Decays of excited vector mesons

Milena Piotrowska[1]

F. Giacosa[1,2], C. Reisinger[2]

[1] Jan Kochanowski University, Kielce [2] Goethe University, Frankfurt

Sintra, May 9, 2017

Outline

1. Motivation
2. Introduction
3. Decays of excited vector mesons
   – The model
   – The results
4. Conclusions

Motivation

- Understanding of hadronic resonances.
- Study the decays of two nonets of excited vector mesons predominantly corresponding to 1^3D_1 and 2^3S_1.
- Making predictions for $\bar{s}s$ state in 1^3D_1 nonet.

J^{PC} classification

State	S	L	J	P	C	J^{PC}	Mesons	Name
$^1S_0$	0	0	0	-	+	0^{-+}	π η η' K	pseudoscalar
$^3S_1$	1	0	0	-	-	1^{--}	ρ ω ϕ K^*	vector
$^1P_1$	0	1	1	+	-	1^{+-}	b_1 h_1 h_1' K_1	pseudo-vector
$^3P_0$	1	1	0	+	+	0^{++}	a_0 f_0 f_0' K_0^*	scalar
$^3P_1$	1	1	1	+	+	1^{++}	a_1 f_1 f_1' K_1	axial vector
$^3P_2$	1	1	2	+	+	2^{++}	a_2 f_2 f_2' K_2^*	tensor

- Not all quantum numbers are permitted for a quark - antiquark states.

$$J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, \cdots$$

are exotic quantum numbers.

PDG quark-antiquark listing/1

Table 15.2: Suggested $q\bar{q}$ quark-model assignments for some of the observed light mesons. Mesons in bold face are included in the Meson Summary Table. The wave functions f and f' are given in the text. The singlet-octet mixing angles from the quadratic and linear mass formulae are also given for the well established nonets. The classification of the 0^{++} mesons is tentative: the light scalars $a_0(980)$, $f_0(980)$, $f_0(500)$ and $K_0^*(800)$ are often considered to be meson-meson resonances or four-quark states, and are omitted from the table. The isoscalar 0^{++} mesons are expected to mix. In particular, the $f_0(1710)$ mixes with the $f_0(1500)$ and the $f_0(1370)$. The $a_0(1450)$ is not firmly established. See the "Note on Non-$q\bar{q}$ mesons" and the "Note on Scalar Mesons" in the Meson Listings for details and alternative schemes. In the 1^{++} nonet the isoscalar slot is disputed by the $f_1(1510)$. The isoscalar assignments in the 2^1S_0 (0^{++}) nonet are also tentative. See the "Note on The Pseudoscalar and Pseudovector Mesons in the 1400 MeV Region" in the Meson Listings.

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\bar{d}$, $\bar{u}d$, $\frac{1}{\sqrt{2}}(d\bar{d}-u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s}$, $d\bar{s}$; $\bar{d}s$, $-\bar{u}s$	I = 0 f'	I = 0 f	θ_{quad} [°]	θ_{lin} [°]
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$	−11.4	−24.5
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$	39.1	36.4
$1\,^1P_1$	1^{+-}	$b_1(1235)$	K_{1B}†	$h_1(1380)$	$h_1(1170)$		
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$		
$1\,^3P_1$	1^{++}	$a_1(1260)$	K_{1A}†	$f_1(1420)$	$f_1(1285)$		
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$	32.1	30.5
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)$†	$\eta_2(1870)$	$\eta_2(1645)$		
$1\,^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)$		$\omega(1650)$		
$1\,^3D_2$	2^{--}		$K_2(1820)$				
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$	31.8	30.8
$1\,^3F_4$	4^{++}	$a_4(2040)$	$K_4^*(2045)$		$f_4(2050)$		
$1\,^3G_5$	5^{--}	$\rho_5(2350)$	$K_5^*(2380)$				
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$		
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$		
$2\,^3S_1$	1^{--}	$\rho(1450)$	$K^*(1410)$	$\phi(1680)$	$\omega(1420)$		

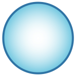
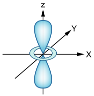
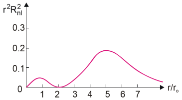
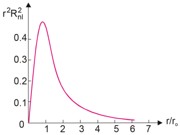
PDG quark-antiquark listing/2

Table 15.3: $q\bar{q}$ quark-model assignments for the observed heavy mesons with established J^{PC}. Mesons in bold face are included in the Meson Summary Table.

