Phenomenology of excited vector mesons and predictions for a yet undiscovered $s\bar{s}$ state $\phi(1930)$

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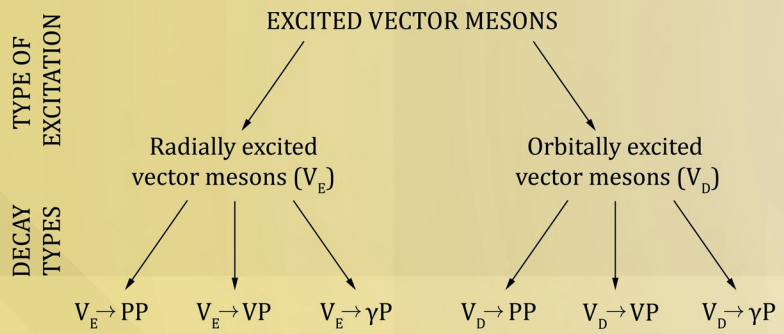
INTRODUCTION

We study the decays of two nonets of excited vector mesons which predominantly correspond to $n\ ^{2S+1}L_J = 2\ ^3S_1$ (radially excited vector mesons) and $n\ ^{2S+1}L_J = 1\ ^3D_1$ (orbitally excited vector mesons) [1]. By using a quantum field theoretical approach we evoluate the decay widths of these mesons into two pseudoscalar mesons and into pseudoscalar and ground-state vector mesons. Moreover by introducing vector meson dominance we study radiative decays of excited vector mesons into a photon and a pseudoscalar meson [2]. We compare our results with the experimental data from PDG [3]. We also make predictions for an unkown $s\bar{s}$ state in $1\ ^3D_1$ nonet, that we call $\phi(1930)$. This state was not yet discovered but can be found in the upcoming GlueX and CLAS12 experiments at Jefferson Lab.

SCHEME OF DECAYS



Associated states:

$$P = \{\pi, K, \eta, \eta'\} \qquad V = \{\rho(770), K^*(892), \omega(782), \phi(1020)\}$$

$$V_E = \{\rho(1450), K^*(1410), \omega(1420), \phi(1680)\}$$

$$V_D = \{\rho(1700), K^*(1680), \omega(1650), \phi(1930)\}$$

THE LAGRANGIAN

The Lagrangian of the model is

$$\mathcal{L} = \mathcal{L}_{EPP} + \mathcal{L}_{DPP} + \mathcal{L}_{EVP} + \mathcal{L}_{DVP}$$

where:

$$\mathcal{L}_{EPP} = ig_{EPP}Tr\left([\partial^\mu P, V_{E,\mu}]P\right)\ , \quad \mathcal{L}_{DPP} = ig_{DPP}Tr\left([\partial^\mu P, V_{D,\mu}]P\right),$$

$$\mathcal{L}_{EVP} = g_{EVP}Tr\left(\tilde{V}_E^{\mu\nu}\{V_{\mu\nu}, P\}\right)\ , \quad \mathcal{L}_{DVP} = g_{DVP}Tr\left(\tilde{V}_D^{\mu\nu}\{V_{\mu\nu}, P\}\right).$$

$g_{EPP}, g_{DPP}, g_{EVP}, g_{DVP}$ - coupling constants of the different decay types.

We can also examine the coupling to photons in the form of V→γP, which is obtained by replacing the vector field strength tensor as [2]:

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

where:

$F_{\mu\nu}$ - field strength tensor for photons,

$$e_0 = \sqrt{4\pi\alpha}, \qquad \alpha \approx 1/137, \qquad Q = diag(\tfrac{2}{3}, -\tfrac{1}{3}, -\tfrac{1}{3}), \qquad g_\rho \approx 5.5 \pm 0.5.$$

