On radiative decay of light mesons

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All data for the radiative decay of light mesons except $\Gamma(\eta\rightarrow\gamma\gamma)$ are in agreement with the η-η' mixing angle $\theta_P \cong -19°$. The Zweig rule breaks down noticeably and SU_3^f is slightly violated.

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The breakdown of SU_3^f symmetry and of the quark-line continuity (QLC) rule, sometimes called the Zweig rule, in the spectrum and decay of light, pseudoscalar mesons is important not only for phenomenology but also for understanding the structure of quantum chromodynamics at distances of the order of the confinement radius. A new phenomenology for the meson spectrum, which can be reconciled with the concepts of quantum chromodynamics, has recently been proposed (see Ref. 1, which gives a detailed description, notations, and references to earlier papers). In particular, new values were obtained for the mixing angles of the octet and singlet states in the η and η' mesons

$$\theta_P = \theta_P(\eta) = -17.2°, \quad \theta_P' = \theta_P(\eta') = -20.6°, \tag{1}$$

which differ from the generally accepted value $\theta_P = \theta_P(\eta) = \theta_P(\eta') = -10°$. A recent experimental study of the production of η and η' mesons at high energies gave the result[2]

$$k = \bar{\sigma}(\pi^- p \rightarrow \eta' n)/\bar{\sigma}(\pi^- p \rightarrow \eta n) = 0.55 \pm 0.06, \quad (p_L = 4-200 \text{ GeV/c}). \tag{2}$$

If we disregard the small nonorthogonality of the quark wave functions corresponding to the angles (1) and assume that at high energies QLC breaks down only in the η-η' transitions, then $k = \cos^2(\theta_0 - \theta_P)$: $\sin^2(\theta_0 - \theta_P')$, where $\theta_0 = \arctan 2^{-1/2} = 35.3°$. We have $k = 0.50$ for the angles (1), in excellent agreement with (2). This value is in good agreement with the average value for other similar experiments performed at a lower energy and with the smaller statistical values,[3] but[4] clearly contradicts the value $\theta_P = -10°$. If $\theta_P = \theta_P' = \bar{\theta}_P$, then it follows from (2) that $\theta_P = -18.2 \pm 1.4°$.[2]

It was pointed out[3] that the widths of the radiative decays of the pseudoscalar (P) and vector (V) mesons ($V\rightarrow P\gamma$, $P\rightarrow V\gamma$) are consistent with the mixing angles (1); however, because of a lack of data for the total width $\Gamma_{\eta'}$, the corresponding results were not published. At present, new data for $\Gamma_{\eta'}$,[4] $\Gamma(\bar{\rho}\rightarrow\pi^-\gamma)$, and $\Gamma(K_V^- K^-\gamma)$[5] are available (see Table I), making it possible to determine the mixing angle and to establish the nature and magnitude of QLC and SU_3^f violation in the matrix elements of radiative decays. We briefly discuss here the most interesting results of this analysis; a more detailed discussion will be published in Yadernaya Fizika (Sov. J. Nucl. Phys.).

TABLE I

No.	Quantity	Experiment Γ, keV	Fit(4) $\theta_P = \theta_P^{(1)}$, $\theta_\phi = 1^\circ$	Fit(5) $\theta_P = \theta_P^{(2)}$, $\theta_\phi = 5^\circ$
1	$\Gamma(\rho \to \pi\gamma)$	63 ± 7 [5]	58	53
2	$\Gamma(\omega \to \pi\gamma)$	889 ± 62 [10]	825	629
3	$\Gamma(\phi \to \pi\gamma)$	5.8 ± 2.1 [10]	6.0	6.5
4	$\Gamma(K_V^- \to K^-\gamma)$	40 ± 15 [5]	33	30
5	$\Gamma(K_V^\circ \to K^\circ\gamma)$	75 ± 35 [10]	130	120
6	$\Gamma(\rho \to \eta\gamma)$	56 ± 14 [10]	54	33
7	$\Gamma(\omega \to \eta\gamma)$	$3^{+2.5}_{-1.8}$ [10]	8.3	2.5
8	$\Gamma(\phi \to \eta\gamma)$	66 ± 9 [10]	71	98
9	$\Gamma(\eta' \to \rho\gamma)$	86 ± 22 [10,4]	78	77
10	$\Gamma(\eta' \to \omega\gamma)$	6.1 ± 1.9 [10,4]	7.2	10
11	$\dfrac{\Gamma(\eta' \to \rho\gamma)}{\Gamma(\eta' \to \omega\gamma)}$	14.2 ± 2.8 [10]	11	7.7
12	$\Gamma(\phi \to \eta'\gamma)$	–	0.86	0.47
13	$\Gamma(\pi \to \gamma\gamma)\cdot 10^3$	7.95 ± 0.55 [10]	7.3 ± 0.8	6.6 ± 0.8
14	$\Gamma(\eta \to \gamma\gamma)$	0.323 ± 0.046 [10]	0.72 ± 0.08	0.34 ± 0.04
15	$\Gamma(\eta' \to \gamma\gamma)$	5.8 ± 1.8 [10,4]	7.5 ± 0.9	6.5 ± 0.8
16	$\dfrac{\Gamma(\eta \to \gamma\gamma)}{\Gamma(\eta \to \pi^+\pi^-\gamma)}$	7.75 ± 0.30 [10]	7.3 ± 1.2	5.6 ± 0.9