$n\,^{2s+1}\ell_J$	J^{PC}	I = 0 $c\bar{c}$	I = 0 $b\bar{b}$	I = $\frac{1}{2}$ $c\bar{u}$, $c\bar{d}$; $\bar{c}u$, $\bar{c}d$	I = 0 $c\bar{s}$; $\bar{c}s$	I = $\frac{1}{2}$ $b\bar{u}$, $b\bar{d}$; $\bar{b}u$, $\bar{b}d$	I = 0 $b\bar{s}$; $\bar{b}s$	I = 0 $b\bar{c}$; $\bar{b}c$
$1\,^1S_0$	0^{-+}	$\eta_c(1S)$	$\eta_b(1S)$	D	$D_s^{\pm}$	B	B_s^0	$B_c^{\pm}$
$1\,^3S_1$	1^{--}	$J/\psi(1S)$	$\Upsilon(1S)$	D^*	$D_s^{*\pm}$	B^*	B_s^*	
$1\,^1P_1$	1^{+-}	$h_c(1P)$	$h_b(1P)$	$D_1(2420)$	$D_{s1}(2536)^{\pm}$	$B_1(5721)$	$B_{s1}(5830)^0$	
$1\,^3P_0$	0^{++}	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$D_0^*(2400)$	$D_{s0}^*(2317)^{\pm\dagger}$			
$1\,^3P_1$	1^{++}	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$D_1(2430)$	$D_{s1}(2460)^{\pm\dagger}$			
$1\,^3P_2$	2^{++}	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$D_2^*(2460)$	$D_{s2}^*(2573)^{\pm}$	$B_2^*(5747)$	$B_{s2}^*(5840)^0$	
$1\,^3D_1$	1^{--}	$\psi(3770)$			$D_{s1}^*(2860)^{\pm\ddagger}$			
$1\,^3D_3$	3^{--}				$D_{s3}^*(2860)^{\pm}$			
$2\,^1S_0$	0^{-+}	$\eta_c(2S)$	$\eta_b(2S)$	$D(2550)$				
$2\,^3S_1$	1^{--}	$\psi(2S)$	$\Upsilon(2S)$		$D_{s1}^*(2700)^{\pm\ddagger}$			
$2\,^1P_1$	1^{+-}		$h_b(2P)$					
$2\,^3P_{0,1,2}$	$0^{++},1^{++},2^{++}$	$\chi_{c0,2}(2P)$	$\chi_{b0,1,2}(2P)$					
$3\,^3P_{0,1,2}$	$0^{++},1^{++},2^{++}$		$\chi_b(3P)$					

† The masses of these states are considerably smaller than most theoretical predictions. They have also been considered as four-quark states.
‡ These states are mixtures of the $1\,^3D_1$ and $2\,^3S_1$ states.
The open flavor states in the 1^{+-} and 1^{++} rows are mixtures of the $1^{+\pm}$ states.

Decays of excited vector mesons

Type of excitation	Radially excited vector mesons	Angular momentum excited vector mesons
Quantum numbers	$n\ ^{2S+1}L_J = 2^3S_1$	$n\ ^{2S+1}L_J = 1^3D_1$
Notation	V_E	V_D
S	1 $\uparrow\uparrow$	1 $\uparrow\uparrow$
n	2	1
L	0	2
orbital		
Radial function		
Associated states	$\rho(1450)$, $K^*(1410)$, $\phi(1680)$, $\omega(1420)$	$\rho(1700)$, $K^*(1680)$, ϕ_P, $\omega(1650)$
Decay types	$V_E \to PP$ $V_E \to VP$ $V_E \to \gamma P$	$V_D \to PP$ $V_D \to VP$ $V_D \to \gamma P$

Nonets of mesons

$$P = \begin{pmatrix} \frac{1}{\sqrt{2}} \frac{\eta_N + \pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta_N - \pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & \eta_S \end{pmatrix} \qquad V^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\omega^\mu + \rho^{\mu 0}}{\sqrt{2}} & \rho^{\mu +} & K_i^{\mu\star +} \\ \rho^{\mu -} & \frac{\omega^\mu - \rho^{\mu 0}}{\sqrt{2}} & K^{\mu\star 0} \\ K^{\mu\star -} & \bar{K}^{\mu\star 0} & \phi^\mu \end{pmatrix}$$

$$V_E^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\omega_E^\mu + \rho_E^{\mu 0}}{\sqrt{2}} & \rho_E^{\mu +} & K_E^{\mu\star +} \\ \rho_E^{\mu -} & \frac{\omega_E^\mu - \rho_E^{\mu 0}}{\sqrt{2}} & K_E^{\mu\star 0} \\ K_E^{\mu\star -} & \bar{K}_E^{\mu\star 0} & \phi_E^\mu \end{pmatrix} \qquad V_D^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\omega_D^\mu + \rho_D^{\mu 0}}{\sqrt{2}} & \rho_D^{\mu +} & K_D^{\mu\star +} \\ \rho_D^{\mu -} & \frac{\omega_D^\mu - \rho_D^{\mu 0}}{\sqrt{2}} & K_D^{\mu\star 0} \\ K_D^{\mu\star -} & \bar{K}_D^{\mu\star 0} & \phi_D^\mu \end{pmatrix}$$

- $P = \{\pi, K, \eta, \eta'\}$
- $V = \{\rho(770), K^*(892), \phi(1020), \omega(782)\}$
- $V_E = \{\rho(1450), K^*(1410), \phi(1680), \omega(1420)\}$
- $V_D = \{\rho(1700), K^*(1680), \phi_p, \omega(1650)\}$

