Heavy quark molecules and heavy quark symmetry

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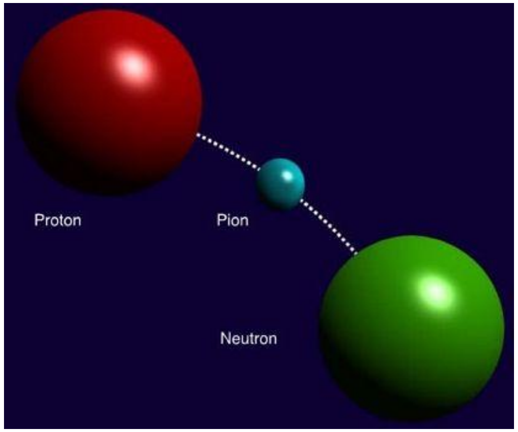
Constraints with heavy quark symmetry

- (I): $Q\bar{Q}$ spin in meson-antimeson molecules
- (II): Strong decays
- (III): Coupled channel effects for exotic JPC

Hadronic bound state: Deuteron

- Shallow NN bound state: ~(pn-np)

  I=0, J=1 $\vec{J} = \vec{L} + \vec{S}$



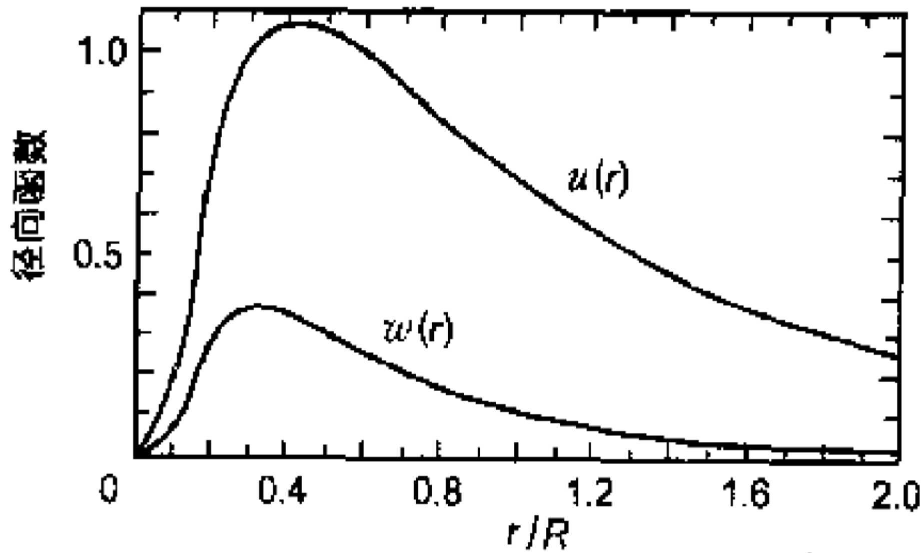
(L=0,2; S=1)

