Molecular interpretation of the XYZ states

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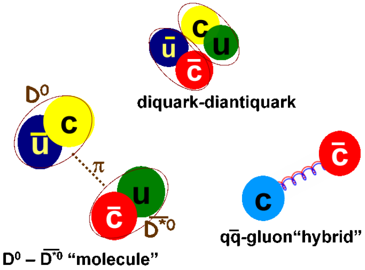


The XYZ particles

Ann. Rev. Nucl. Part. Sci. 2008. 58:51-73. S. Godfrey and S. L. Olsen

state	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR), J/ψ decay
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi, \gamma J/\psi$	$B \to KX(3872)$, $p\bar{p}$
$X(3875)$	3875.5 ± 1.5	$3.0^{+2.1}_{-1.7}$		$D^0\bar{D}^0\pi^0$	$B \to KX(3875)$
$Z(3940)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma$
$X(3940)$	3942 ± 9	37 ± 17	J^{P+}	$D\bar{D}*$	$e^+e^- \to J/\psi X(3940)$
$Y(3940)$	3943 ± 17	87 ± 34	J^{P+}	$\omega J/\psi$	$B \to KY(3940)$
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
$X(4160)$	4156 ± 29	139^{+113}_{-65}	J^{P+}	$D^*\bar{D}*$	$e^+e^- \to J/\psi X(4160)$
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)
Y_b	$\sim 10,870$	?	1^{--}	$\pi^+\pi^- \Upsilon(nS)$	e^+e^-

Table: A summary of the properties of the candidate XYZ mesons discussed in the text. For simplicity, the quoted errors are quadratic sums of statistical and systematic uncertainties.

The XYZ particles

Some of the properties of the X(3872), X(3940), Y(3940), Z(3940) and X(4160) are

- They are just below of the $D\bar{D}^*$, $D^*_{(s)}\bar{D}^*_{(s)}$ thresholds
- They are relatively narrow
- The XYZ$\sim$3940 MeV and X(4160) have C-parity$= +$
- Some of them have estimated partial widths to $\omega J/\psi$ or $\phi J/\psi$ above 1 MeV, quite larger than the measured partial decay widths for hadronic transitions between charmonium states

The hidden gauge formalism

Lagrangian

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

$$\mathcal{L}^{(2)} = \frac{1}{4} f^2 \langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + \chi^\dagger U \rangle \quad (2)$$

$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu} V^{\mu\nu}\rangle + \frac{1}{2} M_V^2 \langle [V_\mu - \frac{i}{g}\Gamma_\mu]^2 \rangle$$

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

$$P \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix}, \quad V_\mu \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}$$

Inclusion of spin-1 fields

$$\begin{aligned} V_{\mu\nu} &= \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu] \\ \Gamma_\mu &= \frac{1}{2}[u^\dagger(\partial_\mu - ieQA_\mu)u + u(\partial_\mu - ieQA_\mu)u^\dagger] \qquad u^2 = U \end{aligned} \tag{4}$$

$$\frac{F_V}{M_V} = \frac{1}{\sqrt{2}g}, \qquad \frac{G_V}{M_V} = \frac{1}{2\sqrt{2}g}, \qquad F_V = \sqrt{2}f, \qquad G_V = \frac{f}{\sqrt{2}}, \qquad g = \frac{M_V}{2f} \tag{5}$$

Upon expansion of $[V_\mu - \frac{i}{g}\Gamma_\mu]^2$

$\mathcal{L}'s$

$$\begin{aligned} \mathcal{L}_{V\gamma} &= -M_V^2 \frac{e}{g} A_\mu \langle V^\mu Q\rangle \\ \mathcal{L}_{V\gamma PP} &= egA_\mu \langle V^\mu (QP^2 + P^2Q - 2PQP)\rangle \\ \mathcal{L}_{VPP} &= -ig\langle V^\mu [P, \partial_\mu P]\rangle \\ \mathcal{L}_{\gamma PP} &= ieA_\mu \langle Q[P, \partial_\mu P]\rangle \\ \widetilde{\mathcal{L}}_{PPPP} &= -\frac{1}{8f^2}\langle [P, \partial_\mu P]^2\rangle. \end{aligned} \tag{6}$$

