{I=0,J=1} = g^2(s - 2m_H^2 + 2E_1E_3)(\frac{1}{m_{J/\psi}^2} + \frac{1}{2m_\omega^2} - \frac{3}{2m_\rho^2})$$

$$V(DD^* \to DD^*)_{I=0} = g^2(s - 2m_H^2 + 2E_1E_3)(\frac{1}{m_{J/\psi}^2} + \frac{1}{2m_\omega^2} - \frac{3}{2m_\rho^2})\vec{\epsilon}\cdot\vec{\epsilon'},$$

$H = D, D^*$. Since using the HGF (hidden gauge lagrangian), $V(DD^* \to DD^*)_{I=0} = V(D^*D^* \to D^*D^*)_{I=0,J=1}$,

$$\frac{1}{2}\lambda + \frac{1}{2}\mu = \frac{3}{4}\lambda + \frac{1}{4}\mu$$

$\Longrightarrow \lambda = \mu$. If $\lambda = \mu$ we obtain,

$$V(DD^* \to D^*D^*)_{I=0,J=1} = 0\ ,$$

in the HQSS and HGS framework.

For identical particles we have to simetrize the wave function. After the exchange of the two D^*'s mesons, we have factors $(-)^{J-j_1-j_2}$ and $(-)^{I-I_1-I_2}$. Thus, for $s-wave$, the potential only survives if $I+J+L=odd$.

$$V(D^* D^* \to D^* D^*)_{I=0,J=0,2} = 0,$$
$$V(D^* D^* \to D^* D^*)_{I=1,J=1} = 0$$

Consistent with the interaction obtained from the hidden gauge lagrangian.

Hidden gauge Lagrangian Bando,Kugo,Yamawaki

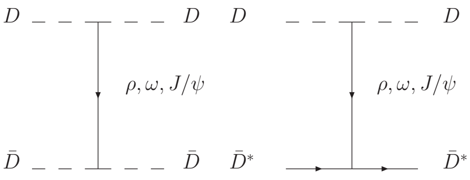
The LEC's, λ and μ, can be evaluated using the hidden gauge lagrangian:

$$\mathcal{L} = \mathcal{L}^{(2)} + \mathcal{L}_{III} \tag{1}$$

$$\mathcal{L}^{(2)} = \frac{1}{4} f^2 \langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + \chi^\dagger U \rangle \tag{2}$$
$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu} V^{\mu\nu} \rangle + \frac{1}{2} M_V^2 \langle [V_\mu - \frac{i}{g}\Gamma_\mu]^2 \rangle$$

$$D_\mu U = \partial_\mu U - ieQA_\mu U + ieUQA_\mu, \qquad U = e^{i\sqrt{2}P/f}, \qquad g = m_V/2f \tag{3}$$

P P and P V interaction



$$\mathcal{L}_{\mathbf{PPV}} = -\mathbf{ig} \langle \mathbf{V}^\mu [\mathbf{P}, \partial_\mu \mathbf{P}] \rangle$$

$$\mathcal{L}_{\mathbf{3V}} = \mathbf{ig} \langle \mathbf{V}^\mu [\mathbf{V}^\nu, \partial_\mu \mathbf{V}_\nu] \rangle$$

Vector-vector scattering Bando,Kugo,Yamawaki

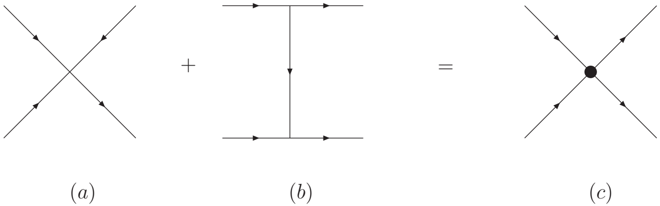
$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu} V^{\mu\nu}\rangle \rightarrow \mathcal{L}_{III}^{(3V)} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu) V^\mu V^\nu\rangle$$

$$\mathcal{L}_{III}^{(c)} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle$$

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu]$$

$$g = \frac{M_V}{2f}$$

$$V_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu$$



The XYZ and doubly charm mesons

- The vector-exchange diagram (b) dominates the interaction
- In the sectors *charm* $= 2$; *strangeness* $= 0, 1$, only the potential from this diagram survives