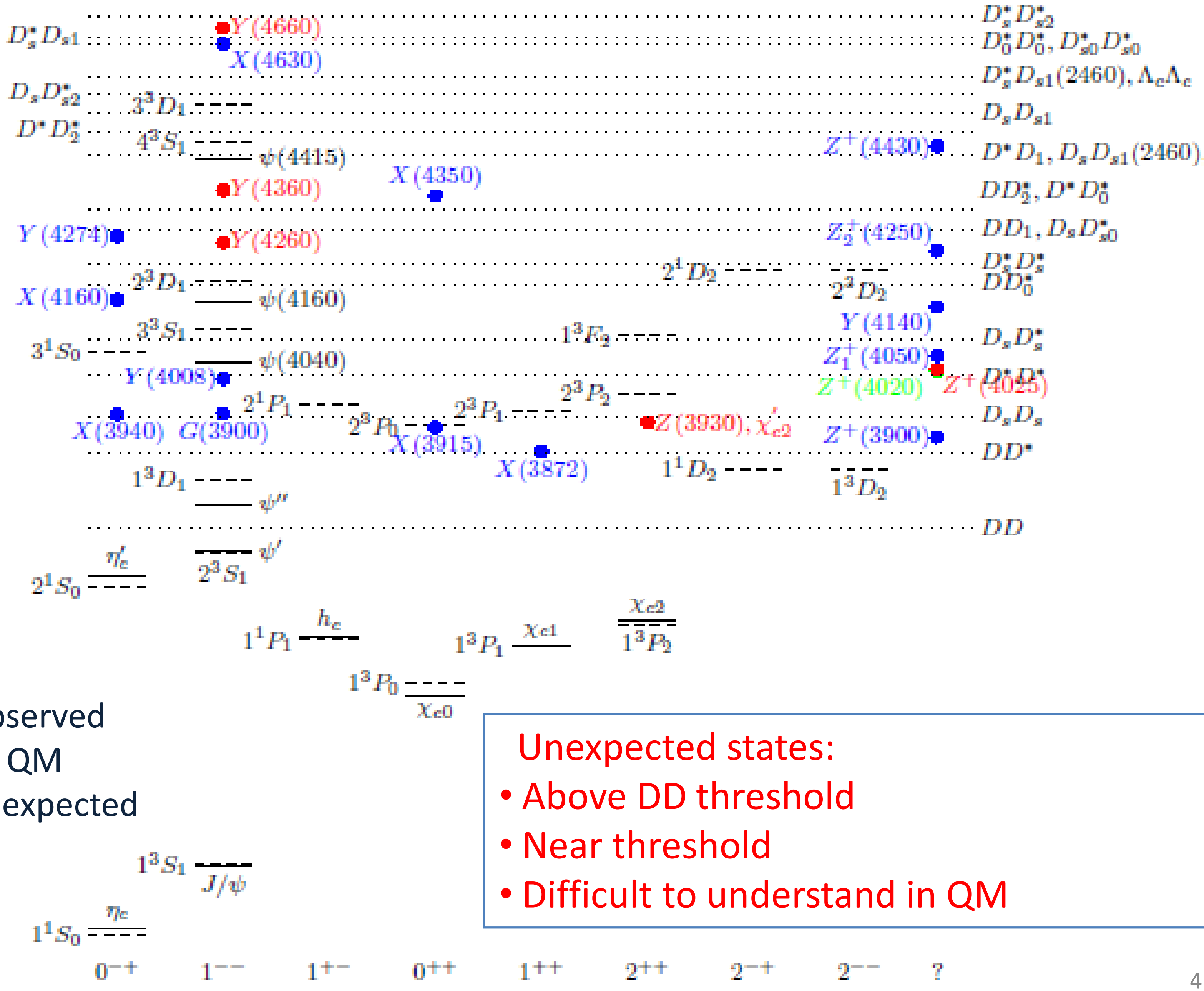
- B.E.≈2.2 MeV

  S-wave: 96%;

  D-wave: 4%

- Tensor force important





Solid: observed
Dashed: QM
Dots: unexpected

Unexpected states:
- Above DD threshold
- Near threshold
- Difficult to understand in QM

Charged exotic mesons

$Z^+(4430)$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle[PRL100-14
					~~BaBar~~[PRD79-1
				$B \to K(\pi^+ J/\psi)$	~~Belle, BaBar~~
				$\bar{B}^0 \to J/\psi K^-\pi^+$	Belle[1408.6457]
	$4475 \pm 7^{+15}_{-25}$	$172 \pm 13^{+37}_{-34}$	1^+	$B^0 \to \psi' K^+\pi^-$	LHCb[1404.1903
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle[PRD78-07
					~~BaBar~~[PRD85-0
$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle[PRD78-07
					~~BaBar~~[PRD85-0
$Z_c(3900)^+$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	?	$e^+e^- \to \pi^-(\pi^+ J/\psi)$	BES[PRL110,25
	$3894.5 \pm 6.6 \pm 4.5$	$63 \pm 24 \pm 26$	?	$e^+e^- \to \pi^-(\pi^+ J/\psi)$	Belle[PRL110,25
	$3885 \pm 5 \pm 1$	$34 \pm 12 \pm 4$	?	$e^+e^- \to \pi^+\pi^- J/\psi$	Cleo-c data[1304
				$e^+e^- \to \pi^+\pi^- h_c$	~~BES~~[1309.1896]
$Z_c(3885)^+$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$	1^+	$e^+e^- \to (D\bar{D}^*)^\pm\pi^\mp$	BES[1310.1163]
$Z_c(4020)^+$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	?	$e^+e^- \to \pi^\mp(\pi^\pm h_c)$	BES[1309.1896]
	$4023.9 \pm 2.2 \pm 3.8$	Same	?	$e^+e^- \to \pi^0(\pi^0 h_c)$	BES[1409.6577]
$Z_c(4025)$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	?	$e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$	BES[1308.2760]
$Z_c(4200)$	4196^{+31+17}_{-29-13}	$370^{+70+70}_{-70-132}$	$1^+(?)$	$\bar{B}^0 \to J/\psi K^-\pi^+$	Belle[1408.6457]