The Lagrangian

The Lagrangian of the model is:

$$\mathcal{L} = \mathcal{L}_{1,E} + \mathcal{L}_{1,D} + \mathcal{L}_{2,E} + \mathcal{L}_{2,D},$$

where:

$$\mathcal{L}_{1,E} = ia_E Tr[\partial^\mu P, V_{E,\mu}]P \qquad \mathcal{L}_{1,D} = ia_D Tr[\partial^\mu P, V_{D,\mu}]P$$

$$\mathcal{L}_{2,E} = b_E Tr[\tilde{V}_E^{\mu\nu}\{V_{\mu\nu}, P\}] \qquad \mathcal{L}_{2,D} = b_D Tr[\tilde{V}_D^{\mu\nu}\{V_{\mu\nu}, P\}]$$

a_E, a_D, b_E, b_D- coupling constants of the different decay types.

- $R \to \gamma P$ through „vector meson dominance"

$$V_{\mu\nu} \to V_{\mu\nu} + \tfrac{e_0}{g_\rho} Q F_{\mu\nu}$$

$F_{\mu\nu}-$ field strength tensor for photons
$e_0 = \sqrt{4\pi\alpha} \quad \alpha \approx 1/137 \quad g_\rho \approx 5.5 \pm 0.5 \quad Q = diag(\tfrac{2}{3}, -\tfrac{1}{3}, -\tfrac{1}{3})$

=

$$\mathcal{L}_1 = ia\,\mathrm{Tr}\big[[\partial^\mu P, V_\mu]P\big] =$$

$$\frac{ia}{4}\Big\{K^{*0}_\mu\Big((\partial^\mu\overline{K}^0)\pi^0 - \overline{K}^0(\partial^\mu\pi^0) - \sqrt{2}(\partial^\mu K^-)\pi^+ + \sqrt{2}K^-(\partial^\mu\pi^+)$$
$$+ (\partial^\mu\eta_N)\overline{K}^0 - \eta_N(\partial^\mu\overline{K}^0) + \sqrt{2}\eta_S(\partial^\mu\overline{K}^0) - \sqrt{2}(\partial^\mu\eta_S)\overline{K}^0\Big)$$
$$+ \overline{K}^{*0}_\mu\Big(K^0(\partial^\mu\pi^0) - (\partial^\mu K^0)\pi^0 - \sqrt{2}K^+(\partial^\mu\pi^-) + \sqrt{2}(\partial^\mu K^+)\pi^-$$
$$+ \eta_N(\partial^\mu K^0) - (\partial^\mu\eta_N)K^0 - \sqrt{2}\eta_S(\partial^\mu K^0) + \sqrt{2}(\partial^\mu\eta_S)K^0\Big)$$
$$+ \mathrm{K}^{*-}_\mu\Big((\partial^\mu K^+)\pi^0 - K^+(\partial^\mu\pi^0) - \sqrt{2}K^0(\partial^\mu\pi^+) + \sqrt{2}(\partial^\mu K^0)\pi^+$$
$$+ \eta_N(\partial^\mu K^+) - (\partial^\mu\eta_N)K^+ - \sqrt{2}\eta_S(\partial^\mu K^+) + \sqrt{2}(\partial^\mu\eta_S)K^+\Big)$$
$$+ \mathrm{K}^{*+}_\mu\Big(K^-(\partial^\mu\pi^0) - (\partial^\mu K^-)\pi^0 - \sqrt{2}(\partial^\mu\overline{K}^0)\pi^- + \sqrt{2\overline{K}^0}(\partial^\mu\pi^-)$$
$$+ (\partial^\mu\eta_N)K^- - \eta_N(\partial^\mu K^-) + \sqrt{2}\eta_S(\partial^\mu K^-) - \sqrt{2}(\partial^\mu\eta_S)K^-\Big)$$
$$+ \rho^0_\mu\Big(\overline{K}^0(\partial^\mu K^0) - (\partial^\mu\overline{K}^0)K^0 + K^+(\partial^\mu K^-) - (\partial^\mu K^+)K^- + 2\pi^+(\partial^\mu\pi^-) - 2(\partial^\mu\pi^+)\pi^-\Big)$$
$$+ \rho^-_\mu\Big(\sqrt{2}K^+(\partial^\mu\overline{K}^0) - \sqrt{2}(\partial^\mu K^+)\overline{K}^0 + 2\pi^0(\partial^\mu\pi^+) - 2(\partial^\mu\pi^0)\pi^+\Big)$$
$$+ \rho^+_\mu\Big(\sqrt{2}K^0(\partial^\mu K^-) - \sqrt{2}(\partial^\mu K^0)K^- + 2(\partial^\mu\pi^0)\pi^- - 2\pi^0(\partial^\mu\pi^-)\Big)$$
$$+ \omega\Big(K^0(\partial^\mu\overline{K}^0) - (\partial^\mu K^0)\overline{K}^0 + K^+(\partial^\mu K^-) - (\partial^\mu K^+)K^-\Big)$$
$$+ \sqrt{2}\phi\Big((\partial^\mu K^0)\overline{K}^0 - K^0(\partial^\mu\overline{K}^0) - K^+(\partial^\mu K^-) + (\partial^\mu K^+)K^-\Big)\Big\}.$$