If the SU_3^f violation is disregarded, then the widths of radiative decays can be expressed in terms of the matrix elements of the octet current $J_i^\lambda (i = 1,...,8)$

$$\langle V_i | J_j | P_k \rangle = g d_{ijk}, \quad \langle V_0 | J_j | P_i \rangle = (g + \epsilon) d_{0ij}, \quad \langle V_i | J_j | P_0 \rangle = (g + \delta) d_{0ij}, \tag{3}$$

where $d_{0ij} = (2/3)^{1/2}\delta_{ij}$; the obvious dependence on polarization and momenta as well as the normalization coefficients are omitted. The exact QLC rule corresponds to $\epsilon = \delta = 0$. The data in Table I are sufficient for determining the mixing angles and the parameters g, ϵ, and δ. For simplicity and clarity, we give only the results of fitting of the parameters g, ϵ, and δ with respect to the minimum of χ^2 for the given mixing angles $\theta_P = \theta'_P = \theta_P^{(1)} = -2(45 - \theta_0)^\circ$, $\theta_P^{(2)} = -(45 - \theta_0)^\circ$, close to (1) and to -10°, respectively. In standard notations (see Ref. 6): $g = g_{\rho\pi\gamma}$

$= -\frac{1}{2}g_{K_V^0K^0\gamma} = g_{K_V^-K^-\gamma}$, $g_{\omega\pi\gamma} \cong 3g + 2\epsilon$, $g_{\phi\pi\gamma} \cong 3gt_\phi + (\sqrt{2})\epsilon$. Here $t_\phi = \tan\theta_\phi$, $\theta_\phi = (\theta_V - \theta_0)$ is the mixing angle of strange and nonstrange quark in the ω and ϕ mesons. In the usual phenomenology, $\theta_\phi = 5 \pm 1^{\circ 3}$, in our phenomenology, $\theta_\phi \cong 1^{\circ 1}$ (the smallness of θ_ϕ and ϵ is taken into account in the expressions for $g_{\omega\pi\gamma}$ and $g_{\phi\pi\gamma}$). The smallness of $\Gamma(\phi \to \pi\gamma)$ [$g_{\phi\pi\gamma} = (0.138 \pm 0.025)\ \text{GeV}^{-1}$] severely limits the value of ϵ ($\epsilon < 0$ for 5° and $\epsilon < 0.1$ for 1°); this causes a discrepancy between $g_{\omega\pi\gamma}$ and $g_{\rho\pi\gamma}$, which cannot be accounted for in terms of the SU_3^f or QLC violation: $g_{\rho\pi\gamma}^{\exp} = 0.70 \pm 0.05$, $g_{\omega\pi\gamma}^{\exp} = 2.58 \pm 0.09$. Filippov[7] proposed a mechanism which increases $g_{\omega\pi\gamma}$ because of the small mass of the π meson: $\omega \to (\rho^\pm\pi^\mp) \to (\rho^\pm\pi^\mp)\gamma \to \pi_0\gamma$, where the virtual particles are enclosed in parentheses. There are no such diagrams in the $\rho \to \pi\gamma$ transition; such mechanism is possible in the $K_V^0 \to K^0\gamma$ and $K_V^- \to K^-\gamma$ decays, but it is probably compensated for by a small SU_3^f violation. A calculation with a cutoff of the momentum of a virtual π meson $|p_\pi| \sim m_\rho$ (in this region the result is almost independent of the cutoff) shows that this mechanism increases $g_{\omega\pi\gamma}$ by 15 $\pm$ 5%. If we take the correction into account, then $g_{\omega\pi\gamma} = 3g + 2\epsilon = g_{\omega\pi\gamma}^{\exp}/(1.15 \pm 0.05)$; we used this value to determine the parameters. To fit these parameters, we took the data 1-11 from Table I, and use the value $\Gamma_{\eta'} = 290 \pm 70$ keV for $\Gamma_{\eta'}$[4]; we took the relative widths of the η' decays from Ref. 10. For $\theta_P = \theta'_P = \theta_P^{(1)}$, $\theta_\phi = 1°$ we obtain