- $Z_b(10610)$, $Z_b(10650)$:

$N_{quark} \geq 4$

$$\pi^\pm \Upsilon(nS) \quad \pi^\pm h_b(mP)$$

PRL 108, 122001 (2012) [Belle]

Heavy quark symmetry

- Heavy quark molecules (hadronic bound states)?

- Heavy quark symmetry (HQS) important in studying internal structures & interactions

- Discuss results constrained with HQS

Heavy quark symmetry

- For $Q\bar{q}$ mesons

  (1) spin doublets

Degenerate doublets $\Rightarrow$

$$H^{L=0}_{j_\ell=\frac{1}{2}} = \begin{pmatrix} (\bar{q}Q)_{J^P=0^-} \\ (\bar{q}Q)_{J^P=1^-} \end{pmatrix}, \qquad m_D = m_{D^*},$$

$$H^{L=1}_{j_\ell=\frac{1}{2}} = \begin{pmatrix} (\bar{q}Q)_{J^P=0^+} \\ (\bar{q}Q)_{J^P=1^+} \end{pmatrix}, \qquad m_{D_0} = m_{D_1'},$$

$$H^{L=1}_{j_\ell=\frac{3}{2}} = \begin{pmatrix} (\bar{q}Q)_{J^P=1^+} \\ (\bar{q}Q)_{J^P=2^+} \end{pmatrix}, \qquad m_{D_1} = m_{D_2},$$

$$\cdots$$

  (2) chiral multiplets

Degenerate before chiral symmetry breaking $\Rightarrow$ $\begin{pmatrix} 0^- \\ 1^- \end{pmatrix}$ $\xleftrightarrow{\text{Chiral partner}}$ $\begin{pmatrix} 0^+ \\ 1^+ \end{pmatrix}$

Bardeen, Eichten, Hill, PRD 68, 054024 (2003).

Heavy quark symmetry

- For $Q\bar{Q}$ mesons, $m^{2S+1}L_J$. Only heavy quark spin symmetry

$$H_m^{L=0} = \begin{pmatrix} (Q\bar{Q})_{S=0,J^{PC}=0^{-+}} \\ (Q\bar{Q})_{S=1,J^{PC}=1^{--}} \end{pmatrix}, \qquad m_{\eta_c} = m_{J/\psi},$$

$$H_m^{L=1} = \begin{pmatrix} (Q\bar{Q})_{S=0,J^{PC}=1^{+-}} \\ (Q\bar{Q})_{S=1,J^{PC}=0^{++}} \\ (Q\bar{Q})_{S=1,J^{PC}=1^{++}} \\ (Q\bar{Q})_{S=1,J^{PC}=2^{++}} \end{pmatrix}, \qquad m_{h_c} = m_{\chi_{c0}} = m_{\chi_{c1}} = m_{\chi_{c2}},$$

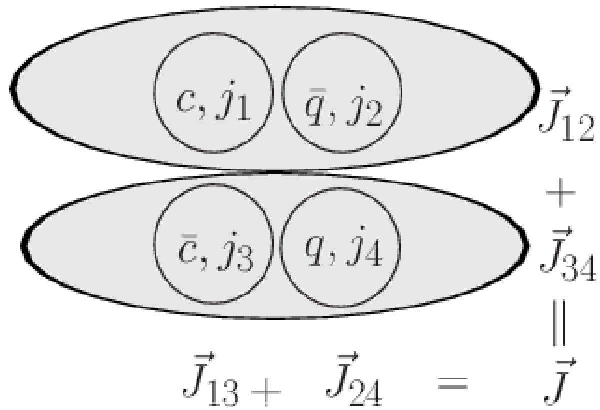
$$\cdots$$

$S_{Q\bar{Q}}$ conserved

Casalbuoni et al, PLB302,95 (1993)

(I): $Q\bar{Q}$ spin in meson-antimeson molecues

Recoupling:



