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# ON RADIATIVE DECAYS OF LIGHT MESONS

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The importance of detecting $SU_3^f$-violations and quark line rule ( QLR, or OZI-rule ) breaking effects in spectra and decays of light mesons is widely recognized. Estimating such effects is important both for constructing a correct phenomenology and for understanding the structure of QCD at large distances. A new phenomenology of the meson spectrum, which is consistent with QCD, has been recently proposed ( see [1], where details as well as notation and references can be found ). This phenomenology predicts new values for the octet-singlet mixing angles in $\eta$ and $\eta'$ meson states

$$\theta_P = \theta_P(\eta) = -17.2^\circ \ , \quad \theta_P' = \theta_P(\eta') = -20.6^\circ . \qquad (I)$$

The result of the latest experiment on high energy $\eta/\eta'$ production [2]

$$K = \bar{\sigma}(\pi^- p \to \eta' n)/\bar{\sigma}(\pi^- p \to \eta n) = .55 \pm .06 \ , \ p_L = 4 \div 200 \ \frac{GeV}{c} \qquad (2)$$

dramatically disagrees with the generally accepted mixing angle $\theta_P = \theta_P(\eta) = \theta_P(\eta') = -10^\circ$, and is in very good agreement with eq.(I). Neglecting the small nonorthogonality of the quark wave functions corresponding to the angles (I), and assuming that the only sourse of the QLR-breaking is, at high energies, in $\eta - \eta'$ mixing one easily finds that

$$K = \cos^2(\theta_0 - \theta_P)/\sin^2(\theta_0 - \theta_P') \ , \quad \theta_0 = \operatorname{arctg} 2^{-1/2} \cong 35.3^\circ .$$

For the angles (I) this gives $K = .50$ , in excellent agreement with the experimental result. This value of $K$ also agrees well with other, less precise experiments performed at lower energies ( see, e.g., [3]), and definitely contradicts $\theta_P = -10^\circ$ . In fact, assuming $\theta_P = \theta_P' = \bar{\theta}_P$ one obtaines from eq. (2) that [2]

$$g^{exp}_{\omega\pi\gamma} = 2.58 \pm .09\ , \qquad g^{exp}_{\rho\pi\gamma} = .70 \pm .05 .$$

In ref. /7/ a mechanism giving an enhancement of $g_{\omega\pi\gamma}$ relative to $g_{\rho\pi\gamma}$ has been proposed. Due to the smallness of the pion mass the process $\omega \to (\rho^\pm \pi^\mp) \to (\rho^\pm \pi^\mp)\gamma \to \pi^\circ \gamma$, where $(\rho^\pm \pi^\mp)$ are virtual particles, contributes to $g_{\omega\pi\gamma}$, and there is no similar process for $\rho \to \pi\gamma$. ( Such a mechanism also contributes to $K^0_V \to K^0 \gamma$ and $K^-_V \to K^- \gamma$, but the effect is probably compensated by some $SU^f_3$ violation ). Making in the corresponding Feynman diagram a cut-off on the virtual pion momentum, $|p_\pi| \leq \Lambda$, $\Lambda \sim m_\rho$ ( the dependence on the cut-off parameter $\Lambda$ is practically negligible for $.5\,GeV < \Lambda < 1\,GeV$), we obtain the enhancement factor $(1.15 \pm .05)$. With this correction,

$$g_{\omega\pi\gamma} = 3g + 2\varepsilon = g^{exp}_{\omega\pi\gamma} / (1.15 \pm .05),$$

and this value of $g_{\omega\pi\gamma}$ is used in our fits. The input data for the fits are the items I) – II) in the Table; for $\Gamma_{\eta'}$ we assume $\Gamma_{\eta'} = (290 \pm 70)\,keV$ /4/, the $\eta'$ branching ratios are taken from PDG /10/. With $\theta_P = \theta'_P = \theta^{(1)}_P,\ \theta_\varphi = 1^\circ$ the best fit is

$$3g = 2.015\ , \quad \varepsilon = .074\ , \quad \delta = .153. \qquad (4)$$

The corresponding widths are given in the second column, for them $\chi^2/8 \cong 1.35$. Omitting the widths of $K^0_V \to K^0\gamma$, $\omega \to \eta\gamma$ we have $\chi^2/6 \cong .65$. The agreement is very good indeed but the experimental widths $\Gamma(K^0_V \to K^0\gamma)$, $\Gamma(\omega \to \eta\gamma)$ are to be suspected; note that they are based on rather a poor statistics, especially $\Gamma(\omega \to \eta\gamma)$. With $\theta_P = \theta'_P = \theta^{(2)}_P$, $\theta_\varphi = 5^\circ$ the best fit is

$$3g = 1.922, \quad \varepsilon = -.016\ , \quad \delta = .061\ ; \qquad (5)$$

in this case $\chi^2/8 \cong 4$, and in poor agreement are the most credible data ($\omega \to \pi\gamma$, $\varphi \to \eta\gamma$, $\rho \to \eta\gamma$, $\eta' \to \omega\gamma$; $\eta' \to \omega\gamma / \eta' \to \rho\gamma$). Taking into account $SU^f_3$ violation does not improve significantly this fit, and so the angle $\theta_P = \theta'_P = \theta^{(2)}_P \cong -10^\circ$ is in contradiction with the data on $P$ and $V$ radiative decays as well as with eq. (2).

