Phenomenology of the Tensor Mesons

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Abstract

We study the strong and radiative decays of the antiquark-quark ground state nonet$\{\rho_3(1690), K_3^*(1780), \phi_3(1850), \omega_3(1670)\}$ in the framework of an effective quantum field theory approach, based on the $SU_V(3)$ flavor symmetry. The effective model is fitted to experimental data listed by the Particle Data Group [Zyla et al. (2020)]. We predict numerous experimentally unknown decay widths and branching ratios. An overall agreement of theory (fit and predictions) with experimental data confirms the $q\bar{q}$ nature of the states and qualitatively validates the effective approach in [Jafarzade et al. (2021)].

Introduction

We are given the following table of the mesons in [Zyla et al. (2020)]

$n^{2s+1}\ell_J$	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	$\eta'(958)$	−11.3	−24.5
1^3S_1	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$	39.2	36.5
1^1P_1	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1415)$	$h_1(1170)$		
1^3P_0	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$		
1^3P_1	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$		
1^3P_2	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$	29.6	28.0
1^1D_2	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$		
1^3D_1	1^{--}	$\rho(1700)$	$K^*(1680)^\ddagger$		$\omega(1650)$		
1^3D_2	2^{--}		$K_2(1820)^\dagger$				
1^3D_3	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$	31.8	30.8

Mesons can be grouped to the nonets which transform under the adjoint transformation of the flavour symmetry $U_V(N_f=3)$. This symmetry leaves QCD lagrangian invariant under the exchange of light quarks $q_i=(u,d,s)$ for the same m_i.

Nonet	Parity (P)	Charge conjugation (C)	Flavour ($U_V(3)$)
$0^{-+}=P$	$-P(t,-\vec{x})$	P^t	$UPU^\dagger$
$1^{--}=V^\mu$	$V_\mu(t,-\vec{x})$	$-(V^\mu)^t$	$UV^\mu U^\dagger$
$2^{++}=T_2^{\mu\nu}$	$T_{2\,\mu\nu}(t,-\vec{x})$	$(T_2^{\mu\nu})^t$	$UT_2^{\mu\nu}U^\dagger$
$3^{--}=W^{\mu\nu\rho}$	$W_{\mu\nu\rho}(t,-\vec{x})$	$-(W^{\mu\nu\rho})^t$	$UW^{\mu\nu\rho}U^\dagger$

Methodology

From a technical point of view, we construct $SU_V(3)$- invariant effective actions/Lagrangians that involve the mesonic nonet as well as its various decay products consisting in the well-established $\overline{q}q$ nonets that were previously introduced. We construct the following tree level lagrangians with minimal number of derivatives

Decay Mode	Interaction Lagrangians
$3^{--}\longrightarrow 0^{-+}+0^{-+}$	$\mathcal{L}_{WPP}=g_{WPP}\,\mathbf{tr}\big[W^{\mu\nu\rho}\big[P,(\partial_\mu\partial_\nu\partial_\rho P)\big]_-\big]$
$3^{--}\longrightarrow 0^{-+}+1^{--}$	$\mathcal{L}_{WVP}=g_{WVP}\,\varepsilon^{\mu\nu\rho\sigma}\,\mathbf{tr}\big[W_{\mu\alpha\beta}\{(V_{\nu\rho}),(\partial^\alpha\partial^\beta\partial_\sigma P)\}_+\big]$

and corresponding decay amplitude squares which appear in the decay rate formula

$$\Gamma_{W\to A+B}=\frac{|\vec{k}_{A,B}|}{8\pi m_W^2}|-i\mathcal{M}|^2\Theta(m_W-m_A-m_B)$$

Decay Mode	$\frac{1}{7}\times|-i\mathcal{M}|^2$
$3^{--}\longrightarrow 0^{-+}+0^{-+}$	$g_{WPP}^2\times\frac{2|\vec{k}_{P_1,P_2}|^6}{35}$
$3^{--}\longrightarrow 0^{-+}+1^{--}$	$g_{WVP}^2\times\frac{8|\vec{k}_{V,P}|^6\,m_W^2}{105}$

The coupling constants are determined via fits to experimental data, rather than by ab initio QCD-calculations. All calculations for the decays are therefore performed at tree-level.

