Scalar, axial-vector and tensor resonances from $\rho(\omega)D^*$ and $D^*\bar{D}^*$, $D_s^*\bar{D}_s^*$

R. Molina[1], H. Nagahiro[3], A. Hosaka[3], D. Nicmorus[2], L. S. Geng[1] and E. Oset[1]

[1]Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain

[2]Fachbereich Theoretische Physik Institut für Physik Karl-Franzens-Universität Graz Universitätsplatz 5 A-8010 Graz, Austria

[3]Ibaraki, Osaka 567-0047, Japan

Outline

- Formalism: The *VV* interaction
- Generalization to SU(4)
  - The ρD^* system
  - The XYZ particles
- Conclusions

Formalism: The VV interaction

$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu}V^{\mu\nu}\rangle \tag{1}$$

$$\mathcal{L}_{III}^{(3V)} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle \tag{2}$$

$$\mathcal{L}_{III}^{(c)} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle \tag{3}$$

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

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

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

Formalism: The *VV* interaction

Approximation

$$\epsilon_1^\mu = (0,1,0,0)$$
$$\epsilon_2^\mu = (0,0,1,0)$$
$$\epsilon_3^\mu = (|\vec{k}|,0,0,k^0)/m$$

$$k^\mu = (k^0,0,0,|\vec{k}|)$$

$$\vec{k}/m \simeq 0,$$
$$k_j^\mu \epsilon_\mu^{(l)} \simeq 0$$

$$\epsilon_1^\mu = (0,1,0,0)$$
$$\epsilon_2^\mu = (0,0,1,0)$$
$$\epsilon_3^\mu = (0,0,0,1)$$

Spin projectors

$$\mathcal{P}^{(0)} = \frac{1}{3}\epsilon_\mu\epsilon^\mu\epsilon_\nu\epsilon^\nu$$
$$\mathcal{P}^{(1)} = \frac{1}{2}(\epsilon_\mu\epsilon_\nu\epsilon^\mu\epsilon^\nu - \epsilon_\mu\epsilon_\nu\epsilon^\nu\epsilon^\mu)$$
$$\mathcal{P}^{(2)} = \{\frac{1}{2}(\epsilon_\mu\epsilon_\nu\epsilon^\mu\epsilon^\nu + \epsilon_\mu\epsilon_\nu\epsilon^\nu\epsilon^\mu) - \frac{1}{3}\epsilon_\alpha\epsilon^\alpha\epsilon_\beta\epsilon^\beta\}$$

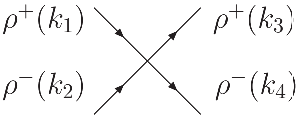
Formalism: The *VV* interaction

Example

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

$$t^{(I=1)} = 3g^2(\epsilon_\mu \epsilon_\nu \epsilon^\mu \epsilon^\nu - \epsilon_\mu \epsilon_\nu \epsilon^\nu \epsilon^\mu) \quad (4)$$

$$L + S + I = even \quad (5)$$

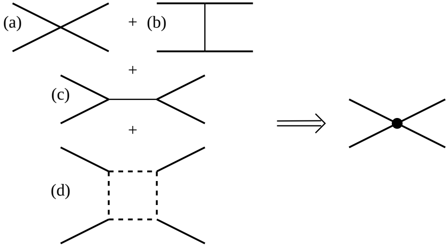


$$\mathcal{P}^{(1)} = \frac{1}{2}(\epsilon_\mu \epsilon_\nu \epsilon^\mu \epsilon^\nu - \epsilon_\mu \epsilon_\nu \epsilon^\nu \epsilon^\mu) \quad (6)$$

$$t^{(I=1,S=1)} \equiv 6g^2 \quad (7)$$

$$t^{(I=0,S=0)} = 8g^2 \qquad t^{(I=2,S=0)} = -4g^2$$
$$t^{(I=0,S=2)} = -4g^2 \qquad t^{(I=2,S=2)} = 2g^2$$