Using the parameters obtained above, we can predict $\Gamma(P \to \gamma\gamma)$ in the vector dominance model ( VDM ) with $SU^f_3$ ( now we know that $SU^f_3$ violation effects are of no importance in radiative decays ). The VDM for $P \to \gamma\gamma$ is in good agreement with the current algebra results. In fact, comparing $\Gamma(\pi \to \gamma\gamma)$ and $\Gamma(\eta' \to \gamma\gamma)$

$$\theta_P = -(18.2 \pm 1.4)^\circ .$$

As has been pointed out in ref.[3], the experimental widths of radiative decays of light mesons ( $V \to P\gamma$, $P \to V\gamma$, $P$ - pseudoscalar and $V$ - vector particles ) contradict equation (I). However the more detailed discussion has not been published, for the lack of data on $\Gamma_{\eta'}$, which are extremely important in this context. Now the new data on $\Gamma_{\eta'}$ [4] as well as on $\Gamma(\rho^- \to \pi^- \gamma)$ and $\Gamma(K_V^- \to K^- \gamma)$ [5] are available ( see the Table ), thus allowing an unambiguous determination of the mixing angles from the data on radiative decays. In addition, the $SU_3^f$ and QLR breaking in the matrix elements of these decays can be detected. Here we present only highlights of the analysis; a more complete version will be published elsewhere.

Neglecting $SU_3^f$ violation in the matrix elements, we can express the radiative widths in terms of the octet currents $J_i^\lambda$, $i=1,\dots,8$:

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

Here $d_{0ij} = \sqrt{2/3}\, \delta_{ij}$ ; the obvious dependence on polarizations and momenta as well as normalization factors are suppresed. The exact QLR requires $\varepsilon = \delta = 0$ . Using the data in the Table one can determine both the mixing angles and the parameters $g$ $\varepsilon$ and $\delta$ . For simplicity here we present only the fits for the parameters with fixed mixing angles $\theta_P = \theta_P' = \theta_P^{(1)} = -2(45-\theta_0)^\circ$ and $\theta_P^{(2)} = -(45-\theta_0)^\circ$, which are approximately equal to (I) and to $-10^\circ$ respectively. In standard notation ( see, e.g.[6] ):

$$g = g_{\rho\pi\gamma} = -\tfrac{1}{2} g_{K_V^0 K^0 \gamma} = g_{K_V^- K^- \gamma} , \quad g_{\omega\pi\gamma} \cong 3g + 2\varepsilon , \quad g_{\varphi\pi\gamma} \cong 3g\, t_\varphi + \sqrt{2}\, \varepsilon ,$$

where $t_\varphi = tg\, \theta_\varphi$ , and $\theta_\varphi = (\theta_V - \theta_0)$ is the strange/nonstrange quark mixing angle in the $\omega$ and $\varphi$ mesons. In standard phenomenology ( related to the so-called "quadratic mass formulae" ) $\theta_\varphi = (5 \pm 1)^\circ$ [3], in our phenomenology $\theta_\varphi \cong 1^\circ$ [1] ( in the above expressions for $g_{\omega\pi\gamma}$ and $g_{\varphi\pi\gamma}$ the smallness of $\theta_\varphi$ and $\varepsilon$ is used ). The smallness of $\Gamma(\varphi \to \pi\gamma)$ ( $g_{\varphi\pi\gamma} = (.138 \pm .025)$ GeV/c ) restricts the value of $\varepsilon$ to $\varepsilon < 0$ for $\theta_\varphi = 5^\circ$ and to $\varepsilon < .1$ for $\theta_\varphi = 1^\circ$ . This gives rise to a well known discrepansy between $g_{\omega\pi\gamma}$ and $g_{\rho\pi\gamma}$ , which cannot be attributed to $SU_3^f$ and QLR violations:

Table.