Vector-vector scattering

Bando,Kugo,Yamawaki

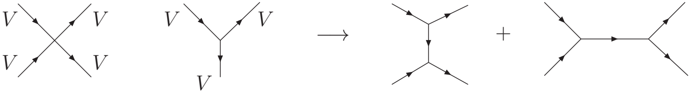
$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu} V^{\mu\nu}\rangle \rightarrow \mathcal{L}_{III}^{(3V)} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu) V^\mu V^\nu\rangle$$

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

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

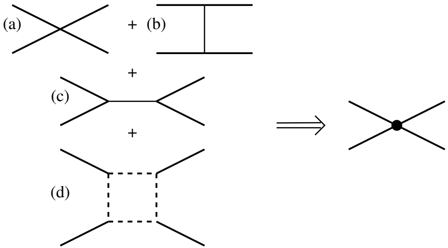
$$g = \frac{M_V}{2f}$$

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



a) b) c) d)

The VV interaction



- (a) and (b)$\rightarrow$ Pole mass and width
- (c) $\rightarrow$ p-wave repulsive (not include)
- (d)$\rightarrow$ Pole width

The hidden charm sector

We include all the possible channels $D^*\bar{D}^*$, $D_s^*\bar{D}_s^*$, $\omega J/\psi$, $\phi J/\psi$, $K^*\bar{K}^*$, $\rho\rho$, $\omega\omega$, ...
In principle we suppose SU(4) symmetric vertices:

$$V_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu , \qquad (7)$$

but...

- In the heavy - heavy sector we have ρ, ω (ϕ) exchange
- The heavy - heavy sector is conected to the light - light sector through D^*-exchange

The hidden charmed sector

1. The heavy meson exchange is suppressed by a factor $\kappa = \frac{m_\rho^2}{m_{D*}^2}$ Thesis of D. Gamermann, 2010 PP including $D\bar{D}$ mediated by $\rho(\omega)$ exchange; A. Ramos and T. Mizutani DN interaction PRC74 (2006), L. Tolos (Temperature) PRC77 (2008), Hyodo (see Wednesday talk's)

   D^*-exchange $\sim \frac{\kappa g^2}{M_\rho^2}(k_1 + k_4) \cdot (k_2 + k_3)$, $\kappa = \frac{M_\rho^2}{M_{D*}^2} \sim 0.15 \Longrightarrow$

   $$V(D^* - exchange) \simeq 10\%\ V(\rho - exchange)$$

   In PRD76 D. Gamermann, E. Oset, D. Strottman and M. J. Vacas, the chiral model and the phenomenological one lead to qualitatively the same results and small quantitative discrepancies

2. We vary g^2, evaluating for $g_\rho^2 \equiv g^2$, gg_D and g_D^2, with $g_\rho = m_\rho/2f_\pi$ and $g_{D*} = m_{D*}/2f_D$ (see uncertainties)

The hidden charm sector

Table taken from Phys.Rev. D76 (2007) 074016 (D. Gamermann et al.)

Channel	f_0 $\|\tilde{g}_i\|$ (GeV)	σ $\|\tilde{g}_i\|$ (GeV)	"X(3700)" $\|\tilde{g}_i\|$ (GeV)
$\pi\pi$	1.96	4.23	0.21
$K\bar{K}$	3.82	1.28	0.03
$\eta\eta$	4.47	0.47	0.00
$D\bar{D}$	0.71	4.08	10.41
$D_s\bar{D}_s$	3.73	0.49	6.73
$\eta\eta_c$	2.07	1.04	0.29

Table: Residues for the poles in the C=0, S=0, I=0 sector

The charm sector

The X(3872): see D. Gamermann Thesis page 97 and Phys.Rev. D80 (2009) 014003,Phys.Rev. D81 (2010) 014029

