Phenomenology of the Tensor Mesons

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Abstract

We study the 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. We extend the investigation on the tensor mesons to the ground state mesons of spin-2 states with the quantum number $J^{PC} = 2^{++}$: $\{a_2(1320), K_2^*(1430), f_2(1270)$, and $f_2'(1525)\}$ by considering the effective model based on the approximate chiral symmetry of QCD. Both of the effective models are fitted to the experimental data listed by the Particle Data Group [Zyla et al. (2020)] and are compared to the advanced Lattice simulations results. We predict numerous experimentally unknown decay widths for the missing $J^{PC} = 2^{--}$ resonances within the chiral model.

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 into the nonets which transform under the adjoint transformation of the flavour symmetry $U_V(N_f = 3)$. This symmetry leaves the QCD lagrangian invariant under the exchange of light quarks $q_i = (u, d, s)$ for the same masses m_i. Another approximate symmetry of the QCD lagrangian is the chiral symmetry $U(3)_L \times U(3)_R$ in the limit of $m_i \to 0$. Transofrmation of the nonets under symmetries:

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

- We construct the tree level lagrangians with the minimal number of derivatives which are $SU_V(3)$- invariant effective 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 in Jafarzade et al. (2021).

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

Decay amplitude squares:

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

Decay rate formula

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

- In order to study the decays of the spin-2 mesons we introduce the chiral invariant lagrangian $g_2^{\text{ten}}\Big(\text{tr}\big\{\mathbf{L}_{\mu\nu}L^\mu L^\nu\big\} + \text{tr}\big\{\mathbf{R}_{\mu\nu}R^\mu R^\nu\big\}\Big)$ Jafarzade et al. (2022) where the chiral left (right) nonets are defined as the sum (difference) between the vector and the axial-vector. In a similar way for the tensors and the axial-tensors. Amplitude squares for the decays of the spin-2 fields have the following forms

Decay Mode	$\frac{1}{5} \times \lvert\mathcal{M}\rvert^2$
$2^{++} \longrightarrow 0^{-+} + 0^{-+}$	$g_2^{\text{ten}\,2} \times \frac{2\lvert\vec{k}_{p(1),p(2)}\rvert^4}{15}$
$2^{--} \longrightarrow 0^{-+} + 1^{--}$	$g_2^{\text{ten}\,2} \times \frac{\lvert\vec{k}_{v,p}\rvert^2}{15}\Big(5 + \frac{2\lvert\vec{k}_{v,p}\rvert^2}{m_v^2}\Big)$

Results for the spin-3 mesons

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

Decay process (in model)	Theory (MeV)	PDG (MeV)
$\rho_3(1690) \longrightarrow \pi\,\pi$	32.7 ± 2.3	$38.0 \pm 3.2 \leftrightarrow (23.6 \pm 1.3)\%$
$\rho_3(1690) \longrightarrow \bar{K}\,K$	4.0 ± 0.3	$2.54 \pm 0.45 \leftrightarrow (1.58 \pm 0.26)\%$
$K_3^*(1780) \longrightarrow \pi\,\bar{K}$	18.5 ± 1.3	$29.9 \pm 4.3 \leftrightarrow (18.8 \pm 1.0)\%$
$K_3^*(1780) \longrightarrow \bar{K}\,\eta$	7.4 ± 0.6	$47.7 \pm 21.6 \leftrightarrow (30 \pm 13)\%$
$\omega_3(1670) \longrightarrow \bar{K}\,K$	3.0 ± 0.2	
$\phi_3(1850) \longrightarrow \bar{K}\,K$	18.8 ± 1.4	seen

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

$\rho_3(1690) \to \rho(770)\,\eta$	3.8 ± 0.8	seen
$\rho_3(1690) \to \bar{K}^*(892)\,K$	3.4 ± 0.7	
$\rho_3(1690) \to \omega(782)\,\pi$	35.8 ± 7.4	25.8 ± 9.8
$\rho_3(1690) \to \phi(1020)\,\pi$	0.036 ± 0.007	
$K_3^*(1780) \to \rho(770)\,K$	16.8 ± 3.5	49.3 ± 15.7
$K_3^*(1780) \to \bar{K}^*(892)\,\pi$	27.2 ± 5.6	31.8 ± 9.0
$K_3^*(1780) \to \bar{K}^*(892)\,\eta$	0.09 ± 0.02	
$K_3^*(1780) \to \omega(782)\,\bar{K}$	4.3 ± 0.9	
$K_3^*(1780) \to \phi(1020)\,\bar{K}$	1.2 ± 0.3	