| Quantity | Experim. | Fit (4) | Fit (5) |
|---|---|---|---|
| I) $\Gamma(\rho\to\pi\gamma)$ | $63\pm7$ /5/ | 58 | 53 |
| 2) $\Gamma(\omega\to\pi\gamma)$ | $889\pm62$ /I0/ | 825 | 629 |
| 3) $\Gamma(\varphi\to\pi\gamma)$ | $5.8\pm2.I$ /I0/ | 6.0 | 6.5 |
| 4) $\Gamma(K_V^-\to K^-\gamma)$ | $40\pm I5$ /5/ | 33 | 30 |
| 5) $\Gamma(K_V^0\to K^0\gamma)$ | $75\pm35$ /I0/ | I30 | I20 |
| 6) $\Gamma(\rho\to\eta\gamma)$ | $56\pm I4$ /I0/ | 54 | 33 |
| 7) $\Gamma(\omega\to\eta\gamma)$ | $3^{+2.5}_{-I.8}$ /I0/ | 8.3 | 2.5 |
| 8) $\Gamma(\varphi\to\eta\gamma)$ | $66\pm9$ /I0/ | 7I | 98 |
| 9) $\Gamma(\eta'\to\rho\gamma)$ | $86\pm22$ /I0,4/ | 78 | 77 |
| I0) $\Gamma(\omega\to\omega\gamma)$ | $6.I\pm I.9$ /I0,4/ | 7.2 | I0 |
| II) $\dfrac{\Gamma(\eta'\to\rho\gamma)}{\Gamma(\eta'\to\omega\gamma)}$ | $I4.2\pm2.8$ /I0/ | II | 7.7 |
| I2) $\Gamma(\varphi\to\eta'\gamma)$ | – | .86 | .47 |
| I3) $\Gamma(\pi\to\gamma\gamma)\cdot10^3$ | $7.95\pm.55$ /I0/ | $7.3\pm.8$ | $6.6\pm.8$ |
| I4) $\Gamma(\eta\to\gamma\gamma)$ | $.323\pm.046$ /I0/ | $.72\pm.08$ | $.34\pm.04$ |
| I5) $\Gamma(\eta'\to\gamma\gamma)$ | $5.8\pm I.8$ /I0,4/ | $7.5\pm.9$ | $6.5\pm.8$ |
| I6) $\dfrac{\Gamma(\eta\to\gamma\gamma)}{\Gamma(\eta\to\pi^+\pi^-\gamma)}$ | $7.75\pm.30$ /I0/ | $7.3\pm I.2$ | $5.6\pm.9$ |

with those in current algebra /8/ or in chiral models /9/, one easily finds the relations

$$g/\gamma_\rho = (4\pi^2 F_\pi)^{-1}\ ,\quad F_2/F_1 = 1+\delta/g\ ;\quad F_\pi \cong .095\ \text{Gev.} \qquad (6)$$

Equations (4) and (6) give $\gamma_\rho^2/4\pi \cong .505$, which is in good agreement with $\gamma_\rho^2/4\pi = .51\pm.06$ obtained from $\Gamma(\rho\to e^+e^-)$ ( see, e.g., /I0/ ). The last value for $\gamma_\rho^2/4\pi$ is used for predicting the items 13) – 16) in the Table. A dispersion in these predictions is related to the dispersion in $\gamma_\rho$ . In calculating the ratio 16) the relation $g_{\rho\pi\pi} = 2\gamma_\rho$ is used.

The width $\Gamma_{exp}(\eta \to \gamma\gamma)$ agrees well with $\theta_P = \theta_P' = \theta_P^{(2)}$, and disagrees with $\theta_P = \theta_P' = \theta_P^{(1)}$ . However, all the other data require $\theta_P \cong \theta_P' \cong \theta_P^{(1)}$ , and a new measurement of this important quantity would be extremely desirable. Note that our prediction $\Gamma(\eta \to \gamma\gamma) = .65 \div .75$ keV is close to the average of two existing measurements ( see, e.g., /10/ ). Some $SU_3^f$ violation can make $\Gamma(\eta' \to \gamma\gamma)$ somewhat lower, but the prediction for $\Gamma(\eta \to \gamma\gamma)$ cannot be changed significantly. The discrepancy between eq. (1) and the $SU_3^f$ relation for the decays $P \to \gamma\gamma$ was first mentioned in ref. /11/; however, only the complete analysis of all the data on radiative decays of light mesons makes it possible to find the most probable sourse of this discrepancy, too low experimental value of $\Gamma_{\eta'}$ , as given in ref. /10/.

Our conclusions are as follows. In the matrix elements of $P$ and $V$ radiative decays the QLR is violated (          ), and there is no significant $SU_3^f$ breaking. The VDM and the current algebra relations are fulfilled. The widths of the decays are in good agreement with the mixing angles (1) and definitely disagree with the standard angle $\theta_P \simeq -10^\circ$. New measurements of $\Gamma(\eta \to \gamma\gamma)$ as well as of $\Gamma(K_V^0 \to K^0\gamma)$ and $\Gamma(\omega \to \eta\gamma)$ are necessary, and detecting of $\psi \to \eta'\gamma$ decay is highly desirable.

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