- S-wave $A\bar{B} \pm B\bar{A}$: only $S_{c\bar{c}} = 1$

  (1) $J = max(J_\ell) + 1$ or $J = min(J_\ell) - 1$

  (2) $J^C = 1^+, 2^-, 3^+, \cdots$ if (A,B) form a doublet

YRL, PRD.88,074008(2013)

(I): $Q\bar{Q}$ spin in meson-antimeson molecues

- Hosaka et al in PRD 86, 117502 (2012) :

  P-wave $B\bar{B}^*$ with $J^{PC}=J^{--}$, only $S_{c\bar{c}}=1$

- L-wave case:

$$\chi_J = \frac{1}{\sqrt{2}}\left\{(j_1\bar{j}_2)_{J_{12}}(\bar{j}_3 j_4)_{J_{34}} + C_X(-1)^{J-J_{12}-J_{34}}(j_3\bar{j}_4)_{J_{34}}(\bar{j}_1 j_2)_{J_{12}}\right\}$$

↓

$$\chi_J = \frac{1}{\sqrt{2}}\left\{(j_1\bar{j}_2)_{J_{12}}(\bar{j}_3 j_4)_{J_{34}} + C_X(-1)^{L+S-J_{12}-J_{34}}(j_3\bar{j}_4)_{J_{34}}(\bar{j}_1 j_2)_{J_{12}}\right\}$$

$\Rightarrow$For $B\bar{B}^*$, P-wave $J^{PC}=J^{--}$ and S-wave $J^{PC}=1^{++}$:

the same spin selection rule

Consistent results!

Selection rules & strong decays for $D\bar{D}^*$

$S_{Q\bar{Q}}$ conserved

State	J^C	J_{24}	Selection rule for $J_{c\bar{c}} \neq 0$
$D\bar{D}^*/D_0^*\bar{D}_1'$	$1^\pm$	$0,1$	$J^C = 1^+$
$D^*\bar{D}^*/D_1'\bar{D}_1'$	$0^+,1^-,2^+$	$0,1$	$J=2$
$D^*\bar{D}_1'$	$0^\pm,1^\pm,2^\pm$	$0,1$	$J=2$
$D^*\bar{D}_1/D_1'\bar{D}_1$	$0^\pm,1^\pm,2^\pm$	$1,2$	$J=0$
$D^*\bar{D}_2^*/D_1'\bar{D}_2^*$	$1^\pm,2^\pm,3^\pm$	$1,2$	$J=3$
$D_1\bar{D}_2^*$	$1^\pm,2^\pm,3^\pm$	$0\sim 3$	$J^C=1^+,2^-,3^+$
$D_2^*\bar{D}_2^*$	$0^+,1^-,2^+,3^-,4^+$	$0\sim 3$	$J=4$

$J_{c\bar{c}} = 1$ $\qquad$ $J_{c\bar{c}} = 0, 1$

$$I^G(J^{PC}) = 0^+(1^{++}),\quad 1^-(1^{++}),\quad 1^+(1^{+-}),\quad 0^-(1^{+-})$$

X(3872) $\qquad$ Not observed $\qquad$ Zc(3900) $\qquad$ Not observed

$Z_c(3885)?$

$J/\psi\pi\pi$

$\pi^0\chi_{cJ}$

$J/\psi\pi$

$\chi_{c0,1,2}\pi\pi$

$\eta_c\rho$

$h_c\pi$

Tetraquark?

(II):

Strong decays

- Hidden charm decay: (1406.6879)
- Open charm decay:

$\psi(nS) \rightarrow DD: DD^*: D^*D^*$ => 1:4:7

[Rujula, Georgi, Glashow, PRL 37,398 (76)]

$\psi(nD) \rightarrow DD: DD^*: D^*D^*$ => 5:5:2(?)

$\psi(nS) \rightarrow D_1D_1: D_1D_2: D_2D_2$ => 1:7:4 (?)

...