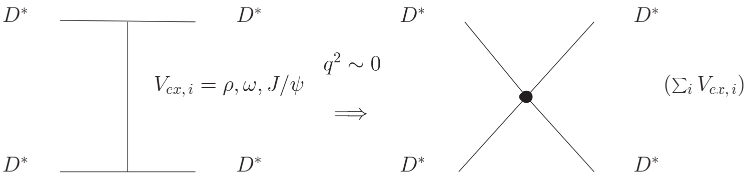


Figure : Point-like vector-vector interaction for $D^* D^* \to D^* D^*$.

R. Molina, T. Branz and E. Oset, Phys. Rev. D 82, 014010 (2010)

The XYZ and doubly charm mesons

In the hidden gauge formalism, the potential takes the form,

$$\begin{aligned} V_{ij} &= -\frac{g^2}{m^2_{V_{ex}}} A_{ij}(s-u) \quad \text{for} \quad J=0,1,2, \quad t-channel \\ V_{ij} &= -\frac{g^2}{m^2_{V_{ex}}} B_{ij}(s-t) \quad \text{for} \quad J=0,2, \quad u-channel \\ &= \frac{g^2}{m^2_{V_{ex}}} B_{ij}(s-t) \quad \text{for} \quad J=1, \quad u-channel \end{aligned} \tag{4}$$

And $V_{ex} = \rho, \omega, J/\psi$. The SU(4) flavour symmetry is broken:

1) Masses are taken from the PDG.

2) The exchange of heavy particles, f. ex. J/ψ is supressed.

3) Different coupling constants "g" are taken, "g_h^2" for $V_h V_h \to V_h V_h$, "$g_h g_l$" for $V_h V_h \to V_l V_l$, and "g_l^2" for $V_l V_l \to V_l V_l$, with $g_h = g_{D^*} = m_{D^*}/(2f_D)$, or $g_l = m_\rho/(2f_\pi)$, with $f_D = 206/\sqrt{2}$ MeV and $f_\pi = 93$ MeV.

The XYZ states and doubly charm mesons

- Bethe Salpeter equation:

$$T = (\hat{1} - VG)^{-1} V \, . \qquad (5)$$

- The potencial V here is a 10×10 matrix in $I = 0$: $D^*\bar{D}^*$, $D^*_s\bar{D}^*_s$, $K^*\bar{K}^*$, $\rho\rho$, $\omega\omega$, $\phi\phi$, $J/\psi J/\psi$, $\omega J/\psi$, $\phi J/\psi$, $\omega\phi$. In $I = 1$, V is a 6×6: $D^*\bar{D}^*$, $K^*\bar{K}^*$, $\rho\rho$, $\rho\omega$, $\rho J\psi$, $\rho\phi$
- *charm* $= 2$; *strangeness* $= 0$: D^*D^*, *strangeness* $= 1$: $D^*D^*_s$
- G is a diagonal matrix with

$$G_i(P) = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_1^2 + i\epsilon} \frac{1}{(P-q)^2 - m_2^2 + i\epsilon} \, , \qquad (6)$$

$G_i(P)$ is a function of $\alpha(\mu)$ in dimensional regularization or $q_{\max}$ with cutoff.

XYZ and doubly charm mesons

To investigate the effect of the SU(4) $g = \frac{m_V}{2f}$ breaking, we have performed the calculation by using two parameter sets:

1) SU(4) symmetric coupling, $g_l = m_\rho/(2f_\pi)$ and $\alpha_h = -1.4$ ($\mu = 1500$ MeV) in all channels

2) SU(4) breaking for couplings, we use g_h^2 or $g_l g_h$, being $g_h = m_{D^*}/(2f_D)$ for heavy particles, and $\alpha_h = -1.27$.