Formalism: The VV interaction



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

Bethe equation

$$T = [I - VG]^{-1}V \qquad G = \int_0^{q_{max}} \frac{q^2 dq}{(2\pi)^2} \frac{\omega_1+\omega_2}{\omega_1\omega_2[(P^0)^2-(\omega_1+\omega_2)^2+i\epsilon]}$$

Formalism: The VV interaction

$I^G(J^{PC})$	Theory	PDG data		
	(Mass,Width)	Name	Mass	Width
$0^+(0^{++})$	(1520,257-396)	$f_0(1370)$	1200∼1500	200∼500
$0^+(0^{++})$	(1720,133-151)	$f_0(1710)$	1724 ± 7	137 ± 8
$0^-(1^{+-})$	(1802,49)	h_1		
$0^+(2^{++})$	(1275,97-111)	$f_2(1270)$	1275.1 ± 1.2	$185.0^{+2.9}_{-2.4}$
$0^+(2^{++})$	(1525,45-51)	$f'_2(1525)$	1525 ± 5	73^{+6}_{-5}
$1^-(0^{++})$	(1777,148-172)	a_0		
$1^+(1^{+-})$	(1703,188)	b_1		
$1^-(2^{++})$	(1567,47-51)	$a_2(1700)$??		
$1/2(0^+)$	(1639,139-162)	K_0^*		
$1/2(1^+)$	(1743,126)	$K_1(1650)$?		
$1/2(2^+)$	(1431,56-63)	$K_2^*(1430)$	1429 ± 1.4	104 ± 4

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One step forward to $SU(4)$: The $\rho(\omega)D^*$ system

- In view of the good results of [1] and [2] we make attempt to pass to $SU(4)$ studying the $\rho(\omega)D^*$ system

$$V_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu , \qquad (8)$$

The $\rho(\omega)D^*$ system

$$\mathcal{L}_{III}^{(c)} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle \,, \tag{9}$$

$$\mathcal{L}_{III}^{(3V)} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle \,, \tag{10}$$

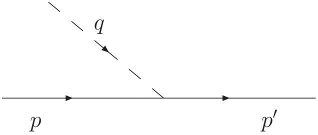


Figure: Terms of the $\mathcal{L}_{III}$ Lagrangian: a) four vector contact term, Eq. (2); b) three-vector interaction, Eq. (3); c) t and u channels from vector exchange; d) s channel for vector exchange.

The $\rho(\omega)D^*$ system

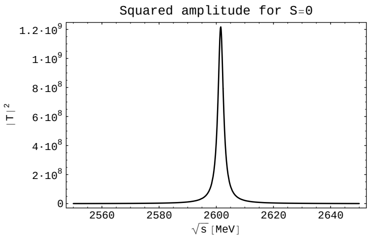
I	S	Contact	ρ-exchange	$\sim$ Total$[I(J^P)]$
$1/2$	0	$+5g^2$	$-2\frac{g^2}{M_\rho^2}(k_1+k_3)\cdot(k_2+k_4)$	$-15g^2[1/2(0^+)]$
$1/2$	1	$+\frac{9}{2}g^2$	$-2\frac{g^2}{M_\rho^2}(k_1+k_3)\cdot(k_2+k_4)$	$-15.5g^2[1/2(1^+)]$
$1/2$	2	$-\frac{5}{2}g^2$	$-2\frac{g^2}{M_\rho^2}(k_1+k_3)\cdot(k_2+k_4)$	$-22.5g^2[1/2(2^+)]$
$3/2$	0	$-4g^2$	$+\frac{g^2}{M_\rho^2}(k_1+k_3)\cdot(k_2+k_4)$	$+6g^2[3/2(0^+)]$
$3/2$	1	0	$+\frac{g^2}{M_\rho^2}(k_1+k_3)\cdot(k_2+k_4)$	$+10g^2[3/2(1^+)]$
$3/2$	2	$+2g^2$	$+\frac{g^2}{M_\rho^2}(k_1+k_3)\cdot(k_2+k_4)$	$+12g^2[3/2(2^+)]$

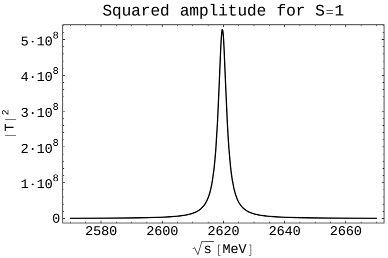
Table: $V(\rho D^* \to \rho D^*)$ for the different spin-isospin channels including the exchange of one heavy vector meson. The approximate Total is obtained at the threshold of ρD^*.