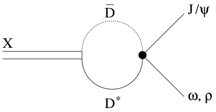
Channel	g_i [MeV]
$\frac{1}{\sqrt{2}}(K^*\bar{K}^* + cc)$	$5 - 17i$
$\frac{1}{\sqrt{2}}(D^*\bar{D} + cc)$	$7274 - 1i$
$\frac{1}{\sqrt{2}}(D_s^*\bar{D}_s^* - cc)$	$4857 + 0.3i$

Table: Residues for the pole at $(3866 - 0.003i)$ MeV in the $C = 0$; $S = 0$; $I = 0$ sector and positive C-parity

$$\frac{\mathcal{B}(X \to J/\psi\pi\pi)}{\mathcal{B}(X \to J/\psi\pi\pi\pi)} = \left(\frac{G_{11} - G_{22}}{G_{11} + G_{22}}\right)^2 \frac{\int_0^\infty q\mathcal{S}\left(s, m_\rho, \Gamma_\rho\right)\theta\left(m_X - m_{J/\psi} - \sqrt{s}\right) ds}{\int_0^\infty q\mathcal{S}\left(s, m_\omega, \Gamma_\omega\right)\theta\left(m_X - m_{J/\psi} - \sqrt{s}\right) ds} \frac{\mathcal{B}_\rho}{\mathcal{B}_\omega}$$

no ρ mass distribution, $R_{\rho/\omega} = 0.032$, with ρ mass dist. $R_{\omega/\rho} = 1.4$

The X(3872)



$$g_i G_{ii}^{\alpha} = \hat{\psi}_i$$

"Essentially the couplings are proportional to the value of the wave function at the origin in coordinate space or the averaged value within the range of the interaction. They are not sensitive to the wave function at long distances and the averaged value of the wave function at the origin is the only information that is needed when dealing with short range processes,"

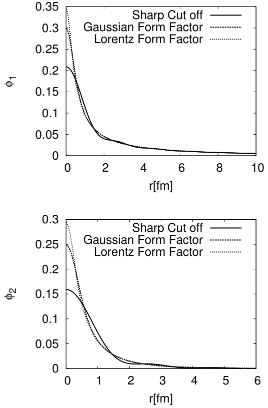


Figure: Wave functs. for different form factors in the potential.

HHChPT for heavy-heavy meson molecules

J. Nieves and M. P. Valderrama, arXiv:1204.2790 (2012)

- The fields $H_a^{(Q)}$ transform as a $(2, \bar{2})$ representation under the heavy quark spin $\otimes SU(2)_V$ isospin symmetry,
  $H_a^{(Q)} \rightarrow S(H^{(Q)} U^\dagger)_a$
- At leading order in the EFT expansion, the potential is the sum of a contact + pion exchange term (OPE)

$$V_{H\bar{H}}^{(0)}(\vec{q}) = C_0^{(0)} + \eta \frac{g^2}{2 f_\pi^2} \frac{(\vec{a}\cdot\vec{q})(\vec{b}\cdot\vec{q})}{\vec{q}^2 + m_\pi^2} \tag{8}$$

- To have bound states compatible with power counting,

$$|\Phi_B\rangle = G_0(E) V |\Phi_B\rangle \qquad O(V) = O(V G_0 V)$$
$$\frac{1}{C_0(\Lambda)} \sim \frac{\mu}{2\pi}(\gamma_B - \frac{2}{\pi}\Lambda) \tag{9}$$

with $\mu_B = \sqrt{-2\mu E_B}$.