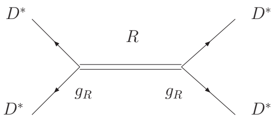
$C; S$	I,J	M_R		channel	$\lvert g_R \rvert$		g_W		PDG
		(g_l)	(g_h)		(g_l)	(g_h)	(g_l)	(g_h)	
0; 0	0, 0	3936	3950	$D^*\bar{D}^*$	18700	18000	18050	17200	Y(3940)
	0, 1	3940	3955	$D^*\bar{D}^*$	18260	17200	17800	16900	"$X(3940)$"
	0, 2	3921	3922	$D^*\bar{D}^*$	20600	21000	18800	18800	Z(3930)
	0, 2	4174	4160	$D_s^*\bar{D}_s^*\,(D^*\bar{D}^*)$	20400	19500	16700	17700	X(4160)
	1, 2	3970	3924	$D^*\bar{D}^*\,(\rho J/\psi)$	20500	20560	15800	18700	"$Z_c(3945)$"
2; 0	0, 1	3968	3942	D^*D^*	16800	19500	15900	17800	"$R_c(3970)$"
2; 1	1/2, 1	4100	4070	$D_s^*D^*$	13400	17700	13100	16400	"$S_c(4100)$"

Table : Masses and couplings to the most important channel in MeV.

$$\frac{g_W^2}{4\pi} = 4(m_1 + m_2)^2 \sqrt{\frac{2B}{\mu}}\left(1 + O\left(\frac{\sqrt{2\mu B}}{\beta}\right)\right)$$

And also doubly charm mesons! R. Molina, T. Branz and E. Oset, PRD 82, 014010 (2010)

Couplings (g_a) of the doubly charm mesons to $D^*D^*_{(s)}$



$$T \simeq \frac{[g_R \frac{1}{2}(\epsilon_1^i \epsilon_2^j - \epsilon_1^j \epsilon_2^i)][g_R \frac{1}{2}(\epsilon_1^i \epsilon_2^j - \epsilon_2^j \epsilon_2^i)]}{s - s_p}$$

C, S	*Name*	$I[J^P]$	Channel	$\sqrt{s}_{\rm pole}$ (MeV)	$g_R[MeV]$
2; 0	R_{cc}	$0[1^+]$	D^*D^*	3970	16800
2; 1	S_{cc}	$1/2[1^+]$	$D^*D^*_s$	4100	13400

- Note we use the same value of $\alpha_H = -1.3 - (-1.4)$ to reproduce the Y(3940), X(4160) and R_{cc}'s!

Doubly charm mesons from the *PV* interaction

With this value of the subtraction constant, we obtain also DD^* bound states, which are also quite stable.
For α between $-1.1 - (-1.4)$,

$$M_{R(DD^*)} = 3820 - 3870\,\mathrm{MeV},$$
$$g_{R(DD^*)} = 10000 - 16000\,\mathrm{MeV} \qquad (7)$$

We call it $R_{cc}(3850)$. In order to estimate the effect of a possible $DD^* - D^*D^*$ coupling, we introduce anomalous couplings which allows processes $D^*D^* \to DD^*$ via the exchange of a pion.

$$\mathcal{L}_{VVP} = \frac{G'}{\sqrt{2}} \epsilon^{\mu\nu\alpha\beta} \langle \partial_\mu V_\nu \partial_\alpha V_\alpha P \rangle \qquad (8)$$

Anomalous couplings for the $D^*D^* \to DD^*$ transition

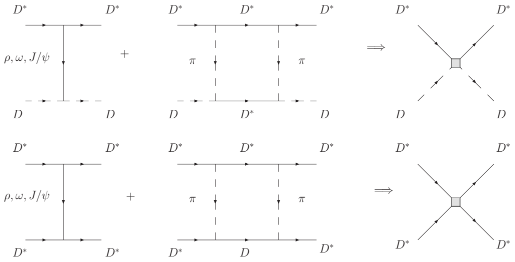


Figure : Feynman diagrams evaluated with $D^*D^* - DD^*$ transition. The integral of the loop is logarithmically divergent and has to be regularized using a cutoff $q_{\mathrm{max},b}$. We use two different sets of parameters for the couplings $D^*D\pi$ and $D^*D^*\pi$ with an offshell pion,

1) $g = m_\rho/2f_\pi$, $G' = 0.014$ MeV^{-1} and $F(q^2) = 1$.