$$
\begin{aligned}
\mathcal{L}_2 &= b\,\mathrm{Tr}\big[\tilde{E}^{\mu\nu}\{V_{S,\mu\nu}, P\}\big] = 2b\,\epsilon^{\mu\nu\alpha\beta}\,\mathrm{Tr}\big[(\partial_\alpha E_\beta)\{(\partial_\mu V_{S,\nu}), P\}\big] \\
&= \frac{b}{2}\epsilon^{\mu\nu\alpha\beta}\Big\{(\partial_\alpha \rho^0_{E,\beta})\Big(2\pi^0(\partial_\mu\omega_\nu) + 2\eta_N(\partial_\mu\rho^0_\nu) - \overline{K}^0(\partial_\mu K^{*0}_\nu) - K^0(\partial_\mu \overline{K}^{*0}_\nu) + K^+(\partial_\mu K^{*-}_\nu) + K^-(\partial_\mu \\
&+ \sqrt{2}(\partial_\alpha \rho^-_{E,\beta})\Big(\sqrt{2}\pi^+(\partial_\mu\omega_\nu) + \sqrt{2}\eta_N(\partial_\mu\rho^+_\nu) + K^+(\partial_\mu \overline{K}^{*0}_\nu) + \overline{K}^0(\partial_\mu K^{*+}_\nu)\Big) \\
&+ \sqrt{2}(\partial_\alpha \rho^+_{E,\beta})\Big(\sqrt{2}\pi^-(\partial_\mu\omega_\nu) + \sqrt{2}\eta_N(\partial_\mu\rho^-_\nu) + K^-(\partial_\mu K^{*0}_\nu) + K^0(\partial_\mu K^{*-}_\nu)\Big) \\
&+ \sqrt{2}(\partial_\alpha \phi_{E,\beta})\Big(2\eta_S(\partial_\mu\phi_\nu) + K^0(\partial_\mu \overline{K}^{*0}_\nu) + \overline{K}^0(\partial_\mu K^{*0}_\nu) + K^+(\partial_\mu K^{*-}_\nu) + K^-(\partial_\mu K^{*+}_\nu)\Big) \\
&+ (\partial_\alpha \omega_{E,\beta})\Big(2\pi^0(\partial_\mu\rho^0_\nu) + 2\pi^+(\partial_\mu\rho^-_\nu) + 2\pi^-(\partial_\mu\rho^+_\nu) + 2\eta_N(\partial_\mu\omega_\nu) \\
&+ K^0(\partial_\mu \overline{K}^{*0}_\nu) + \overline{K}^0(\partial_\mu K^{*0}_\nu) + K^+(\partial_\mu K^{*-}_\nu) + K^-(\partial_\mu K^{*+}_\nu)\Big) \\
&+ (\partial_\alpha K^{*0}_{E,\beta})\Big(\overline{K}^0(\partial_\mu\omega_\nu) - \pi^0(\partial_\mu \overline{K}^{*0}_\nu) + \sqrt{2}\pi^+(\partial_\mu K^{*-}_\nu) - \overline{K}^0(\partial_\mu\rho^0_\nu) + \sqrt{2}K^-(\partial_\mu\rho^+_\nu) \\
&+ \eta_N(\partial_\mu \overline{K}^{*0}_\nu) + \sqrt{2}\eta_S(\partial_\mu \overline{K}^{*0}_\nu) + \sqrt{2}\overline{K}^0(\partial_\mu\phi_\nu)\Big) \\
&+ (\partial_\alpha \overline{K}^{*0}_{E,\beta})\Big(K^0(\partial_\mu\omega_\nu) - \pi^0(\partial_\mu K^{*0}_\nu) + \sqrt{2}\pi^-(\partial_\mu K^{*+}_\nu) - K^0(\partial_\mu\rho^0_\nu) + \sqrt{2}K^+(\partial_\mu\rho^-_\nu) \\
&+ \eta_N(\partial_\mu K^{*0}_\nu) + \sqrt{2}\eta_S(\partial_\mu K^{*0}_\nu) + \sqrt{2}K^0(\partial_\mu\phi_\nu)\Big) \\
&+ (\partial_\alpha K^{*-}_{E,\beta})\Big(K^+(\partial_\mu\omega_\nu) + \pi^0(\partial_\mu K^{*+}_\nu) + \sqrt{2}\pi^+(\partial_\mu K^{*0}_\nu) + K^+(\partial_\mu\rho^0_\nu) + \sqrt{2}K^0(\partial_\mu\rho^+_\nu) \\
&+ \eta_N(\partial_\mu K^{*+}_\nu) + \sqrt{2}\eta_S(\partial_\mu K^{*+}_\nu) + \sqrt{2}K^+(\partial_\mu\phi_\nu)\Big) \\
&+ (\partial_\alpha K^{*+}_{E,\beta})\Big(K^-(\partial_\mu\omega_\nu) + \pi^0(\partial_\mu K^{*-}_\nu) + \sqrt{2}\pi^-(\partial_\mu \overline{K}^{*0}_\nu) + K^-(\partial_\mu\rho^0_\nu) + \sqrt{2}\overline{K}^0(\partial_\mu\rho^-_\nu) \\
&+ \eta_N(\partial_\mu K^{*-}_\nu) + \sqrt{2}\eta_S(\partial_\mu K^{*-}_\nu) + \sqrt{2}K^-(\partial_\mu\phi_\nu)\Big)\Big\}
\end{aligned}
$$