HHChPT for heavy-heavy meson molecules

J. Nieves and M. P. Valderrama, arXiv:1204.2790 (2012)

J^{PC}	$H\bar{H}$	$^{2S+1}L_J$	$E(\Lambda = 0.5\,GeV)$	$E(\Lambda = 1\,GeV)$	Exp
0^{++}	$D\bar{D}$	$^1S_0$	3708	3720	-
1^{++}	$D^*\bar{D}$	$^3S_1 - ^3D_1$	Input	Input	3872
1^{+-}	$D^*\bar{D}$	$^3S_1 - ^3D_1$	3816	3823	-
0^{++}	$D^*\bar{D}^*$	$^1S_0 - ^5D_2$	Input	Input	3917
1^{+-}	$D^*\bar{D}^*$	$^3S_1 - ^3D_1$	3954	3958	3942
2^{++}	$D^*\bar{D}^*$	$^1D_2 - ^5S_2 - ^5S_2 - ^5G_2$	4015	4014	-

If the X(3872) is a molecular state, then there is a 2^{++} X(4015)

- D-wave probabilities small $1-4\%$ (pion exchange suppressed)
- Coupled channel effect small $|\Delta E_B| \simeq |E_B|(\frac{\gamma}{\Lambda_c})^2$
- Hidden gauge $D\bar{D}$: X(3700), $D\bar{D}^*$: X(3872), D. Gamermann (2007,2008)

The compositeness condition in $D_s^* \bar{D}_s^*$ molecules

T. Branz, T. Gutsche and V. E. Lyubovitskij, Phys.Rev. D80 (2009), assume the Y(3940) and Y(4140) are $D^*_{(s)} \bar{D}^*_{(s)}$ molecules with 0^{++} or 2^{++}

- "molecular content of the deuteron" Weinberg (1963)

$$\frac{g_{eff}^2}{4\pi} = 4(m_1 + m_2)^2 \lambda^2 \sqrt{2\epsilon/\mu} + O(\frac{\sqrt{2\mu\epsilon}}{\beta}) \leq 4(m_1 + m_2)^2 \sqrt{2\epsilon/\mu} + O(\frac{\sqrt{2\mu\epsilon}}{\beta}) \qquad (10)$$

- λ^2 gives the probability of finding the molecular states in the physical state
- Can be generalized to unstables particles if the width is narrow and for resonances very near to threshold (Varu'04):

$$\mathcal{L}_Y(x) = g_Y Y_{ij}(x) J_{Y_{ij}}(x) \to Z_Y = 1 - \Sigma'_Y(m_Y^2) = 0 \to g_{eff}^2 \qquad (11)$$

Part II

Results I

The XYZ particles

$$T_{ij} \approx \frac{g_i g_j}{s - s_{pole}} \,, \tag{12}$$

$$\sqrt{s}_{pole} = 3943 + i7.4,\ I^G[J^{PC}] = 0^+[0^{++}]$$

$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$
$18810 - i682$	$8426 + i1933$	$10 - i11$	$-22 + i47$	$1348 + i234$

$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$-1000 - i150$	$417 + i64$	$-1429 - i216$	$889 + i196$	$-215 - i107$

Table: Couplings g_i in units of MeV for $I = 0$, $J = 0$.

The XYZ particles

$$\sqrt{s}_{pole} = 3945 + i0,\ I^G[J^{PC}] = 0^-[1^{+-}]$$

$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$	$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$18489 - i0.78$	$8763 + i2$	$11 - i38$	0	0	0	0	0	0	0

Table: Couplings g_i in units of MeV for $I = 0$, $J = 1$.

$$\sqrt{s}_{pole} = 3922 + i26,\ I^G[J^{PC}] = 0^+[2^{++}]$$

$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$
$21100 - i1802$	$1633 + i6797$	$42 + i14$	$-75 + i37$	$1558 + i1821$

$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$-904 - i1783$	$1783 + i197$	$-2558 - i2289$	$918 + i2921$	$91 - i784$

Table: Couplings g_i in units of MeV for $I = 0$, $J = 2$.