2) $g = g^{\mathrm{exp}}_{D^*D\pi} = 8.95$, $G'_{\mathrm{exp}} = 0.0087$ MeV^{-1} ($\Gamma_{\mathrm{exp}}(D^*D\gamma)$) and $F(q^2) = e^{q^2/\Lambda^2}$. $\Lambda \sim 1$ GeV, (Navarra, Nielsen, Bracco, Phys. Rev. D 65 037502(2002)).

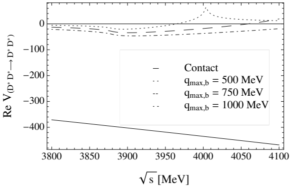


Figure : Real part of the potential for the contact and box diagrams for $D^* D^* \rightarrow D^* D^*$. Left: set 1) using g. Right: set 2) using $g_{\rm exp}$, $G'_{\rm exp}$ and $\Lambda = 1$ GeV

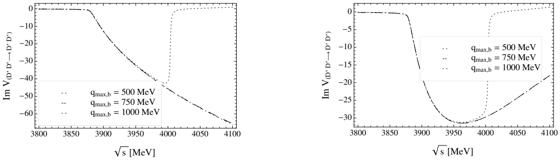
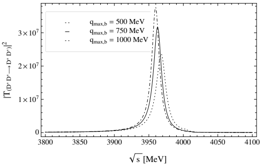


Figure : Imaginary part of the potential for the contact and box diagrams for $D^* D^* \rightarrow D^* D^*$. Left: set 1) using g. Right: set 2) using $g_{\rm exp}$, $G'_{\rm exp}$ and $\Lambda = 1$ GeV



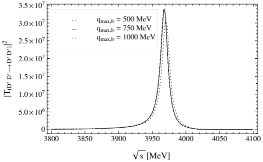


Figure : $|T(D^* D^* -> D^* D^*|^2$ including the contact and box diagrams for $D^* D^* \to D^* D^*$. Left: prescription 1) using g. Right: Prescription 2) using $g_{\rm exp}$, $G'_{\rm exp}$ and $\Lambda = 1$ GeV

.

Conclusions

Mass of the $R_{cc}(3970)$ is still around $3960 - 3970$ MeV and coupling barely changes $g_{R(D^* D^*)} \simeq 20000$ MeV. But the width increases a bit, $\simeq 20$ MeV.

Decays of double charm states to $D_{(s)} D^*_{(s)}$

R_{cc} has isospin $I = 0$ and S_{cc} ($S = 1$) $I = \frac{1}{2}$:

- $|D^* D^*, I = 0, I_3 = 0\rangle$

$$= \frac{1}{\sqrt{2}}(-D^{*+}(q, \epsilon_1)D^{*0}(P - q, \epsilon_2) + D^{*0}(q, \epsilon_1)D^{*+}(P - q, \epsilon_2)) \quad (9)$$

- $|D^* D^*_s, I = \frac{1}{2}, I_3 = -\frac{1}{2}\rangle = -D^{*0}(q, \epsilon_1)D^{*+}_s(P - q, \epsilon_2)$
- $|D^* D^*_s, I = \frac{1}{2}, I_3 = \frac{1}{2}\rangle = D^{*+}(q, \epsilon_1)D^{*+}_s(P - q, \epsilon_2)$

$$\text{Isospin multiplets}: \begin{pmatrix} D^{*+} \\ -D^{*0} \end{pmatrix}, \quad D^{*+}_s \quad (10)$$

R^+_{cc} S^+_{cc} S^{++}_{cc}

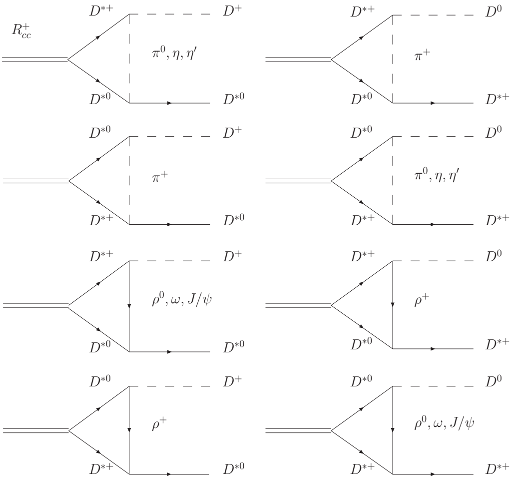


Figure : Feynmann diagrams evaluated in the decay $R_{cc} \to DD^*$.