Results

- $W\longrightarrow P+P$ **decay rates**

Decay process (in model)	Theory (MeV)	PDG (MeV)
$\rho_3(1690)\longrightarrow\pi\,\pi$	32.7 ± 2.3	$38.0\pm3.2\leftrightarrow(23.6\pm1.3)\%$
$\rho_3(1690)\longrightarrow\bar{K}\,K$	4.0 ± 0.3	$2.54\pm0.45\leftrightarrow(1.58\pm0.26)\%$
$K_3^*(1780)\longrightarrow\pi\,\bar{K}$	18.5 ± 1.3	$29.9\pm4.3\leftrightarrow(18.8\pm1.0)\%$
$K_3^*(1780)\longrightarrow\bar{K}\,\eta$	7.4 ± 0.6	$47.7\pm21.6\leftrightarrow(30\pm13)\%$
$\omega_3(1670)\longrightarrow\bar{K}\,K$	3.0 ± 0.2	
$\phi_3(1850)\longrightarrow\bar{K}\,K$	18.8 ± 1.4	seen

Results

The comparison of theoretical and experimental results, which is obtained by using this value for the coupling constant, is reported in the above Table. A good overall agreement is obtained, but there is also a sizable mismatch: the experimental value for $K_3^*(1780)\to\overline{K}\eta$ is much larger than our theoretical prediction. Still, the experimental error is large and a better experimental determination would be interesting. Moreover, a noteworthy prediction concerning $\phi_3(1850)\to K\overline{K}$ is obtained. From the theoretical large prediction, we conclude that an experimental determination should be feasible.

- $W\longrightarrow V+P$ **decay rates**

$\rho_3(1690)\to\rho(770)\,\eta$	3.8 ± 0.8	seen	$\omega_3(1670)\to\rho(770)\,\pi$	97 ± 20	seen
$\rho_3(1690)\to\bar{K}^*(892)\,K$	3.4 ± 0.7		$\omega_3(1670)\to\bar{K}^*(892)\,K$	2.9 ± 0.6	
$\rho_3(1690)\to\omega(782)\,\pi$	35.8 ± 7.4	25.8 ± 9.8	$\omega_3(1670)\to\omega(782)\,\eta$	2.8 ± 0.6	
$\rho_3(1690)\to\phi(1020)\,\pi$	0.036 ± 0.007		$\omega_3(1670)\to\phi(1020)\,\eta$	$(7.6\pm1.6)\cdot10^{-6}$	
$K_3^*(1780)\to\rho(770)\,K$	16.8 ± 3.5	49.3 ± 15.7	$\phi_3(1850)\to\rho(770)\,\pi$	1.1 ± 0.2	
$K_3^*(1780)\to\bar{K}^*(892)\,\pi$	27.2 ± 5.6	31.8 ± 9.0	$\phi_3(1850)\to\bar{K}^*(892)\,K$	35.5 ± 7.3	seen
$K_3^*(1780)\to\bar{K}^*(892)\,\eta$	0.09 ± 0.02		$\phi_3(1850)\to\omega(782)\,\eta$	0.015 ± 0.003	
$K_3^*(1780)\to\omega(782)\,\bar{K}$	4.3 ± 0.9		$\phi_3(1850)\to\omega(782)\,\eta'(958)$	0.003 ± 0.001	
$K_3^*(1780)\to\phi(1020)\,\bar{K}$	1.2 ± 0.3		$\phi_3(1850)\to\phi(1020)\,\eta$	3.8 ± 0.8	

We observe that an acceptable agreement is reached, although the $\Gamma_{K_3(1780)\to\rho(770)K}$ mode is theoretically underestimated (the experimental error is nevertheless large). Quite remarkably, the two theoretically sizable and dominant decays $\omega_3(1670)\to\rho(770)K$ and $\phi_3(1850)\to K^*(892)K$ have been indeed seen in experiments, though they could not be quantified.