$\omega_3(1670) \to \rho(770)\,\pi$	97 ± 20	seen
$\omega_3(1670) \to \bar{K}^*(892)\,K$	2.9 ± 0.6	
$\omega_3(1670) \to \omega(782)\,\eta$	2.8 ± 0.6	
$\omega_3(1670) \to \phi(1020)\,\eta$	$(7.6 \pm 1.6) \cdot 10^{-6}$	
$\phi_3(1850) \to \rho(770)\,\pi$	1.1 ± 0.2	
$\phi_3(1850) \to \bar{K}^*(892)\,K$	35.5 ± 7.3	seen
$\phi_3(1850) \to \omega(782)\,\eta$	0.015 ± 0.003	
$\phi_3(1850) \to \omega(782)\,\eta'(958)$	0.003 ± 0.001	
$\phi_3(1850) \to \phi(1020)\,\eta$	3.8 ± 0.8	

Effective model vs LQCD

- We compare our results to the recent LQCD 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

Results for the spin-2 mesons

- $T_2 \longrightarrow P + P$ **decay rates**

Decay process (in model)	eLSM (MeV)	PDG (MeV)
$a_2(1320) \longrightarrow \bar{K}\,K$	4.06 ± 0.14	$7.0^{+2.0}_{-1.5} \leftrightarrow (4.9 \pm 0.8)\%$
$a_2(1320) \longrightarrow \pi\,\eta$	25.37 ± 0.87	$18.5 \pm 3.0 \leftrightarrow (14.5 \pm 1.2)\%$
$a_2(1320) \longrightarrow \pi\,\eta'(958)$	1.01 ± 0.03	$0.58 \pm 0.10 \leftrightarrow (0.55 \pm 0.09)\%$
$K_2^*(1430) \longrightarrow \pi\,\bar{K}$	44.82 ± 1.54	$49.9 \pm 1.9 \leftrightarrow (49.9 \pm 0.6)\%$
$f_2(1270) \longrightarrow \bar{K}\,K$	3.54 ± 0.29	$8.5 \pm 0.8 \leftrightarrow (4.6^{+0.5}_{-0.4})\%$
$f_2(1270) \longrightarrow \pi\,\pi$	168.82 ± 3.89	$157.2^{+4.0}_{-1.1} \leftrightarrow (84.2^{+2.9}_{-0.9})\%$
$f_2(1270) \longrightarrow \eta\,\eta$	0.67 ± 0.03	$0.75 \pm 0.14 \leftrightarrow (0.4 \pm 0.08)\%$
$f_2'(1525) \longrightarrow \bar{K}\,K$	23.72 ± 0.60	$75 \pm 4 \leftrightarrow (87.6 \pm 2.2)\%$
$f_2'(1525) \longrightarrow \pi\,\pi$	0.67 ± 0.14	$0.71 \pm 0.14 \leftrightarrow (0.83 \pm 0.16)\%$
$f_2'(1525) \longrightarrow \eta\,\eta$	1.81 ± 0.05	$9.9 \pm 1.9 \leftrightarrow (11.6 \pm 2.2)\%$

- SSB of the Chiral symmetry leads the mass of missing ρ_2 around 1663 MeV and the chiral model predictions for the decays

Decay process (in model)	PDG Fit (MeV)	LQCD Fit (MeV)	LQCD (MeV)
$\rho_2(?) \longrightarrow \rho(770)\,\eta$	87	30	–
$\rho_2(?) \longrightarrow \bar{K}^*(892)\,K + \text{c.c.}$	77	27	36
$\rho_2(?) \longrightarrow \omega(782)\,\pi$	376	122	125
$\rho_2(?) \longrightarrow \phi(1020)\,\pi$	0.8	0.3	–

Conclusion

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 widths which are all reported by PDG and LQCD simulations, we conclude that the $\overline{q}q$ assignment works quite well. Effective chiral model describes spin-2 tensor mesons well and predict some unknown decay rates for the missing axial-tensor mesons. They are expected to be quite broad and the vector-pseudoscalar mode being the most prominent decay mode. Nevertheless, their experimental observation seems to be possible in future experiments.

References

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