STRONG DECAYS OF EXCITED VECTOR MESONS*

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We study two nonets of excited vector mesons, predominantly corresponding to radially excited vector mesons with quantum numbers $n^{2S+1}L_J = 2^3S_1$ and to orbitally excited vector mesons with quantum numbers $n^{2S+1}L_J = 1^3D_1$. We evaluate two types of decays of these mesons: into two pseudoscalar mesons and into a pseudoscalar and a ground-state vector meson. We compare the results with experimental data taken from PDG. We also make predictions for the strange–antistrange state in the 1^3D_1 nonet denoted as $\phi(1930)$, which has not yet been discovered.

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1. Introduction

Quantum Chromodynamics (QCD) is the theory describing the strong interactions between quarks and gluons, which build up the hadrons. Mesons, in general, are bosonic hadrons, while a so-called "conventional meson" is a quark–antiquark ($q\bar{q}$) state [1]. For the discussion of "non-conventional" mesons which are predominantly four-quark or gluonic states, see Refs. [2–5].

In the low-energy sector (*i.e.*, with light quarks u, d, and s), numerous experiments and theoretical calculations have provided a wide range of information about $q\bar{q}$ ground-state mesons with various quantum numbers [6, 7]. On the contrary, excited states are rather poorly determined. Yet, the study of excited states is necessary to confirm the validity of the $q\bar{q}$ picture and to identify states beyond the conventional assignment. Quite interestingly, two nonets of excited vector mesons were experimentally identified: $\{\rho(1450)$, $K^*(1410)$, $\omega(1420)$, $\phi(1680)\}$ and $\{\rho(1700)$, $K^*(1680)$, $\omega(1650)$, $\phi(???)\}$. They predominately correspond to radially excited, $n^{2S+1}L_J = 2^3S_1$, and

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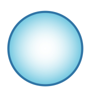
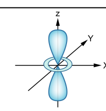
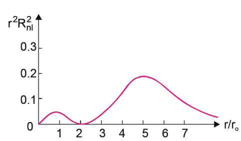
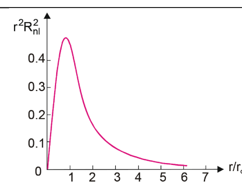
orbitally excited, 1^3D_1, spectroscopic configurations (both of them with $J^{PC} = 1^{--}$ as the standard, ground-state vector mesons). Even if experimental data require improvement, there is enough information on masses and decays for a systematic analysis of these resonances. A summary about both nonets is presented in Table I.

TABLE I

Basic informations about radially and orbitally 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	$\rho(1450), K^*(1410), \omega(1420), \phi(1680)$	$\rho(1700), K^*(1680), \omega(1650), \phi(1930)$
Decay types	$V_E \to PP$ $V_E \to VP$	$V_D \to PP$ $V_D \to VP$

In this work, following the forthcoming publication [8], we use a Quantum Field Theoretical (QFT) model based on flavour symmetry in order to study the strong decays of the two nonets mentioned above. This type of approach has been already used in the past in a series of papers on tensor mesons [9], pseudovector mesons [10], pseudotensor mesons [11], as well as the more controversial scalar mesons [12]. Hence, it appears naturally and promising to perform this study for excited vector mesons as well. As an outcome of our approach, we shall show that the interpretation of the mesons listed above as standard $q\bar{q}$ states is upheld. Moreover, we can make predictions for the decay widths of the not-yet measured orbitally excited $s\bar{s}$ state, denoted as $\phi(???) \equiv \phi(1930)$, where 1930 MeV is an estimate of its mass from the relation $m_{\phi(???)} - m_{\phi(1680)} \simeq m_{\rho(1700)} - m_{\rho(1450)} \simeq 250$ MeV [8].

2. The model

In our approach, we use a relativistic QFT model that couples four nonets of mesons. It is invariant under parity P, charge conjugation C, and $\mathrm{U(3)_V}$ flavour transformation. The Lagrangian of our model reads

$$\begin{aligned}\mathcal{L} \;=\; & ig_{EPP}\mathrm{Tr}\left([\partial^\mu P, V_{E,\mu}]P\right) + ig_{DPP}\mathrm{Tr}\left([\partial^\mu P, V_{D,\mu}]P\right) \\ & + g_{EVP}\mathrm{Tr}\left(\tilde{V}_E^{\mu\nu}\{V_{\mu\nu}, P\}\right) + g_{DVP}\mathrm{Tr}\left(\tilde{V}_D^{\mu\nu}\{V_{\mu\nu}, P\}\right) . \end{aligned} \tag{1}$$