- Furthermore, we would like to mention a recent lattice QCD study in [Johnson & Dudek (2021)], which also confirms our overall predictions on dominant and less dominant vector-pseudoscalar decay channels

Decay process (in model)	Theory (MeV)	LQCD (MeV)
$\rho_3(1690)\longrightarrow\bar{K}^*(892)\,K+\mathbf{c.c.}$	3	2
$\rho_3(1690)\longrightarrow\omega(782)\,\pi$	36	22
$\omega_3(1670)\longrightarrow\rho(770)\,\pi$	97	62
$\omega_3(1670)\longrightarrow\bar{K}^*(892)\,K+\mathbf{c.c.}$	2.9	2
$\omega_3(1670)\longrightarrow\omega(782)\,\eta$	2.8	1
$\phi_3(1850)\longrightarrow\bar{K}^*(892)\,K+\mathbf{c.c.}$	36	20
$\phi_3(1850)\longrightarrow\phi(1020)\,\eta$	4	3

- Predictions for the radiative decays the photon-vector-meson mixing through the shift

$$V_{\mu\nu}\to V_{\mu\nu}+\frac{e}{g_\rho}F_{\mu\nu}Q\;,$$

where $V_{\mu\nu}\equiv\partial_\mu V_\nu-\partial_\nu V_\mu$, $Q=\text{diag}\{2/3,-1/3,-1/3\}$ is the charge quark matrix, $F_{\mu\nu}$ the electromagnetic field tensor, $e=\sqrt{4\pi\alpha}$ is the electric coupling constant, and $g_\rho\simeq5.5$ parametrizes the photon-vector-meson transition.

	Γ/keV		
$\rho_3^{\pm/0}(1690)\to\gamma\,\pi^{\pm/0}$	69 ± 14	$\omega_3(1670)\to\gamma\,\pi^0$	560 ± 120
$\rho_3^0(1690)\to\gamma\,\eta$	157 ± 32	$\omega_3(1670)\to\gamma\,\eta$	19 ± 4
$\rho_3^0(1690)\to\gamma\,\eta'(958)$	20 ± 4	$\omega_3(1670)\to\gamma\,\eta'(958)$	1.4 ± 0.3
$K_3^\pm(1780)\to\gamma\,K^\pm$	58 ± 12	$\phi_3(1850)\to\gamma\,\pi^0$	4 ± 1
$K_3^0(1780)\to\gamma\,K^0$	231 ± 48	$\phi_3(1850)\to\gamma\,\eta$	129 ± 26
		$\phi_3(1850)\to\gamma\,\eta'(958)$	35 ± 7

Discussion and conclusions

We have studied the decays of the lightest mesonic nonet with quantum numbers $J^{PC}=3^{--}$ using an effective QFT model based on flavor symmetry. Our model retained only the dominant terms in an large-N_c expansion and the lowest possible number of derivatives. By comparing the theoretical results with the current status of experimental data for decay width and some known branching ratios, which are all reported by PDG, we conclude that the $\overline{q}q$ assignment works quite well. However, also in our work some of the decay channels deserve deeper theoretical and experimental investigation.

References

Jafarzade, S., Koenigstein, A., & Giacosa, F. (2021). Phenomenology of $J^{PC}=3^{--}$ tensor mesons. *Phys. Rev. D*, *103*(9), 096027.

Johnson, C. T., & Dudek, J. J. (2021). Excited J^{--} meson resonances at the SU(3) flavor point from lattice QCD. *Phys. Rev. D*, *103*(7), 074502.

Zyla, P. A., et al. (2020). Review of Particle Physics. *PTEP*, *2020*(8), 083C01.

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