Decay widths

TYPE OF DECAY

- $R \to PP$

$\Gamma_{R\to PP} = S\frac{|\vec{k}|^3}{6\pi m_R^2}[\frac{a_i}{2}\lambda_{RPP}]^2$

- $R \to VP, R \to \gamma P$

$\Gamma_{R\to VP} = S\frac{|\vec{k}|^3}{12\pi}[\frac{b_i}{2}\lambda_{RVP}]^2$

EXAMPLES

- $K^*(1410) \to K\eta$

$\Gamma_{K^*(1410)\to K\eta} = \frac{|\vec{k}|^3}{6\pi m_{K^*(1410)}^2}[\frac{a_E}{2}\frac{1}{2}(cos\theta_p - \sqrt{2}sin\theta_p)]^2$

- $\phi(1680) \to \phi(1020)\eta$

$\Gamma_{\phi(1680)\to\phi(1020)\eta} = \frac{|\vec{k}|^3}{12\pi}[\frac{b_E}{2}\frac{sin\theta_p}{\sqrt{2}}]^2$

where:

$|\vec{k}| = \frac{\sqrt{m_R^2 + (m_a^2 - m_b^2)^2 - 2(m_a^2 + m_b^2)m_R^2}}{2m_R}$;

m_R- mass of the decaying resonance;

a_i, b_i- coupling constants ($i = E, D$);

$\theta-$ mixing angle ($\theta = 42^{\circ}$);

m_a, m_b- masses of decay products;

$S-$ symmetry factor;

$\lambda-$ amplitude factor.

Preditions for ϕ_p state

- $s\bar{s}$ state in 1^3D_1 nonet - resonance not yet known.
- Mass of ϕ_p

V_E	$\rho(1450)$	$K^*(1410)$	$\phi(1680)$	$\omega(1420)$
V_D	$\rho(1700)$	$K^*(1680)$	ϕ_p	$\omega(1650)$
Difference	250 MeV	270 MeV	?	230 MeV

$$m_{\phi_p} \simeq m_{\phi(1680)} + 270MeV \simeq 1950MeV$$

Coupling constants a_E, b_E

- $\Gamma^{exp}_{K^*(1410)\to K\pi} = 15.3 \pm 3.3$ MeV

– $\Gamma^{theory}_{K^*(1410)\to K\pi} = 3\frac{|\vec{k}(m_{K^*(1410)}, m_K, m_\pi)|^3}{6\pi m^2_{K^*(1410)}}(\frac{a_E}{2}\frac{1}{2})^2$

- $\Gamma^{tot,exp}_{\phi(1680)} = 150 \pm 50$ MeV

– $\Gamma^{theory}_{\phi(1680)\to K^*(892)K} = 4\frac{|\vec{k}(m_{\phi(1680)}, m_K, m_{K^*(892)})|^3}{12\pi}(\frac{b_E}{2}\frac{1}{2\sqrt{2}})^2$

– $\Gamma^{theory}_{\phi(1680)\to \phi(1020)\eta} = \frac{|\vec{k}(m_{\phi(1680)}, m_{\phi(1020)}, m_\eta)|^3}{12\pi}(\frac{b_E}{2}\frac{sin\theta_p}{\sqrt{2}})^2$

– $\Gamma^{theory}_{\phi(1680)\to \bar{K}K} = 2\frac{|\vec{k}(m_{\phi(1680)}, m_K, m_K)|^3}{6\pi m^2_{\phi(1680)}}(\frac{a_E}{2}\frac{1}{\sqrt{2}})^2$

- $F(a_E, b_E) = (\frac{\Gamma^{theory}_{K^*(1410\to K\pi)}(a_E) - 15.3}{3.3})^2 + (\frac{\Gamma^{theory}_{\phi(1680)\to K^*(892)K} + \Gamma^{theory}_{\phi(1680)\to\phi(1020)\eta} + \Gamma^{theory}_{\phi(1680)\to\bar{K}K} - 150}{50})^2$