The XYZ particles

$$\sqrt{s}_{pole} = 4169 + i66,\ I^G[J^{PC}] = 0^+[2^{++}]$$

$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$
$1225 - i490$	$18927 - i5524$	$-82 + i30$	$70 + i20$	$3 - i2441$

$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$1257 + i2866$	$2681 + i940$	$-866 + i2752$	$-2617 - i5151$	$1012 + i1522$

Table: Couplings g_i in units of MeV for $I = 0$, $J = 2$ (second pole).

$$\sqrt{s}_{pole} = 3919 + i74,\ I^G[J^{PC}] = 1^-[2^{++}]$$

$D^*\bar{D}^*$	$K^*\bar{K}^*$	$\rho\rho$	$\rho\omega$	$\rho J/\psi$	$\rho\phi$
$20267 - i4975$	$148 - i33$	0	$-1150 - i3470$	$2105 + i5978$	$-1067 - i2514$

Table: Couplings g_i in units of MeV for $I = 1$, $J = 2$.

The XYZ particles

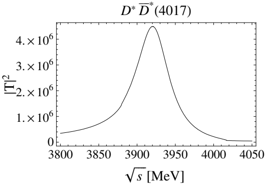


Figure: $|T|^2$ for $I = 0; J = 2$.

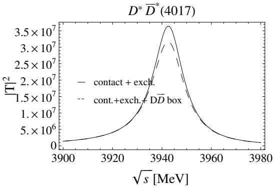


Figure: $|T|^2$ for $I = 0; J = 0$.

$$\Gamma((3943, 0^+[0^{++}]) \to \omega J/\psi) = \frac{p\,|g_{Y\omega J/\psi}|^2}{8\pi\, M_Y^2}$$

$$g_{Y\omega J/\psi} = (-1429 - i\,216)\ \mathrm{MeV}$$

$$\boxed{\Gamma((3943, 0^+[0^{++}]) \to \omega J/\psi) = 1.52\ \mathrm{MeV}}$$

The XYZ particles

$I^G[J^{PC}]$	Theory		Experiment			
	Mass [MeV]	Width [MeV]	Name	Mass [MeV]	Width [MeV]	J^{PC}
$0^+[0^{++}]$	3943	17	$Y(3940)$	3943 ± 17	87 ± 34	J^{P+}
				$3914.3^{+4.1}_{-3.8}$	33^{+12}_{-8}	
$0^-[1^{+-}]$	3945	0	"$Y_p(3945)$"			
$0^+[2^{++}]$	3922	55	$Z(3930)$	3929 ± 5	29 ± 10	2^{++}
$0^+[2^{++}]$	4157	102	$X(4160)$	4156 ± 29	139^{+113}_{-65}	J^{P+}
$1^-[2^{++}]$	3912	120	"$Y_p(3912)$"			

Table: Comparison of the mass, width and quantum numbers with the experiment.

Heavy quark spin symmetry?

In our model we can build the matrices for $I = 0, J = 0$: $T^{(0)}$ with $T_{11}^{(0)} = t(D\bar{D} \to D\bar{D})$, $T_{12}^{(0)} = t(D\bar{D} \to D^*\bar{D}^*)$ and $T_{22}^{(0)} = t(D^*\bar{D}^* \to D^*\bar{D}^*)$,

$$\begin{pmatrix} -\frac{2g^2}{m_\rho^2}(s-u) & \text{int. pseudos.} \\ \text{int. pseudos.} & -\frac{2g^2}{m_\rho^2}(s-u) \end{pmatrix} \qquad (13)$$

where $t(D^*(q_1)\bar{D}^*(q_2) \to D(q_3)\bar{D}(q_4)) \sim \frac{g^2}{q^2-m_\pi^2}\epsilon_1^\mu q_{3\mu}\epsilon_2^\nu q_{4\nu}$.

Close to the threshold, $\epsilon_1^\mu q_{3\mu} \sim -\epsilon_1^i q_3^i$, and in the c.m. frame,

$$t(D^*\bar{D}^* \to D\bar{D}) \sim \frac{g^2 q_{3,z}^2}{m_D^2 - m_{D^*}^2 - m_\pi^2} \sim \frac{g^2(m_{D^*}^2 - m_D^2)}{m_D^2 - m_{D^*}^2 - m_\pi^2} \sim g^2 \qquad (14)$$

There's a cancellation between the box and the contact term and our potential for $\rho(\omega, \phi)$ exchange corresponds to $C_{0b} = 0$ of the HHChPT Lagrangian