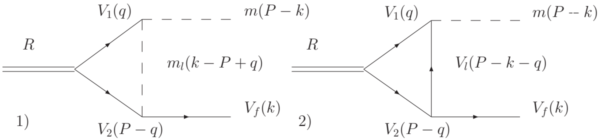


Figure : PPV and 3V Feynmann diagrams for the evaluation of the $R_{cc} \to DD^*_{(s)}$ decay width.

$$t_{RVV} = \frac{I\, g_R}{2}(\epsilon_1^i \epsilon_2^j - \epsilon_1^j \epsilon_2^i) \tag{11}$$

$$\mathcal{L}_{3V} = ig\langle (V^\mu \partial_\nu V_\mu - \partial_\nu V_\mu V^\mu) V^\nu) \rangle \Longrightarrow$$

$$t_{V_3} = V_3 g\{(2k + q - P)^\mu \epsilon_{(l)\,\nu} \epsilon_{2\,\mu} \epsilon^\nu_{(f)} - (k + P - q)^\mu \epsilon_{2\,\nu} \epsilon_{(l)\,\mu} \epsilon^\nu_{(f)} + (2(P - q) - k)_\mu \epsilon_{(l)\,\nu} \epsilon^\mu_{(f)} \epsilon^\nu_2 \} \tag{12}$$

$$\mathcal{L}_{VVP} = \frac{G'}{\sqrt{2}} \epsilon^{\mu\nu\alpha\beta} \langle \partial_\mu V_\nu \partial_\alpha V_\alpha P \rangle \Longrightarrow t_{VVP} = AG' \epsilon^{\alpha\beta\gamma\delta} (P - q)_\alpha \epsilon_{2\,\beta} k_\gamma \epsilon_{(f)\,\delta} \,, \tag{13}$$

$$\mathcal{L}_{PPV} = -ig\langle V^\mu [P, \partial_\mu P] \rangle \Longrightarrow t_{PPV} = g\, P_V \epsilon_1^\mu (2(P - k) - q)_\mu \,. \tag{14}$$

Decays of double charm states to $D_{(s)}D^*_{(s)}$

$$-it^{ij} = -\frac{1}{2}AIV_3 g_R G' g \int \frac{d^4q}{(2\pi)^4} \frac{q_\alpha (P-k)_\gamma}{(q^2-m_1^2)((P-q)^2-m_2^2)((k+q-P)^2-M_l^2)}$$
$$\times\{\epsilon_{(f)\,\delta}((2k+q-P)^j \epsilon^{\alpha i\gamma\delta} - (2k+q-P)^i \epsilon^{\alpha j\gamma\delta}$$
$$-(k+P)_\delta(\epsilon^{\alpha i\gamma\delta}\epsilon^j_{(f)} - \epsilon^{\alpha j\gamma\delta}\epsilon^i_{(f)})$$
$$+(2(P-q)-k)_\mu \epsilon^\mu_{(f)}(\epsilon^{\alpha i\gamma j} - \epsilon^{\alpha j\gamma i})\} \tag{15}$$

- The integral is logarithmically divergent.
- We take a Feynmann parametrization for the convergent part.
- Perform integral in q^0 and use a cutoff in momenta $q_{\rm max} = 750$ MeV to get the dynamically generated states $R_c(3970)$ and $S_c(4100)$ MeV.

Amplitud including pseudoscalar and vector meson exchange

$$t_1^{ij} = g g_X G' \epsilon_{(f)\,\delta}\{\mathcal{H} P_\alpha k_\gamma (k^i \epsilon^{\alpha j\gamma\delta} - k^j \epsilon^{\alpha i\gamma\delta}) + (\mathcal{I} k_\gamma + \mathcal{J} P_\gamma)\epsilon^{ij\gamma\delta}$$
$$+\mathcal{F} P_\gamma k_\alpha P^\delta \epsilon^{ij\gamma\alpha}\} \tag{16}$$