- $a_E \to 3.66 \pm 0.4$ $\qquad b_E \to 18.4 \pm 3.8$

Decay widths $R \rightarrow PP$

Decay channel		Symmetry factor	Amplitude
$V_E \rightarrow PP$	$V_D \rightarrow PP$		
$\rho(1450) \rightarrow \bar{K}K$	$\rho(1700) \rightarrow \bar{K}K$	2	$\frac{1}{2}$
$\rho(1450) \rightarrow \pi\pi$	$\rho(1700) \rightarrow \pi\pi$	1	1
$K^*(1410) \rightarrow K\pi$	$K^*(1680) \rightarrow K\pi$	3	$\frac{1}{2}$
$K^*(1410) \rightarrow K\eta$	$K^*(1680) \rightarrow K\eta$	1	$\frac{1}{2}(Cos\theta_p - \sqrt{2}Sin\theta_p)$
$K^*(1410) \rightarrow K\eta'$	$K^*(1680) \rightarrow K\eta'$	1	$\frac{1}{2}(\sqrt{2}Cos\theta_p + Sin\theta_p)$
$\phi(1680) \rightarrow \bar{K}K$	$\phi_p \rightarrow \bar{K}K$	2	$\frac{1}{\sqrt{2}}$
$\omega(1420) \rightarrow \bar{K}K$	$\omega(1650) \rightarrow \bar{K}K$	2	$\frac{1}{2}$

Decay widths $R \to VP$

Decay channel		Symmetry factor	Amplitude
$V_E \to VP$	$V_D \to VP$		
$\rho(1450) \to \omega\pi$	$\rho(1700) \to \omega\pi$	1	$\frac{1}{2}$
$\rho(1450) \to K^*(892)K$	$\rho(1700) \to K^*(892)K$	4	$\frac{1}{4}$
$\rho(1450) \to \rho(770)\eta$	$\rho(1700) \to \rho(770)\eta$	1	$\frac{1}{2}Cos\theta_p$
$\rho(1450) \to \rho(770)\eta'$	$\rho(1700) \to \rho(770)\eta'$	1	$\frac{1}{2}Sin\theta_p$
$K^*(1410) \to K\rho$	$K^*(1680) \to K\rho$	3	$\frac{1}{4}$
$K^*(1410) \to K\phi$	$K^*(1680) \to K\phi$	1	$\frac{1}{2\sqrt{2}}$
$K^*(1410) \to K\omega$	$K^*(1680) \to K\omega$	1	$\frac{1}{4}$
$K^*(1410) \to K^*(892)\pi$	$K^*(1680) \to K^*(892)\pi$	3	$\frac{1}{4}$
$K^*(1410) \to K^*(892)\eta$	$K^*(1680) \to K^*(892)\eta$	1	$\frac{1}{4}(Cos\theta_p + \sqrt{2}Sin\theta_p)$
$K^*(1410) \to K^*(892)\eta'$	$K^*(1680) \to K^*(892)\eta'$	2	$\frac{1}{4}(\sqrt{2}Cos\theta_p - Sin\theta_p)$
$\phi(1680) \to K\bar{K}^*$	$\phi_p \to K\bar{K}^*$	4	$\frac{1}{2\sqrt{2}}$
$\phi(1680) \to \phi(1020)\eta$	$\phi_p \to \phi(1020)\eta$	1	$\frac{1}{\sqrt{2}}Sin\theta_p$
$\phi(1680) \to \phi(1020)\eta'$	$\phi_p \to \phi(1020)\eta'$	1	$\frac{1}{\sqrt{2}}Cos\theta_p$
$\omega(1420) \to \rho\pi$	$\omega(1650) \to \rho\pi$	3	$\frac{1}{2}$
$\omega(1420) \to K^*(892)K$	$\omega(1650) \to K^*(892)K$	4	$\frac{1}{4}$
$\omega(1420) \to \omega(782)\eta$	$\omega(1650) \to \omega(782)\eta$	1	$\frac{1}{2}Cos\theta_p$
[illegible]	[illegible]	[illegible]	[illegible]

Decay widths $R \to \gamma P$

Decay channel		Symmetry factor	Amplitude
$V_E \to \gamma P$	$V_D \to \gamma P$		
$\rho(1450) \to \gamma\pi$	$\rho(1700) \to \gamma\pi$	1	$\frac{1}{6}$
$\rho(1450) \to \gamma\eta$	$\rho(1700) \to \gamma\eta$	1	$\frac{1}{2} Cos\theta_p$
$\rho(1450) \to \gamma\eta'$	$\rho(1700) \to \gamma\eta'$	1	$\frac{1}{2} Sin\theta_p$
$K^*(1410) \to \gamma K$	$K^*(1680) \to \gamma K$	1	$\frac{1}{3}$
$\phi(1680) \to \gamma\eta$	$\phi_p \to \gamma\eta$	1	$\frac{1}{3} Sin\theta_p$
$\phi(1680) \to \gamma\eta'$	$\phi_p \to \gamma\eta'$	1	$\frac{1}{3} Cos\theta_p$
$\omega(1420) \to \gamma\pi$	$\omega(1650) \to \gamma\pi$	1	$\frac{1}{2}$
$\omega(1420) \to \gamma\eta$	$\omega(1650) \to \gamma\eta$	1	$\frac{1}{6} Cos\theta_p$
$\omega(1420) \to \gamma\eta'$	$\omega(1650) \to \gamma\eta'$	1	$\frac{1}{6} Cos\theta_p$