Here, P represents the matrix of pseudoscalar mesons $\{\pi, K, \eta(547), \eta'(958)\}$, $V_{\mu\nu}$ the matrix of ground-state vector mesons $\{\rho(770),\ K^*(892),\ \omega(782),\ \phi(1020)\}$, while $V_{E,\mu}$ contains $\{\rho(1450),\ K^*(1410),\ \omega(1420),\ \phi(1680)\}$ and $V_{D,\mu}$ contains $\{\rho(1700),\ K^*(1680),\ \omega(1650),\ \phi(???)\}$. The Lagrangian describes decays of the type $V_{E(D)} \to PP$ (first two terms) and of the type $V_{E(D)} \to VP$ (third and fourth terms). Moreover, $[.,.]$ is the usual commutator, $\{.,.\}$ the anticommutator, and $\tilde{V}^{\mu\nu}_{E(D)} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}(\partial_\alpha V_{E(D),\beta} - \partial_\beta V_{E(D),\alpha})$ are the dual fields. According to our model, the tree-level decay widths of a resonance R ($R = V_E$ or $R = V_D$) read

$$\Gamma_{R\to PP} = \frac{s_{RPP}|\vec{k}|^3}{6\pi m_R^2}\left(\frac{g_{RPP}}{2}\lambda_{RPP}\right)^2 , \qquad \Gamma_{R\to VP} = \frac{s_{RVP}|\vec{k}|^3}{12\pi}\left(\frac{g_{RVP}}{2}\lambda_{RVP}\right)^2 , \tag{2}$$

where $\vec{k}$ is the tree-momentum of an outgoing resonance (see, *e.g.*, the review on kinematics in the PDG [6]), s_{RPP} an isospin factor, and λ_{RPP} a coefficient which is determined by expanding the traces in Eq. (1) [8]. Note, Eq. (1) implements only flavour symmetry, hence there are no chiral partners. An extension of the present approach to full chiral symmetry is possible following Refs. [13, 14]; this is left for the future.

3. Results

Lagrangian (1) contains four coupling constants g_{EPP}, g_{EVP}, g_{DPP}, g_{DVP}. In order to determine them, we use experimental data from PDG: $\Gamma_{K^*(1410)\to K\pi}$, the total width of $\phi(1680)$, the ratio $\frac{\Gamma_{K^*(1680)\to K\rho}}{\Gamma_{K^*(1680)\to K\pi}}$, and also $\Gamma_{K^*(1680)\to K\pi}$, out of which we obtain: $g_{EPP} = 3.66\pm0.4$, $g_{EVP} = 18.4\pm3.8$, $g_{DPP} = 7.15 \pm 0.94$, and $g_{DVP} = 16.5 \pm 3.5$.

The results for the decays into two pseudoscalar mesons and into a pseudoscalar and a ground-state vector meson are presented in Table II, where a comparison to some experimental data listed in PDG is shown. We use the following notation: $(\rho_R, K^*_R, \omega_R, \phi_R)$ is either identified with $\{\rho(1450), K^*(1410), \omega(1420), \phi(1680)\}$ or with $\{\rho(1700), K^*(1680), \omega(1650), \phi(1930)\}$, respectively. The decay channels which are large according to theory are also

TABLE II

Values of decay widths for two types of decay of excited vector mesons. (+) stands that the decay channel was seen, while (—) was not seen and (*) means that decaying resonance has not yet been discovered.

	Radially excited vector mesons [MeV]		Orbitally excited vector mesons [MeV]	
Decay channel	Theory	Exp.	Theory	Exp.
		$V_R \to PP$		
$\rho_R \to \bar{K}K$	6.6 ± 1.4	$< 6.7 \pm 1.0$	40 ± 11	$8.3^{+10}_{-8.3}$
$\rho_R \to \pi\pi$	30.8 ± 6.7	$\sim 27 \pm 4$	140 ± 37	75 ± 30
$K^*_R \to K\pi$	15.3 ± 3.3	15.3 ± 3.3	82 ± 22	125 ± 43
$K^*_R \to K\eta$	6.9 ± 1.5	—	52 ± 14	—
$K^*_R \to K\eta'$	≈ 0	—	0.72 ± 0.02	—
$\omega_R \to \bar{K}K$	5.9 ± 1.3	—	37 ± 10	—
$\phi_R \to \bar{K}K$	19.8 ± 4.3	+	104 ± 28	*
		$V_R \to VP$		
$\rho_R \to \omega\pi$	74.7 ± 31.0	$\sim 84 \pm 13$	140 ± 59	+
$\rho_R \to K^*(892)K$	6.7 ± 2.8	+	56 ± 23	83 ± 66
$\rho_R \to \rho(770)\eta$	9.3 ± 3.9	$< 16.0 \pm 2.4$	41 ± 17	68 ± 42
$\rho_R \to \rho(770)\eta'$	≈ 0	—	≈ 0	—
$K^*_R \to K\rho$	12.0 ± 5.0	$< 16.2 \pm 1.5$	64 ± 27	101 ± 35
$K^*_R \to K\phi$	≈ 0	—	13 ± 6	—
$K^*_R \to K\omega$	3.7 ± 1.5	—	21 ± 9	—
$K^*_R \to K^*(892)\pi$	28.8 ± 12.0	$> 93 \pm 8$	81 ± 34	96 ± 33
$K^*_R \to K^*(892)\eta$	≈ 0	—	0.5 ± 0.2	—
$K^*_R \to K^*(892)\eta'$	≈ 0	—	≈ 0	—
$\omega_R \to \rho\pi$	196 ± 81	dominant	370 ± 156	205 ± 23
$\omega_R \to K^*(892)K$	2.3 ± 1.0	—	42 ± 18	—
$\omega_R \to \omega(782)\eta$	4.9 ± 2.0	—	32 ± 13	56 ± 30
$\omega_R \to \omega(782)\eta'$	≈ 0	—	≈ 0	—
$\phi_R \to K\bar{K}^*$	110 ± 46	dominant	260 ± 109	*
$\phi_R \to \phi(1020)\eta$	12.2 ± 5.1	+	67 ± 28	*
$\phi_R \to \phi(1020)\eta'$	≈ 0	—	≈ 0	*