(III):

HQSS constraints

- For interactions: EFT

$$\mathcal{L}_{PP^*} = D_\mu P D^\mu P^\dagger - M_P^2 P P^\dagger + f_Q (P A^\mu P_\mu^{*\dagger} + P_\mu^* A^\mu P^\dagger) - \frac{1}{2} P^{*\mu\nu} P_{\mu\nu}^{*\dagger} + M_{P^*}^2 P^{*\mu} P_\mu^{*\dagger} + \frac{1}{2} g_Q \varepsilon_{\mu\nu\lambda\kappa} (P^{*\mu\nu} A^\lambda P^{*\kappa\dagger} + P^{*\kappa} A^\lambda P^{*\mu\nu\dagger}) , \quad (2.20)$$

T.M. Yan et a l., PRD46,1148 (1992)

HQSS $\Rightarrow$ $g = \frac{1}{2} f$

- With doublets

$$\mathcal{L} = g Tr[H \not{A} \gamma_5 \bar{H}] + g' Tr[S \not{A} \gamma_5 \bar{S}] + g'' Tr[T_\mu \not{A} \gamma_5 \bar{T}^\mu] + [h Tr[S \not{A} \gamma_5 \bar{H}] + h.c.] + [h' Tr[T^\mu A_\mu \gamma_5 \bar{S}] + h.c.] + \frac{h_1}{\Lambda_\chi} Tr[T^\mu (D_\mu \not{A}) \gamma_5 \bar{H}] + h.c. + \frac{h_2}{\Lambda_\chi} Tr[T^\mu (\not{D} A_\mu) \gamma_5 \bar{H}] + h.c.$$

$$H = \frac{1+\not{v}}{2}[P^{*\mu}\gamma_\mu + \delta_H P \gamma_5], \quad S = \frac{1+\not{v}}{2}[P_1'^\mu \gamma_\mu + \delta_S P_0^*],$$

$$T^\mu = \frac{1+\not{v}}{2} P_2^{*\mu\nu} \gamma_\nu + \delta_T \sqrt{\frac{3}{2}} P_1^\nu \gamma_5 [g_\nu^\mu - \frac{1}{3}\gamma_\nu(\gamma^\mu - v^\mu)]$$

Phys.Rep.281, 145

(III):

Meson-antimeson states: exotic J^{PC}

0^{--}	$D\bar{D}_0^*, D^*\bar{D}_1, D^*\bar{D}_1'$
0^{+-}	$D_1\bar{D}_1'$
1^{-+}	$D\bar{D}_1, D\bar{D}_1', D^*\bar{D}_0, D^*\bar{D}_1, D^*\bar{D}_1', D^*\bar{D}_2^*$
2^{+-}	$D_0^*\bar{D}_2^*, D_1\bar{D}_1', D_1\bar{D}_2^*, D_1'\bar{D}_2^*$
3^{-+}	$D^*\bar{D}_2^*$

$S_{c\bar{c}} = 1$

TABLE I: The meson-antimeson states with exotic J^{PC}.

Tensor force may also be important

States	Angular momentum	Channels 1	2	3	4	5	6	7	8
$D\bar{D}_0^*$	J=0	$^1S_0$							
$D^*\bar{D}_1, D^*\bar{D}_1', D_1\bar{D}_1'$	J=0	$^1S_0$	$^5D_0$						
	J=1	$^3S_1$	$^3D_1$	$^5D_1$					
	J=2	$^5S_2$	$^1D_2$	$^3D_2$	$^5D_2$	$^5G_2$			
$D^*\bar{D}_2^*, D_1\bar{D}_2^*, D_1'\bar{D}_2^*$	J=1	$^3S_1$	$^3D_1$	$^5D_1$	$^7D_1$	$^7G_1$			
	J=2	$^5S_2$	$^3D_2$	$^5D_2$	$^7D_2$	$^5G_2$	$^7G_2$		
	J=3	$^7S_3$	$^3D_3$	$^5D_3$	$^7D_3$	$^3G_3$	$^5G_3$	$^7G_3$	$^7I_3$

TABLE II: Coupled channels ($^{2S+1}L_J$) for various meson-antimeson systems.

(III):

Reformulated Lagrangian

$$V(NN \to NN): V(r) = V_C(r) + S_{ten} V_T(r)$$

$$V(NN \to N\Delta):$$

transition spin

- Spin-3/2: $$\Delta_\mu \equiv S_\mu \chi$$

$$\chi_{s_z=3/2} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad \chi_{s_z=1/2} = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \quad \chi_{s_z=-1/2} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}, \quad \chi_{s_z=-3/2} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

$$V(r) = V_C(r) + S_{ten} V_T(r)$$

- Now: mesonic case

(III):