Results

Radially excited vector mesons: $V_E \to VP$

Decay process $V_E \to VP$	Theory [MeV]	Experiment [MeV]
$\rho(1450) \to \omega\pi$	74.7 ± 31.0	$\sim 84 \pm 13$ seen by CLEGG
$\rho(1450) \to K^*(892)K$	6.7 ± 2.8	possibly seen by COAN
$\rho(1450) \to \rho(770)\eta$	9.3 ± 3.9	$< 16.0 \pm 2.4$ seen by DONNACHIE
$\rho(1450) \to \rho(770)\eta'$	≈ 0	not listed in PDG
$K^*(1410) \to K\rho$	12.0 ± 5.0	$< 16.2 \pm 1.5$ by PDG
$K^*(1410) \to K\phi$	≈ 0	not listed in PDG
$K^*(1410) \to K\omega$	3.7 ± 1.5	not listed in PDG
$K^*(1410) \to K^*(892)\pi$	28.8 ± 12.0	$> 93 \pm 8$ by PDG
$K^*(1410) \to K^*(892)\eta$	≈ 0	not listed in PDG
$K^*(1410) \to K^*(892)\eta'$	≈ 0	not listed in PDG
$\phi(1680) \to K\bar{K}^*$	110 ± 46	dominant, $\Gamma_{tot} = 150 \pm 50$ by PDG
$\phi(1680) \to \phi(1020)\eta$	12.2 ± 5.1	seen by ACHASOV
$\phi(1680) \to \phi(1020)\eta'$	≈ 0	not listed in PDG
$\omega(1420) \to \rho\pi$	196 ± 81	dominant, $\Gamma_{tot} = (180 - 250)$ by PDG
$\omega(1420) \to K^*(892)K$	2.3 ± 1.0	not listed in PDG
$\omega(1420) \to \omega(782)\eta$	4.9 ± 2.0	not listed in PDG
$\omega(1420) \to \omega(782)\eta'$	≈ 0	not listed in PDG

- $\Gamma_{R\to VP} = S\frac{|\vec{k}|^3}{12\pi}[\frac{b_i}{2}\lambda_{RVP}]^2$

Results

Radially excited vector mesons: $V_E \to PP$

Decay process $V_E \to PP$	Theory [MeV]	Experiment [MeV]
$\rho(1450) \to \bar{K}K$	6.6 ± 1.4	$< 6.7 \pm 1.0$ seen by DONNACHE
$\rho(1450) \to \pi\pi$	30.8 ± 6.7	$\sim 27 \pm 4$, seen by CLEGG
$K^*(1410) \to K\pi$	15.3 ± 3.3	15.3 ± 3.3 by PDG
$K^*(1410) \to K\eta$	6.9 ± 1.5	not listed in PDG
$K^*(1410) \to K\eta'$	≈ 0	not listed in PDG
$\phi(1680) \to \bar{K}K$	19.8 ± 4.3	seen by BUON
$\omega(1420) \to \bar{K}K$	5.9 ± 1.3	not listed in PDG

- $\Gamma_{R \to PP} = S \frac{|\vec{k}|^3}{6\pi m_R^2} [\frac{a_i}{2} \lambda_{RPP}]^2$

Results

Radially excited vector mesons: $V_E \to \gamma P$

Decay process $V_E \to \gamma P$	Theory [MeV]	Experiment [MeV]
$\rho(1450) \to \gamma\pi$	0.072 ± 0.042	not listed
$\rho(1450) \to \gamma\eta$	0.23 ± 0.14	0.09 ± 0.045
$\rho(1450) \to \gamma\eta'$	0.056 ± 0.033	not listed
$K^*(1410) \to \gamma K$	0.18 ± 0.11	seen
$\phi(1680) \to \gamma\eta$	0.14 ± 0.09	seen
$\phi(1680) \to \gamma\eta'$	0.076 ± 0.045	not listed
$\omega(1420) \to \gamma\pi$	0.60 ± 0.36	2 ± 1
$\omega(1420) \to \gamma\eta$	0.023 ± 0.014	not listed
$\omega(1420) \to \gamma\eta'$	0.0050 ± 0.0030	not listed

- $\Gamma_{R\to\gamma P} = S\frac{|\vec{k}|^3}{12\pi}[\frac{b_i}{2}\lambda_{RVP}]^2$

Results

Angular momentum excited vector mesons: $V_D \to PP$

Decay process $V_D \to PP$	Theory [MeV]	Experiment [MeV]
$\rho(1700) \to \bar{K}K$	65 ± 37	8.3 ± 3.3 seen by DELCOURT
$\rho(1700) \to \pi\pi$	227 ± 129	75 ± 30 seen by BECKER
$K^*(1680) \to K\pi$	133 ± 75	125 ± 43 by PDG
$K^*(1680) \to K\eta$	85 ± 48	not listed in PDG
$K^*(1680) \to K\eta'$	1.2 ± 0.7	not listed in PDG
$\phi_P \to \bar{K}K$	172 ± 97	resonance not yet known
$\omega(1650) \to \bar{K}K$	60 ± 34	not listed in PDG