DECAY WIDTHS

Type of decay

- $R \to PP$
$$\Gamma_{R\to PP} = s_{RPP}\frac{|\vec{k}|^3}{6\pi m_R^2}\left(\frac{g_{RPP}}{2}\lambda_{RPP}\right)^2$$
- $R \to VP$,
$$\Gamma_{R\to VP} = s_{RVP}\frac{|\vec{k}|^3}{12\pi}\left(\frac{g_{RVP}}{2}\lambda_{RVP}\right)^2$$
- $R \to \gamma P$
$$\Gamma_{R\to\gamma P} = \frac{|\vec{k}|^3}{12\pi}\left(\frac{g_{RVP}}{2}\frac{e_0}{g_\rho}\lambda_{R\gamma P}\right)^2$$

where:

$$|\vec{k}| = \frac{\sqrt{m_R^4 + (m_A^2 - m_B^2)^2 - 2(m_A^2 + m_B^2)m_R^2}}{2m_R};$$

m_R - mass of the decaying resonance;

m_A, m_B - masses of decay products;

s_{RPP}, s_{RVP} - symmetry factors;

λ - amplitude factor;

g_{RPP}, g_{RVP} - coupling constants (R = E, D);

θ_p - pseudoscalar mixing angle;

$\theta_p = -42°$.

Examples

- $\rho(1450) \to \rho(770)\eta$
$$\Gamma_{\rho(1450)\to\rho(770)\eta} = \frac{|\vec{k}|^3}{12\pi}\left[\frac{g_{EVP}}{2}\cos\theta_p\right]^2$$
- $\phi(1680) \to \phi(1020)\eta$
$$\Gamma_{\Phi(1680)\to\Phi(1020)\eta} = \frac{|\vec{k}|^3}{12\pi}\left[\frac{g_{EVP}}{2}\frac{\sin\theta_p}{\sqrt{2}}\right]^2$$

RESULTS

Decay process $V_E \to PP$	Theory [MeV]	Experiment [MeV]
$\rho(1450) \to \bar{K}K$	6.6 ± 1.4	$< 6.7 \pm 1.0$ by DONANCHIE 91
$\rho(1450) \to \pi\pi$	30.8 ± 6.7	$\sim 27 \pm 4$, seen by CLEGG 94
$K^*(1410) \to K\pi$	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
$\omega(1420) \to \bar{K}K$	5.9 ± 1.3	not listed in PDG
$\phi(1680) \to \bar{K}K$	19.8 ± 4.3	seen by BUON 82

Decay process $V_D \to PP$	Theory [MeV]	Experiment [MeV]
$\rho(1700) \to \bar{K}K$	40 ± 11	$8.3^{+10}_{-8.3}$ MeV
$\rho(1700) \to \pi\pi$	140 ± 37	75 ± 30 by BECKER 79
$K^*(1680) \to K\pi$	82 ± 22	125 ± 43 by PDG
$K^*(1680) \to K\eta$	52 ± 14	not listed in PDG
$K^*(1680) \to K\eta'$	0.72 ± 0.02	not listed in PDG
$\omega(1650) \to \bar{K}K$	37 ± 10	not listed in PDG
$\phi(1930) \to \bar{K}K$	104 ± 28	resonance not yet known

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 94
$\rho(1450) \to K^*(892)K$	6.7 ± 2.8	possibly seen by COAN 04
$\rho(1450) \to \rho(770)\eta$	9.3 ± 3.9	$< 16.0 \pm 2.4$ by Donnachie 91
$\rho(1450) \to \rho(770)\eta'$	≈ 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
$\omega(1420) \to \rho\pi$	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
$\phi(1680) \to K\bar{K}^*$	110 ± 46	dominant, $\Gamma_{tot} = 150 \pm 50$ by PDG
$\phi(1680) \to \phi(1020)\eta$	12.2 ± 5.1	seen by ACHASOV 14
$\phi(1680) \to \phi(1020)\eta'$	≈ 0	not listed in PDG

Decay process $V_D \to VP$	Theory [MeV]	Experiment [MeV]
$\rho(1700) \to \omega\pi$	140 ± 59	seen
$\rho(1700) \to K^*(892)K$	56 ± 23	83 ± 66 MeV
$\rho(1700) \to \rho\eta$	41 ± 17	68 ± 42 MeV
$\rho(1700) \to \rho\eta'$	≈ 0	not listed in PDG
$K^*(1680) \to K\rho$	64 ± 27	101 ± 35 by PDG
$K^*(1680) \to K\phi$	13 ± 6	not listed in PDG
$K^*(1680) \to K\omega$	21 ± 9	not listed in PDG
$K^*(1680) \to K^*(892)\pi$	81 ± 34	96 ± 33 by PDG
$K^*(1680) \to K^*(892)\eta$	0.5 ± 0.2	not listed in PDG
$K^*(1680) \to K^*(892)\eta'$	≈ 0	not listed in PDG
$\omega(1650) \to \rho\pi$	370 ± 156	~ 205, 154 ± 44, ~ 273, 120 ± 18
$\omega(1650) \to K^*(892)K$	42 ± 18	not listed in PDG
$\omega(1650) \to \omega(782)\eta$	32 ± 13	~ 100, 56 ± 30
$\omega(1650) \to \omega(782)\eta'$	≈ 0	not listed in PDG
$\phi(1930) \to K\bar{K}^*$	260 ± 109	resonance not yet known
$\phi(1930) \to \phi(1020)\eta$	67 ± 28	resonance not yet known
$\phi(1930) \to \phi(1020)\eta'$	≈ 0	resonance not yet known