For $I=0, J=1$,
$T^{(1)}_{11}=t(D^*\bar{D}^*\to D^*\bar{D}^*)$, $T^{(1)}_{22}=t(D^*\bar{D}\to D^*\bar{D})$,
$T^{(1)}_{33}=t(D\bar{D}^*\to D\bar{D}^*)$, $T^{(1)}_{12}=t(D^*\bar{D}^*\to D^*\bar{D})$,
$T^{(1)}_{13}=t(D^*\bar{D}^*\to D\bar{D}^*)$ and $T^{(1)}_{23}=t(D^*\bar{D}\to D\bar{D}^*)$

$$\left(\begin{array}{ccc} -\frac{2g^2}{m_\rho^2}(s-u) & \text{int. pseu.\&anomal.} & \text{int. pseu.\&anomal.} \\ \text{int. pseu.\&anomal.} & -\frac{2g^2}{m_\rho^2}(s-u)\epsilon\cdot\epsilon' & \text{int. pseu.\&anomal.} \\ \text{int. pseu.\&anomal.} & \text{int. pseu.\&anomal.} & -\frac{2g^2}{m_\rho^2}(s-u)\epsilon\cdot\epsilon' \end{array}\right) \quad (15)$$

For $I=0, J=2$,
$T^{(2)}=t(D^*\bar{D}^*\to D^*\bar{D}^*)=-\frac{2g^2}{m_\rho^2}(s-u)$
Same interaction for $D\bar{D}$, $D\bar{D}^*$, D^*D^* in the diagonal elements in the vector exchange terms

Heavy-heavy meson molecules

For the most important channel,

- $D\bar{D}$: $X(3700) \Rightarrow \varepsilon = m_D + m_{\bar{D}} - m_{X(3700)} = 30$ MeV
- $D\bar{D}^* + c.c$: $X(3875) \Rightarrow \varepsilon = m_{D^*} + m_{\bar{D}} - m_{X(3875)} = 5$ MeV
- D^*D^*: $X(3940) \Rightarrow \varepsilon = m_{D^*} + m_{\bar{D}^*} - m_{X(3940)} = 70$ MeV

Weinberg's formula for the deuteron:

$$\frac{g_{eff}^2}{4\pi} = 4(m_1 + m_2)^2 \sqrt{\frac{2\varepsilon}{\mu}}(1 + 0(\sqrt{\frac{2\mu\varepsilon}{\beta}})) \tag{16}$$

We can compare with our couplings (units of MeV):

	Weinberg formula	hidden gauge
X(3700)	13300	10400
X(3875)	8760	7270
X(3940)	18000	18800

Differences of the $10 - 20\%$ or less.

Decay of the $X(3872) \to J/\psi\gamma$

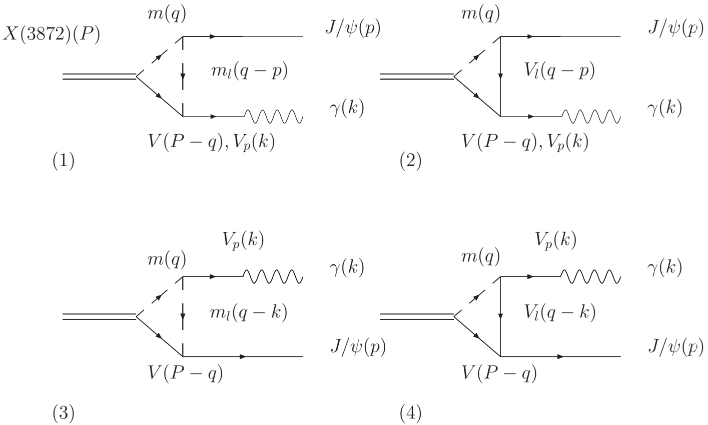


Figure: Different types of Feynmann diagrams for the decay of the X(3872) into $J/\psi\gamma$, with $m = D^0, D^+, D^-, \bar{D}^0, D_s^-$ or D_s^+, and $V = D^{*0}, D^{*+}, D^{*-}, \bar{D}^{*0}$ or D_s^{*-}, D_s^{*+}.