$$3g = 2.015, \quad \epsilon = 0.74, \quad \delta = 0.153 \tag{4}$$

The corresponding widths are listed in the second column, $\chi^2/8 = 1.34$; disregarding $K_V^0 \to K^0\gamma$ and $\omega \to \eta\gamma$: $\chi^2/6 = 0.63$. Thus, the agreement is very good, but the data for $K_V^0 \to K^0\gamma$ and $\omega \to \eta\gamma$ must be refined (note that they are poorly accounted for statistically, especially $\omega \to \eta\gamma$). For $\theta_P = \theta_P^{(2)}, \theta_\phi = 5°$, we obtain (the widths are given in Table I)

$$3g = 1.922, \quad \epsilon = -0.016, \quad \delta = 0.061. \tag{5}$$

In this case $\chi^2/8 \cong 4$, and the reliable data ($\omega \to \pi\gamma, \phi \to \eta\gamma, \rho \to \eta\gamma, \eta' \to \omega\gamma, \eta'' \to \omega\gamma/\rho\gamma$) are in poor agreement with the fit. This fit cannot be improved significantly by taking into account the SU_3^f violation. Thus, the angle $\theta_P = \theta'_P = \theta_P^{(2)} \cong -10°$ contradicts not only (2)(but also the data for the radiative decays of P and V mesons.

The obtained parameters can be used to predict $\Gamma(P \to \gamma\gamma)$ in the vector-dominance model (VDM) by using SU_3^f. By comparing the VDM with the results obtained for the $\pi \to \gamma\gamma$ and $\eta' \to \gamma\gamma$ decays in the current algebra[8] and in the chiral model,[9] we can find the relations

$$g/\gamma_\rho = (4\pi^2 F_\pi)^{-1}. \quad F_8/F_1 \approx 1 + \delta/g; \quad F_\pi \cong 0.095\ \text{GeV}. \tag{6}$$

It follows from (4) and (6) that $\gamma_\rho^2/4\pi = 0.505$, in good agreement with $\gamma_\rho^2/4\pi = 0.51 \pm 0.06$ corresponding to $\Gamma(\rho \to e^+e^-)$.[10] The latter decay was used to predict the values 13–16 in Table I. The errors in the predicted values correspond to the uncertainity in γ_ρ; in the calculation of the relation 16, we assumed that $g_{\rho\pi\pi} = 2\gamma_\rho$. Although $\Gamma_{\exp}(\eta \to \gamma\gamma)$ agrees with $\theta_P = \theta'_P = \theta_P^{(2)}$ the remaining experimental data require the value $\theta_P \approx \theta'_P \approx \theta_P^{(1)}$, and $\Gamma(\eta \to \gamma\gamma)$ must be measured again. Note that our prediction $\Gamma(\eta \to \gamma\gamma) = 0.65–0.75$ keV is close to the average of the two existing experiments (see Ref. 10). Allowance for the violation of the SU_3^f symmetry may reduce somewhat the prediction for $\Gamma(\eta' \to \gamma\gamma)$, but it does not affect our conclusion significantly. Although the contradiction between (1) and the SU_3^f symmetry relations in the $P \to \gamma\gamma$ decay was pointed out in Ref. 11, only an analysis of all the data for the radiative decay of light mesons will make it possible to determine with adequate confidence the most probable source of this contradiction—the experimental value of Γ_η is too low.[10]

Thus, there is a strong violation of the QLC rule and a weak violation of SU_3^f in the matrix elements of electromagnetic decays with the participation of light pseudoscalar mesons, and the VDM and current algebra are satisfied. The widths of these decays agree with the angles (1) but do not agree with the standard angle $\theta_P = -10°$; however, new measurements of $\Gamma(\eta \to \gamma\gamma)$ as well as $\Gamma(\omega \to \eta\gamma)$ and $\Gamma(K_V^0 \to K^0\gamma)$ are needed. It is desirable to find the $\eta' \to \phi\gamma$ decay.

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