Reformulated Lagrangian

$$\mathcal{L}_g = -\frac{2g}{f}\mathrm{Tr}\Big\{\Sigma_{V\mu}[\Phi_V\partial^\mu\mathcal{M}\Phi_V^\dagger] - \delta_H^\dagger S_V^\mu[\Phi_V\partial_\mu\mathcal{M}P^\dagger] - \delta_H S_V^{\dagger\mu}[P\partial_\mu\mathcal{M}\Phi_V^\dagger]\Big\},$$

$$\mathcal{L}_{g'} = -\frac{2g'}{f}\mathrm{Tr}\Big\{\Sigma_{A,\mu}[\Phi'_A\partial^\mu\mathcal{M}\Phi'^\dagger_A] - \delta_S^\dagger S_A^\mu[\Phi'_A\partial_\mu\mathcal{M}P_0^{*\dagger}] - \delta_S S_A^{\dagger\mu}[P_0^*\partial_\mu\mathcal{M}\Phi'^\dagger_A]\Big\},$$

$$\mathcal{L}_{g''} = -\frac{2g''}{f}\mathrm{Tr}\Big\{\Sigma_{T,\alpha}[\Phi_T(\partial^\alpha\mathcal{M})\Phi_T^\dagger] - \frac{5}{6}\Sigma_{A,\alpha}[\Phi_A(\partial^\alpha\mathcal{M})\Phi_A^\dagger]$$
$$-\delta_T^\dagger\sqrt{\frac{1}{6}}\Sigma_{TA,\alpha}[\Phi_T(\partial^\alpha\mathcal{M})\Phi_A^\dagger] - \delta_T\sqrt{\frac{1}{6}}\Sigma^\dagger_{TA,\alpha}[\Phi_A(\partial^\alpha\mathcal{M})\Phi_T^\dagger]\Big\},$$

$$[\Sigma_{V\mu},\Sigma_{V\nu}] = i\epsilon_{\mu\nu\alpha\beta}v^\alpha\Sigma_V^\beta$$

$$[\Sigma_{T\mu},\Sigma_{T\nu}] = -\frac{i}{2}\epsilon_{\mu\nu\alpha\beta}v^\alpha\Sigma_T^\beta$$

$$\mathcal{L}_h = -\frac{2h}{f}\mathrm{Tr}\Big\{v_\mu\Sigma_{AV}[\Phi'_A(\partial^\mu\mathcal{M})\Phi_V^\dagger] - \delta_S\delta_H^\dagger v^\mu[P_0^*(\partial_\mu\mathcal{M})P^\dagger]\Big\} + h.c.,$$

$$\mathcal{L}_{h'} = -\frac{h'}{f}\mathrm{Tr}\Big\{-2\Sigma^\mu_{TA}[\Phi_T(\partial_\mu\mathcal{M})\Phi'^\dagger_A] + \delta_T\sqrt{\frac{2}{3}}\Sigma^\mu_A[\Phi_A(\partial_\mu\mathcal{M})\Phi'^\dagger_A] + \delta_T\delta_S^\dagger\sqrt{\frac{8}{3}}S^\mu_A[\Phi_A(\partial_\mu\mathcal{M})P_0^{*\dagger}]\Big\} + h.c.,$$

$$\mathcal{L}_{h_\chi} = -\frac{2h_\chi}{f}\mathrm{Tr}\Big\{\Sigma^{\mu\alpha}_{TV}[\Phi_T(\partial_\mu\partial_\alpha\mathcal{M})\Phi_V^\dagger] - \delta_H^\dagger S_T^{\mu\nu}[\Phi_T(\partial_\mu\partial_\nu\mathcal{M})P^\dagger] - \delta_T\sqrt{\frac{1}{6}}\Sigma^{\mu\alpha}_{AV}[\Phi_A(\partial_\mu\partial_\alpha\mathcal{M})\Phi_V^\dagger]\Big\} + h.c.$$

(III):

Formalism: OPEP

$(D^* \bar{D}_2^*)_J$

Chiral quark model: g”=-g

$$V = I_f G^\pi \frac{g g'' m^3}{24\pi f^2}\left\{D_S V_c^{dir}(r) - D_T V_t^{dir}(r)\right\} + I_f G^\pi \frac{|h_\chi|^2 \mu^5}{8\pi f^2} c(-1)^J \left\{\frac{2}{15} C_S V_c^{cro}(r) + \frac{4}{21} C_{T_1} V_{t1}^{cro}(r) + \frac{1}{7} C_{T2} V_{t2}^{cro}(r)\right\}$$