large in experiments. *Vice versa*, theoretically small decays were not measured yet, hence our results are predictions. In general, there is a good agreement of our theory with data, hence the interpretation of the two nonets as radially excited and orbitally excited vector mesons is confirmed (see, however, the discussions in Ref. [15]). For a more detailed description of various decay ratios and some open issue concerning conflicting experimental results, we refer to [8]. Surely, new experimental data would be welcome. For the putative state $\phi(1930)$, there are four different decay channels. Even if this resonance is expected to be broad, it could be measured in the future at the GlueX [16] and CLAS12 [17] experiments at Jefferson Lab.

4. Conclusions

In this work, we have reported on strong decays of the (predominantly) radially excited vector mesons $\{\rho(1450), K^*(1410), \omega(1420), \phi(1680)\}$ and the (predominantly) orbitally excited vector mesons $\{\rho(1700), K^*(1680), \omega(1650), \phi(???) \equiv \phi(1930)\}$ (see Table I for a summary) by using an effective relativistic QFT Lagrangian based on flavour symmetry [8]. In total, we evaluated 48 different decay channels for both nonets of mesons and compared them to known experimental values, see Table II. The overall agreement confirms the validity of the $q\bar{q}$ assignment for these states. Radiative decays can be also studied without any new parameters, see Ref. [8]. Moreover, we made predictions for a not yet discovered resonance $\phi(???) \equiv \phi(1930)$ belonging to the heavier, predominantly 1^3D_1 nonet. We expect new experimental data from GlueX and CLAS12 experiments to compare it to our results.

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REFERENCES

[1] S. Godfrey, N. Isgur, *Phys. Rev. D* **32**, 189 (1985).

[2] E. Klempt, A. Zaitsev, *Phys. Rep.* **454**, 1 (2007) [arXiv:0708.4016 [hep-ph]].

[3] J.R. Peláez, *Phys. Rep.* **658**, 1 (2016) [arXiv:1510.00653 [hep-ph]].

[4] H.X. Chen, W. Chen, X. Liu, S.L. Zhu, *Phys. Rep.* **639**, 1 (2016) [arXiv:1601.02092 [hep-ph]].

[5] W. Ochs, *J. Phys. G* **40**, 043001 (2013) [arXiv:1301.5183 [hep-ph]].

[6] C. Patrignani *et al.* [Particle Data Group], *Chin. Phys. C* **40**, 100001 (2016).

[7] Quark model, Standard Model and Related Topics, Reviews, Tables and Plots of the PDG [6].

[8] M. Piotrowska, C. Reisinger, F. Giacosa, *Phys. Rev. D* **96**, 054033 (2017) [arXiv:1708.02593 [hep-ph]].

[9] F. Giacosa, T. Gutsche, V.E. Lyubovitskij, A. Faessler, *Phys. Rev. D* **72**, 114021 (2005) [arXiv:hep-ph/0511171].

[10] F. Divotgey, L. Olbrich, F. Giacosa, *Eur. Phys. J. A* **49**, 135 (2013) [arXiv:1306.1193 [hep-ph]].

[11] A. Koenigstein, F. Giacosa, *Eur. Phys. J. A* **52**, 356 (2016) [arXiv:1608.08777 [hep-ph]].

[12] F. Giacosa, T. Gutsche, V.E. Lyubovitskij, A. Faessler, *Phys. Rev. D* **72**, 094006 (2005) [arXiv:hep-ph/0509247].

[13] D. Parganlija *et al.*, *Phys. Rev. D* **87**, 014011 (2013) [arXiv:1208.0585 [hep-ph]].

[14] F. Giacosa, J. Sammet, S. Janowski, *Phys. Rev. D* **95**, 114004 (2017) [arXiv:1607.03640 [hep-ph]].

[15] S. Coito, G. Rupp, E. van Beveren, *Bled Workshops Phys.* **16**, 30 (2015) [arXiv:1510.00938 [hep-ph]].

[16] H. Al Ghoul *et al.* [GlueX Collaboration], *AIP Conf. Proc.* **1735**, 020001 (2016) [arXiv:1512.03699 [nucl-ex]].

[17] A. Rizzo [CLAS Collaboration], *PoS* **CD15**, 060 (2016).