The $\rho(\omega)D^*$ system

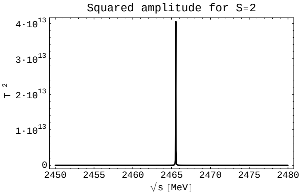
- $\omega D^* \to V \sim g^2$ is very small
- D^*-exchange $\sim \frac{\kappa g^2}{M_\rho^2}(k_1 + k_4)\cdot(k_2 + k_3)$, $\kappa = \frac{M_\rho^2}{M_{D^*}^2} \sim 0.15$

$$T = (1 - VG)^{-1} V \quad (11)$$





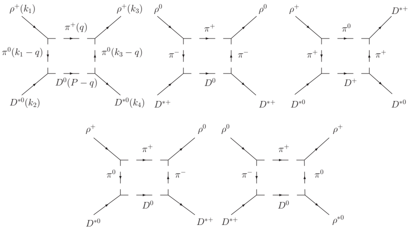
The $\rho(\omega)D^*$ system



Channel	$D_0^*(2600)$	$D_1^*(2640)$	$D_2^*(2460)$
ρD^*	14.32	14.04	17.89
ωD^*	0.53	1.40	2.35

Table: Modules of the couplings g_i in units of GeV.

- πD box: has $J = 0, 2$, not $J = 1$ (VV parity is +)



The $\rho(\omega)D^*$ system

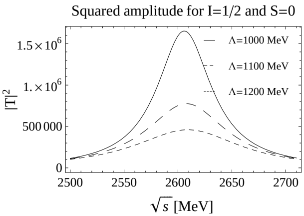
Form factor

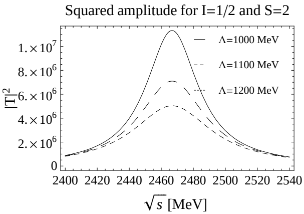
- $g^2_{\rho\pi\pi}\,(g^{exp}_{D^*D\pi})^2\,(e^{-\vec{q}^{\,2}/\Lambda^2})^4$
- $\mathcal{L}_{V\Phi\Phi} = -ig\langle V^\mu[\Phi, \partial_\mu\Phi]\rangle$

$$g_{\rho\pi\pi} = m_\rho/2f_\pi = 4.2$$

$$g^{exp}_{D^*D\pi} = 8.95\,MeV$$

(experimental value)





The $\rho(\omega)D^*$ system

$I^G(J^P)$	Theory	PDG data		
	(Mass,Width)	Name	Mass	Width
$1/2^+(0^+)$	(2608, 61)	"$D_0^*(2600)$"		
$1/2^+(1^+)$	(2620, 4)	$D^*(2640)$	2637	< 15
$1/2^+(2^+)$	(2465, 40)	$D^*(2460)$	2460	$37 - 43$

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- R. Molina, H. Nagahiro, A. Hosaka and E. Oset , arXiv:0903.3823[hep-ph]

The XYZ particles

- We apply the same formalism for $C(Charm) = 0$ and $S(Strangeness) = 0$
- Channels: $I = 0$

$$\mathbf{D^*\overline{D}^*}(4017),\ \mathbf{D_s^*\overline{D}_s^*}(4225),\ \mathbf{K^*\overline{K}^*}(1783),\ \rho\rho(1551),\ \omega\omega(1565)$$

$$\phi\phi(2039),\ \mathbf{J}/\psi\mathbf{J}/\psi(6194),\ \omega\mathbf{J}/\psi(3880),\ \phi\mathbf{J}/\psi(4116),\ \omega\phi(1802)$$

- $I = 1$:

$$\mathbf{D^*\overline{D}^*}(4017),\ \mathbf{K^*\overline{K}^*}(1783),\ \rho\rho(1551),\ \rho\omega(1558),\ \rho\mathbf{J}\psi(3872),\ \rho\phi(1795),$$