- c: C-parity of the state;
- $I_f = 1\ (-3)$ for isovector (isoscalar);
- G^π=-1: G-parity of π meson

$$D_S = \frac{1}{2}[(\vec{\Sigma}_T \cdot \vec{\Sigma}_V) + (V \leftrightarrow T)], \quad D_T = \frac{1}{2}[(\vec{\Sigma}_T \cdot \vec{\Sigma}_V - 3\vec{\Sigma}_T \cdot \hat{r}\vec{\Sigma}_V \cdot \hat{r}) + (V \leftrightarrow T)],$$

$$C_S = \frac{1}{2}[(\Sigma_{TV}^{ij}\Sigma_{VT}^{ij}) + (V \leftrightarrow T)], \quad C_{T1} = \frac{1}{2}[(\Sigma_{TV}^{ij}\Sigma_{VT}^{ij} - 3\Sigma_{TV}^{ij}\hat{r}_j\Sigma_{VT}^{ij'}\hat{r}_{j'}) + (V \leftrightarrow T)],$$

$$C_{T2} = \frac{1}{2}\{[2(\Sigma_{TV}^{ij}\Sigma_{VT}^{ij}) - 20(\Sigma_{TV}^{ij}\hat{r}_j\Sigma_{VT}^{ij'}\hat{r}_{j'}) + 35(\Sigma_{TV}^{ij}\hat{r}_i\hat{r}_j)(T_{VT}^{i'j'}\hat{r}_{i'}\hat{r}_{j'})] + (V \leftrightarrow T)\},$$

Examples: Coupled channel effects

- $D\bar{D}_0$

state	$I^G(J^{PC})$	$\Lambda(GeV)$	$B.E.(Mev)$	$r_{rms}(fm)$
$D\bar{D}_0^*$	$0^-(0^{--})^\dagger$	$1.4 \sim 4$	$30 \sim 24$	$1.3 \sim 1.4$

binding solution always exists (EPJC70,183)

- $D^*\bar{D}_2$

$D^*\bar{D}_2^*$	$1^-(1^{-+})^\dagger$	$3.6 \sim 3.7$	$1.9 \sim 8.3$	$2.2 \sim 1.1$
	$0^+(2^{-+})$	$3.13 \sim 3.15$	$0.94 \sim 6.8$	$3.0 \sim 1.1$
	$0^+(3^{-+})^\dagger$	$2.3 \sim 2.5$	$0.58 \sim 9.6$	$3.9 \sim 1.0$

←S-wave

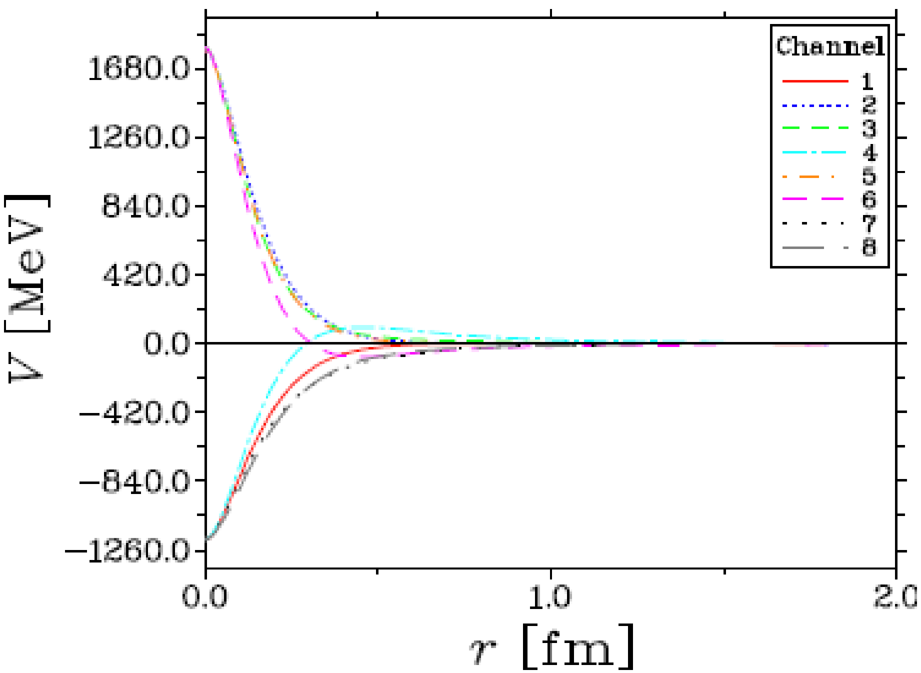
$D^*\bar{D}_2^*$	$1^-(1^{-+})^\dagger$	$3.4 \sim 3.5$	$3.0 \sim 11$	$1.8 \sim 0.97$
	$0^+(1^{-+})^\dagger$	$3.9 \sim 4$	$2.2 \sim 10$	$2.3 \sim 1.2$
	$0^+(2^{-+})$	$3.02 \sim 3.09$	$0.94 \sim 15$	$3.2 \sim 0.85$
	$0^+(3^{-+})^\dagger$	$2.0 \sim 2.3$	$0.91 \sim 16$	$3.3 \sim 0.94$