Decay of the $X(3872) \to J/\psi\gamma$

For diagram (4), we obtain:

$$t = -eG' g_X^c \mathrm{F}_2 k_\gamma \epsilon_\delta^{(\gamma)} \epsilon^{\alpha\beta\gamma\delta} \{ (a_1 \epsilon_\alpha^{(X)} + (c_1 k^\mu + e_1 p^\mu) \epsilon_\mu^{(X)} p_\alpha) \epsilon_\beta^{(J/\psi)} + (a_2 \epsilon_\alpha^{(J/\psi)} + c_2 \epsilon_\mu^{(J/\psi)} k^\mu p_\alpha) \epsilon_\beta^{(X)} \} \quad (17)$$

$$\begin{aligned} a_1 &= -\frac{G(p)}{4} - \frac{1}{64\pi^2} \int_0^1 dx \int_0^x dy \frac{(py)^2 + 2pky(y-x) - m_{V_l}^2}{s_4 + i\epsilon} \\ e_1 &= \frac{1}{16\pi^2} \int_0^1 dx \int_0^x dy \frac{y(y+1)}{s_4 + i\epsilon} \\ c_1 &= \frac{1}{16\pi^2} \int_0^1 dx \int_0^x dy \frac{y(y-x)}{s_4 + i\epsilon} \\ a_2 &= -2a_1 \\ c_2 &= -2c_1 \end{aligned} \quad (18)$$

$$s_4 = -m_{V_l}^2 + (m_{V_l}^2 - m^2)x + (p^2 - m_V^2 + m^2)y + 2kyp(x-y) - p^2 y^2 \quad (19)$$

Decay of the $X(3872) \to J/\psi\gamma$

Theory			Experiment
state	$\Gamma(KeV)$	Ref.	$\Gamma(KeV)$
$c\bar{c}$	11	E. Braaten (2004)	> 21 (Babar)
	139	E.S. Swanson (2004)	
	$11 - 71$	Y. Dong (2011)	
$c\bar{c}$+molecule	$2 - 17$	Y. Dong (2011)	
molecule	8	E.S. Swanson (2004)	
	$125 - 250$	Y. Dong (2008)	
molecule	56 ± 20	Present calc.	
tetraquark	$10 - 20$	S. Dubnicka (2011)	

$$\frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\pi\pi)} = 0.18\ (0.17 \pm 2\,exper.)$$

Radiative decays of the XYZ in $\gamma\gamma$ and $V\gamma$

	T. Branz			Present work		
state	$D^*\bar{D}^*$		$D_s^*\bar{D}_s^*$	$D^*\bar{D}^*$		$D_s^*\bar{D}_s^*$
J^{PC}	0^{++}	2^{++}	2^{++}	0^{++}	2^{++}	2^{++}
$\Gamma_{\gamma\gamma}$ [KeV]	0.33	0.27	0.50	0.031	0.059	0.25
$\Gamma_{\omega J/\psi}$ [MeV]	5.47	7.48		1.52	8.66	12.02
$\Gamma_{\gamma\gamma}\mathcal{B}(X \to \omega J/\psi)$ [eV]	54.7	69.6		1.46	17.6	
$\Gamma^{\rm exp}_{\gamma\gamma}\mathcal{B}(X \to \omega J/\psi)$ [eV]	61	18		61	18	

Table: Comparison with the work of T. Branz and the experiment. To evaluate the branching ratios we have used the experimental central values of the widths of the Y(3940) and Z(3930), $\Gamma = 33^{+12}_{-8}$ MeV and 29 ± 10 MeV

Conclusions

- HHChPT and hidden gauge theory leads to some “compatible” predictions on the existence of $D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$ meson molecules
- Coupled channel ($D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$) and pion exchange have small effects
- ρ, ω, ϕ exchange plays an important role in the heavy meson - heavy meson “molecules “

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, Eq. (20). 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)