Results

Angular momentum excited vector mesons: $V_D \to VP$

Decay process $V_D \to VP$	Theory [MeV]	Experiment [MeV]
$\rho(1700) \to \omega\pi$	80 ± 16	seen by ACHASOV
$\rho(1700) \to K^*(892)K$	32 ± 6	possibly seen by COAN
$\rho(1700) \to \rho\eta$	23 ± 5	$< 10 \pm 4$ seen by DONNACHIE
$\rho(1700) \to \rho\eta'$	≈ 0	not listed in PDG
$K^*(1680) \to K\rho$	37 ± 7	101 ± 35 by PDG
$K^*(1680) \to K\phi$	7.5 ± 1.5	not listed in PDG
$K^*(1680) \to K\omega$	11.9 ± 2.4	not listed in PDG
$K^*(1680) \to K^*(892)\pi$	46 ± 9	96 ± 33 by PDG
$K^*(1680) \to K^*(892)\eta$	0.26 ± 0.05	not listed in PDG
$K^*(1680) \to K^*(892)\eta'$	≈ 0	not listed in PDG
$\phi_P \to K\bar{K}^*$	159 ± 32	resonance not yet known
$\phi_P \to \phi(1020)\eta$	42 ± 8	resonance not yet known
$\phi_P \to \phi(1020)\eta'$	≈ 0	resonance not yet known
$\omega(1650) \to \rho\pi$	212 ± 43	205 ± 23 seen by ACHASOV
$\omega(1650) \to K^*(892)K$	24 ± 5	not listed in PDG
$\omega(1650) \to \omega(782)\eta$	18 ± 4	listed in PDG
$\omega(1650) \to \omega(782)\eta'$	≈ 0	not listed in PDG

Results

Angular momentum excited vector mesons: $V_D \to \gamma P$

Decay process $V_D \to \gamma P$	Theory [MeV]	Experiment [MeV]
$\rho(1700) \to \gamma\pi$	0.055 ± 0.021	not listed
$\rho(1700) \to \gamma\eta$	0.20 ± 0.08	not listed
$\rho(1700) \to \gamma\eta'$	0.074 ± 0.028	not listed
$K^*(1680) \to \gamma K$	0.17 ± 0.07	not listed
$\phi_P \to \gamma\eta$	0.11 ± 0.04	resonance not yet known
$\phi_P \to \gamma\eta'$	0.079 ± 0.030	resonance not yet known
$\omega(1650) \to \gamma\pi$	0.45 ± 0.17	not listed
$\omega(1650) \to \gamma\eta$	0.020 ± 0.008	not listed
$\omega(1650) \to \gamma\eta'$	0.007 ± 0.003	not listed

Conclusions

- Overall agreement of theory with data:
  - theoretically large decays are clearly seen in experiments,
  - theoretically small decays were generally not seen.
- The results for the not−yet discovered resonance ϕ_P are prediction. This resonance, even if broad, is measurable.
- There are some open issues: some theoretical and experimental errors are too large. $K^*(1410)$ is well established, but $K^*(1410) \to K^*(892)\pi$ is too small when compared to data.
- We have just one radially excited ρ but there is evidence that another one $\rho(1250)$ exists.
  S. Coito, G. Rupp and E. van Beveren, Unquenched quark-model calculation of excited ρ resonances and P-wave $\pi\pi$ phase shifts, Bled Workshops Phys. **16** (2015) no.1.
- Radiative decays were determined via VMD. The radiative decays of V_E are still experimentally poorly determined. For the d−vave vector mesons the results are only predictions.
- New experimental results for excited vector states are expected at the GlueX experiment at Jefferson lab.

References

[1] S. Godfrey and N. Isgur, "Mesons in a Relativized Quark Model with Chromodynamics," Phys. Rev. D **32** (1985) 189.
[2] C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).
[3] H. B. O'Connell, B. C. Pearce, A. W. Thomas and A. G. Williams, "$\rho - \omega$ mixing, vector meson dominance and the pion form-factor," Prog. Part. Nucl. Phys. **39** (1997) 201.
[4] C. Reisinger, M. Piotrowska and F. Giacosa,"Strong and electromagnetic decays of excited vector mesons", in preparation.
[5] S. Prelovsek, L. Leskovec, C. B. Lang and D. Mohler, K π scattering and the K* decay width from lattice QCD, Phys. Rev. D **88** (2013) no.5, 054508.
[6] S. Coito, G. Rupp and E. van Beveren, Unquenched quark-model calculation of excited ρ resonances and P-wave $\pi\pi$ phase shifts, Bled Workshops Phys. **16** (2015) no.1.
[7] H. Al Ghoul *et al.* [GlueX Collaboration], "First Results from The GlueX Experiment," AIP Conf. Proc. **1735** (2016) 020001.

Thank you for your attention