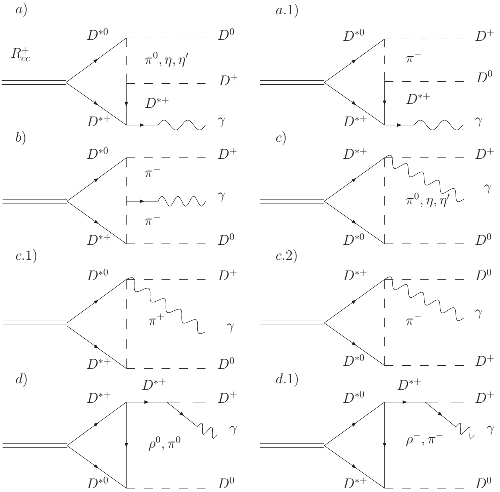
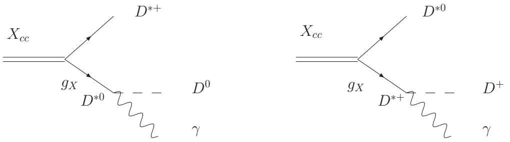


Figure : diagrams for the $R^+_{cc} \to D^0 D^+ \gamma$ decay through one loop.

Decays into $DD^*\gamma$

$$\Gamma = \frac{1}{64 M_X \pi^3 (2J+1)} \int_{E_{1\,\min}}^{E_{1\,\max}} dE_1 \int_{E_{\gamma\,\min}}^{E_{\gamma\,\max}} dE_\gamma\, \theta(1-\cos^2\theta) \sum_{\lambda_{\rm in},\lambda_{\rm fn}} |t_2|^2$$

being $\cos\theta$ the angle between p_1 and k.



$$\Gamma = \frac{1}{32\, M_R \pi^3} \int \frac{\tilde{p}_2 p_1}{\sqrt{s}} \frac{1}{2J+1} \sum_\delta |t_3|^2 dM_{D\gamma} \qquad (17)$$

$$\sum_\delta |t_3|^2 = -\frac{C'^2 I^2 g_R^2 G'^2 e^2}{4g^2} \left(\frac{M_{D\gamma}^2 - m_D^2}{M_{D\gamma}^2 - m_{D^*}^2} \right)^2 \qquad (18)$$

Results

State	*Channel i*	Γ^i [MeV]	*Channel j*	Γ^i_j [MeV]	$\Gamma_{\rm tot}$ [MeV]
$R^+_{cc}(3970)$	$D^0 D^{*+}$	22 ± 6	$D^0(D^+\pi^0)$	7 ± 2	44 ± 12
			$D^0(D^0\pi^+)$	15 ± 4	
			$D^0(D^+\gamma)$	0.4 ± 0.2	
	$D^+ D^{*0}$	22 ± 6	$D^+(D^0\pi^0)$	14 ± 4	
			$D^+(D^0\gamma)$	8 ± 2	
	$D^0 D^+\gamma$	$(2 \pm 1) \times 10^{-3}$			
	$D^{*0} D^+\gamma$	$(0.03 \pm 0.01) \times 10^{-3}$			
	$D^{*+} D^0\gamma$	$(0.5 \pm 0.2) \times 10^{-3}$			

Table : Total and partial decay widths of the different decay modes of the doubly charm states.

Results

State	*Channel i*	Γ^i [MeV]	*Channel j*	Γ^i_j [MeV]	$\Gamma_{\rm tot}$ [MeV]
$S_{cc}^{+}(4100)$	$D^0 D_s^{*+}$	12 ± 4	$D^0(D_s^+\gamma)$	11 ± 4	24 ± 8
	$D_s^+ D^{*0}$	12 ± 4	$D_s^+(D^0\pi^0)$	7 ± 2	
			$D_s^+(D^0\gamma)$	5 ± 2	
	$D^0 D_s^+ \gamma$	$(2 \pm 1) \times 10^{-3}$			
	$D^{*0} D_s^+ \gamma$	$(0.3 \pm 0.1) \times 10^{-3}$			
	$D_s^{*+} D^0 \gamma$	$(4 \pm 1) \times 10^{-3}$			
$S_{cc}^{++}(4100)$	$D^+ D_s^{*+}$	12 ± 4	$D^+(D_s^+\gamma)$	11 ± 4	24 ± 8
	$D_s^+ D^{*+}$	12 ± 4	$D_s^+(D^+\pi^0)$	4 ± 1	
			$D_s^+(D^0\pi^+)$	8 ± 3	
			$D_s^+(D^+\gamma)$	0.2 ± 0.1	
	$D^+ D_s^+ \gamma$	$(1.3 \pm 0.1) \times 10^{-4}$			
	$D^{*+} D_s^+ \gamma$	$(0.3 \pm 0.1) \times 10^{-3}$			
	$D_s^{*+} D^+ \gamma$	$(0.3 \pm 0.1) \times 10^{-3}$			