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	$\sim 0.2 - 1.5$
$\rho(1450) \to \gamma\eta'$	0.056 ± 0.033	not listed
$K^*(1410) \to \gamma K$	0.18 ± 0.11	seen, < 0.0529 MeV PDG+ Alavi-Harati 02B
$\omega(1420) \to \gamma\pi$	0.60 ± 0.36	1.90 ± 0.75
$\omega(1420) \to \gamma\eta$	0.023 ± 0.014	not listed
$\omega(1420) \to \gamma\eta'$	0.0050 ± 0.0030	not listed
$\phi(1680) \to \gamma\eta$	0.14 ± 0.09	seen
$\phi(1680) \to \gamma\eta'$	0.076 ± 0.045	not listed

Decay process $V_D \to \gamma P$	Theory [MeV]	Experiment [MeV]
$\rho(1700) \to \gamma\pi$	0.095 ± 0.058	not listed
$\rho(1700) \to \gamma\eta$	0.35 ± 0.21	not listed
$\rho(1700) \to \gamma\eta'$	0.13 ± 0.08	not listed
$K^*(1680) \to \gamma K$	0.30 ± 0.18	not listed
$\omega(1650) \to \gamma\pi$	0.78 ± 0.47	not listed
$\omega(1650) \to \gamma\eta$	0.035 ± 0.021	not listed
$\omega(1650) \to \gamma\eta'$	0.012 ± 0.007	not listed
$\phi(1930) \to \gamma\eta$	0.19 ± 0.12	resonance not yet known
$\phi(1930) \to \gamma\eta'$	0.13 ± 0.08	resonance not yet known

PREDICTIONS FOR $\phi(1930)$

MESON $\phi(1930)$	
Quark composition	$\approx s\bar{s}$
Old spectroscopy notation	(predom.) $n\ ^{2S+1}L_J = 1^3D_1$
n	(predom.) 1
S	(predom.) 1 ↑↑
L	(predom.) 2
J^{PC}	1^{--}
Mass	$\approx 1930 \pm 40$ MeV

DECAYS	
Decay channel	Decay width [MeV]
$\phi(1930) \to \bar{K}K$	104 ± 28
$\phi(1930) \to K\bar{K}^*$	260 ± 109
$\phi(1930) \to \Phi(1020)\eta$	67 ± 28
$\phi(1930) \to \Phi(1020)\eta'$	≈ 0
$\phi(1930) \to \gamma\eta$	0.19 ± 0.12
$\phi(1930) \to \gamma\eta'$	0.13 ± 0.08

CONCLUSIONS

- The parameters $g_{EPP}, g_{DPP}, g_{EVP}, g_{DVP}$ were fixed by using some of the experimental data [4].
- Overall agreement of theory with data; theoretically large decays are clearly seen in experiments, theoretically small decays were generally not seen.
- There are some open issues: some theoretical and experimental errors are too large; K*(1410) is well established [1,5], but K*(1410)→K*(892)π is too small when compared to data. Concerning ρ(1450), alternative scenarios exist [6].
- The results for the not-yet discovered resonance $\phi(1930)$ are predictions; this resonance, even if broad, is measurable.
- Radiative decays were determined via VMD without new parameters. The radiative decays of V_E are still experimentally poorly determined, but the theoretically predicted sizable decays were seen in experiments. In two cases, numerical values can be extracted. For the d-wave vector mesons the results are only predictions.
- New experimental results for excited vector states are expected at the GlueX and CLAS12 experiments at Jefferson Lab [7].

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