The XYZ particles

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

$$\sqrt{s}_{pole} = 3943 + i7.4$$

$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$
$18809 - i682$	$8430 + i1935$	$10 - i11$	$-22 + i47$	$1349 + i234$

$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$-1000 - i150$	$438 + i67$	$-1430 - i217$	$889 + i196$	$-215 - i107$

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

The XYZ particles

$$\sqrt{s}_{pole} = 3945 + i0$$

D^*D^*	$D_s^*D_s^*$	K^*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 $I = 0, S = 1$.

$$\sqrt{s}_{pole} = 3922 + i26$$

$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$
$21070 - i1788$	$1522 + i6755$	$41 + i16$	$-76 + i37$	$1571 + i1824$

$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$-885 - i1776$	$1945 + i235$	$-2599 - i2303$	$868 + i2902$	$116 - i774$

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

The XYZ particles

$$\sqrt{s}_{pole} = 4170 + i66$$

$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$
$1215 - i438$	$18890 - i5563$	$-84 + i31$	$69 + i21$	$33 - i2411$

$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$1277 + i2887$	$2934 + i1120$	$-941 + i2672$	$-2677 - i5218$	$1045 + i1560$

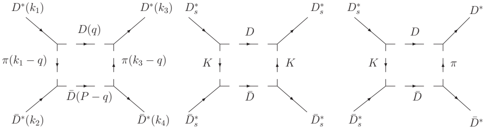
Table: Couplings g_i in units of MeV for $I = 0, S = 2$ (second pole).

$$\sqrt{s}_{pole} = 3919 + i74$$

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

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

The XYZ particles



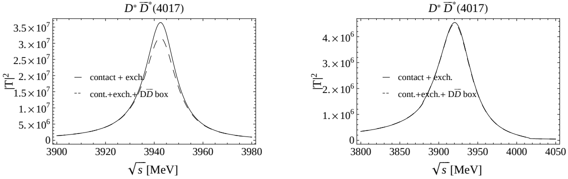


Figure: $|T|^2$ for $I=0, J=0$ (left) and $I=0, J=2$ (right).

The XYZ particles

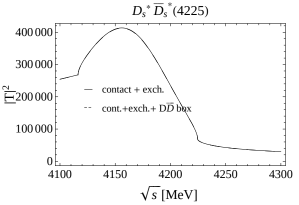


Figure: $|T|^2$ for $I = 0, J = 2$ (left) and $I = 1, J = 2$ (right).

The XYZ particles

Table: Summary of the candidate XYZ mesons by L. S. Olsen.

state	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi$, $D\bar{D}^*$
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$
$Z_1(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$
$Z_2(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$

The XYZ particles

$I^G(J^{PC})$	Theory	Experiment			
	(Mass,Width)	Name	Mass	Width	J^{PC}
$0^+(0^{++})$	(3943, 17)	Y(3940)?	3943 ± 17	87 ± 34	$?^{?+}$
$0^+(1^{+-})$	(3945, 0)	"Y(3945)"			
$0^+(2^{++})$	(3922, 55)	Z(3930)?	3929 ± 5	29 ± 10	2^{++}
$0^+(2^{++})$	(4157, 102)	X(4160)	4156 ± 29	139^{+113}_{-65}	$0^{?+}$
$1^+(2^{++})$	(3912, 120)	"Y(3912)"			

Conclusions

- We provide an explanation on why the $D^*(2640)$ must have $J = 1$
- We predict a new state: The "$D_0^*(2600)$" with $M = 2608$ MeV and $\Gamma = 61$ MeV
- We consider that the $D_0^*(2600)$, $D^*(2640)$ and $D_2^*(2460)$ are ρD^* molecular states
- We predict three resonances in $I = 0$ and $J = 0, 1, 2$ respectively with mass $\sim$ 3940 MeV that could be identified with some of the XYZ states and they are $D^*\bar{D}^*/D_s^*\bar{D}_s^*$ molecular states
- We find a state that could be identified with the $X(4160)$ and is basically composed by $D_s^*\bar{D}_s^*$

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