Table : Total and partial decay widths of the different decay modes of the doubly charm states.

Results

State	*Intermediate meson*	Γ_k [MeV]
$R_{cc}^+(3970)$	ρ	15.2
$(D^{*0} D^+)$	π	7.2
$(\Gamma = 22\,\mathrm{MeV})$	ω	1.7
	J/ψ	0.6
	η	0.14
	η_c	0.07
	η'	0.018
	$\rho + \pi$	30.0
	$\rho + \omega$	7.0
	$\pi + \omega$	6.0

Table : Decay width obtained for the channel DD^* and one meson exchanged.

State	*Intermediate meson*	Γ_k [MeV]
$S_{cc}^{+(+)}(4100)$	K^*	15.0
$(D^{*0(+)} D_s^+)$	K	4.3
$(\Gamma = 12\,\mathrm{MeV})$	J/ψ	1.7
	η	0.4
	η'	0.2
	η_c	0.19
	$K^* + K$	24.9
	$K^* + J/\psi$	9.8
	$J/\psi + K$	4.2

Table : Decay width obtained for the channel DD_s^* and one meson exchanged.

Conclusions

1. The double charm mesons are dynamically generated by the $DD^*_{(s)}$, $D^* D^*_{(s)}$ interactions
2. They are rather narrow: widths around 0, $30-55$ and $15-35$ MeV respectively for the $R_{cc}(3850)$, $R_{cc}(3970)$ and $S_{cc}(4100)$.
3. The transition $D^* D^* \to DD^*$ comes through anomalous couplings and is small.
4. The $D^* D^*$ states decay into DD^* and DD^*_s becoming $DD_{(s)}\pi$ and $DD_{(s)}\gamma$
5. Hopefully, will be able to observe in LHCb

The hidden gauge formalism

Starting from a nonlinear sigma model based on

$G/H = SU(2)_L \otimes SU(2)_R / SU(2)_V$: Bando,Kugo,Yamawaki

$$L = (f_\pi^2/4)\mathrm{Tr}(\partial_\mu U \partial^\mu U^\dagger) \; , \qquad U(x) = \exp[2i\pi(x)/f_\pi] \tag{20}$$

and introduce new variables ξ_L, ξ_R and the field V_μ:

$$U(x) \equiv \xi_L^\dagger(x)\xi_R(x) \; , \; V_\mu = (1/2i)(\partial_\mu \xi_L \cdot \xi_L^\dagger + \partial_\mu \xi_R \cdot \xi_R^\dagger) \tag{21}$$

Any linear combination $L = L_A + aL_V$ of the invariants:

$$L_V = -\frac{f_\pi^2}{4} Tr(D_\mu \xi_L \cdot \xi_L^\dagger + D_\mu \xi_R \cdot \xi_R^\dagger)^2 \quad L_A = -\frac{f_\pi^2}{4} Tr(D_\mu \xi_L \cdot \xi_L^\dagger - D_\mu \xi_R \cdot \xi_R^\dagger)^2$$

is equivalent to the original one. A kinetic term is added, $-(1/4g^2)(V_{\mu\nu})^2$, and choosing $a = 2$ it is obtained

- 1)$m_\rho^2 = 2g_{\rho\pi\pi}^2 f_\pi^2$ (KSFR relation)
- 2)ρ dominance of the electromagnetic form factor of pions
  $(gV_\mu(\pi \times \partial^\mu \pi))$

And, fixing the gauge $\xi_L^\dagger = \xi_R \equiv \xi$ the Lagrangian becomes in the Weinberg's Lagrangian (nonlinear realization of the chiral symmetry)