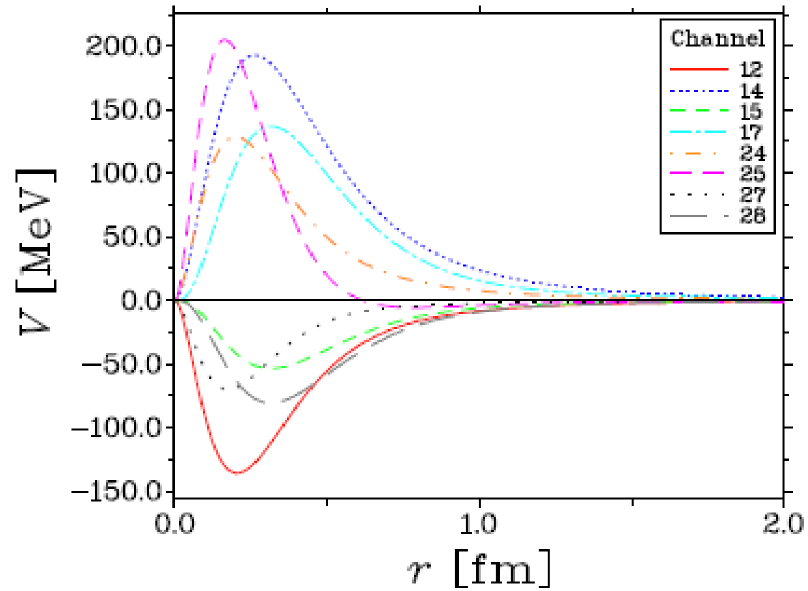
←C.C.

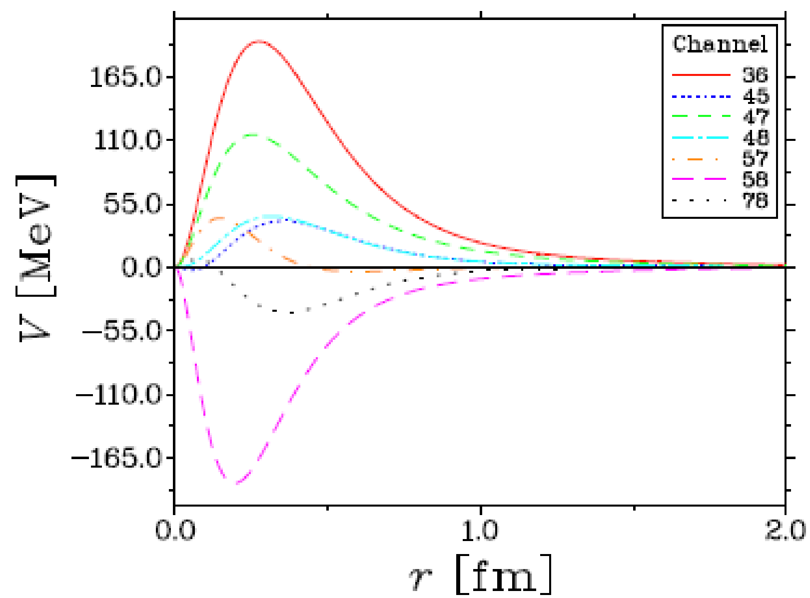
B.E. shift: 15~20 MeV

3^{-+} most attractive

C.C. effects (Λ=2.3 GeV)







- Reasons: V small or 0

Summary

- HQS constraints $Q\bar{Q}$ spin structure of hadrons
- HQS constraints strong decays
- Coupled channel effects are not very large for meson-antimeson states with exotic J^{PC} in OPEP model

Thank you for your attention!