δ(980) as a four-quark state and the radiative decays of vector and scalar mesons

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A large phenomenological value for the decay rate $\Gamma(\delta\to\gamma\gamma)$ contradicts the very small values obtained in a model assuming the δ(980) is a two-quark state, implying that the δ should be treated as a four-quark state. The Okuba-Zweig-Iizuka rule then gives a large ratio of the δ-ρ-ϕ to δ-ρ-ω couplings which is opposite to previous estimates based on vector dominance. Previous calculations of δ radiative decays and three-body radiative decays of vector mesons are modified and new decay rates are obtained.

In a previous calculation of the decay rate for $\eta\to\pi\gamma\gamma$ in which the intermediate state is the δ(980),[1] we found that a good fit to the data is obtained if the decay rate $\Gamma(\delta\to\gamma\gamma)$ is 550 ± 270 keV.[2] Eilam has pointed out[3] that this large rate for $\delta\to\gamma\gamma$ contradicts the results of Babcock and Rosner,[4] who obtain values ranging from 0 to ~370 eV depending on the choice of parameters in their two-quark model of the δ. This contradiction suggests that the two-quark description of the δ is incorrect and is evidence that the δ is the four-quark state $u\bar{d}s\bar{s}$ proposed by Jaffe.[5] The large rate found for $\delta\to\gamma\gamma$ is consistent with the equally large rate needed for the two-photon decay of the charmed δ_c in order to explain[6] the 2.88-GeV enhancement seen in $\pi^- p\to n\gamma\gamma$ at $p_{\text{lab}}=40$ GeV/c.[7]

In our previous calculations,[1,8] it has been necessary to evaluate the ratio $\beta=g_{\delta\rho\phi}/g_{\delta\rho\omega}$. Up until now, we have used a value $\beta\simeq0.07$ which is obtained by setting β equal to $g_{\pi\rho\phi}/g_{\pi\rho\omega}$, where this ratio is calculated using the vector-dominance model and the ratio of the decay widths for $\phi\to\pi\gamma$ and $\rho\to\pi\gamma$. Eilam[3] has pointed out that if the δ is indeed a four-quark state, the Okubo-Zweig-Iizuka (OZI) rule[9] implies that the ratio β could be as large as 10 or larger. This is because the four quarks of the δ connect without annihilation to ρϕ, but not to ρω. We reexamine our previous calculations of the radiative decays of the δ(980) (Ref. 2) and the three-body radiative decays of vector mesons[8] in the light of these observations, by recalculating the decay rates for an arbitrary value of β and then letting $\beta\approx10$, as implied by the OZI rule.

The following relationship is obtained by assuming that the decay $\delta\to\gamma\gamma$ is mediated by vector mesons:

$$g=2\pi\alpha\, g_{\delta\rho\omega}\frac{1}{\gamma_\rho}\left(\frac{1}{\gamma_\omega}+\beta\frac{1}{\gamma_\phi}\right), \tag{1}$$

where g is the δ-γ-γ coupling. The vector-meson–photon couplings from photoproduction[10]

$$\frac{\gamma_\rho^{\,2}}{4\pi}=0.61,\quad \frac{\gamma_\omega^{\,2}}{4\pi}=7.6,\quad \frac{\gamma_\phi^{\,2}}{4\pi}=5.9,$$

and $\Gamma(\delta\to\gamma\gamma)=550\pm270$ keV give

$$g_{\delta\rho\omega}=\frac{1}{\gamma_\phi/\gamma_\omega+\beta}\,(170\pm40)\ \text{GeV}^{-1}, \tag{2}$$

where $\gamma_\phi/\gamma_\omega=0.88$. For radiative decays in which two diagrams contribute, one with an ω converting to a photon and the other with a ϕ converting to a photon, (1) and (2) imply that varying β will not change the calculated decay rate. This is because the overall amplitude is proportional to $g_{\delta\rho\omega}(1/\gamma_\omega+\beta/\gamma_\phi)$, which is constant. Our previous calculations of the three- and four-body radiative decays of η[1] are of this type.

We first consider the radiative decays of the δ(980). Since the decay $\delta\to\rho\gamma$ is mediated by both ω and ϕ, our previous result is unchanged,

$$\Gamma(\delta\to\rho\gamma)=4.7\pm2.1\ \text{MeV}. \tag{3}$$

However, for $\delta\to\omega\gamma$, only the ρ mediates and we now have

$$\Gamma(\delta\to\omega\gamma)=\frac{1}{(\gamma_\phi/\gamma_\omega+\beta)^2}(38\pm16\ \text{MeV}). \tag{4}$$

The expressions for the decay rates in Ref. 2 are generalized to include an arbitrary value of β. For the three-body decays,

$$\Gamma(\delta^\pm\to\pi^\pm\gamma\gamma)=1.1\pm0.8\ \text{keV}, \tag{5a}$$

$$\Gamma(\delta^0\to\pi^0\gamma\gamma)=1.1\pm0.8\ \text{keV}+\frac{1}{(\gamma_\phi/\gamma_\omega+\beta)^2}\times(3.4\pm1.6\ \text{MeV}). \tag{5b}$$

For the decay $\delta\to\eta\gamma\gamma$, the narrow-width approximation is used to obtain the contributions mediated by the ρ and ω. Two sets of branching ratios, $B(\rho\to\eta\gamma)$ and $B(\omega\to\eta\gamma)$, exist, depending on the choice of relative phase between the ρ and ω contributions.[11] For 0° relative phase

$$B(\rho\to\eta\gamma)=(3.6\pm0.9)\times10^{-4}\,,$$

$$B(\omega\to\eta\gamma)=(3.0\pm2.2)\times10^{-4}\,,$$

and for 180° relative phase

$$B(\rho\to\eta\gamma)=(5.4\pm1.1)\times10^{-4}\,,$$

$$B(\omega\to\eta\gamma)=(29\pm7)\times10^{-4}\,.$$

The decay rates of Ref. 2 then become, for 0° relative phase,

$$\Gamma(\delta\to\eta\gamma\gamma)=(1.7\pm1.2\text{ keV})+\frac{1}{(\gamma_\phi/\gamma_\omega+\beta)^2}\times[(11\pm11\text{ keV})+\beta^2(5.0\pm2.2\text{ keV})]\,, \tag{6}$$

and for the 180° relative phase,

$$\Gamma(\delta\to\eta\gamma\gamma)=(2.5\pm1.6\text{ keV})+\frac{1}{(\gamma_\phi/\gamma_\omega+\beta)^2}\times[(110\pm70\text{ keV})+\beta^2(5.0\pm2.2\text{ keV})]\,. \tag{7}$$

Modifications of the expression for the four-body radiative decays of the δ in Ref. 2 proceed in an analogous way. The results are

$$\Gamma(\delta^\pm\to\pi^\pm\pi^+\pi^-\gamma)=\frac{1}{(\gamma_\phi/\gamma_\omega+\beta)^2}(0.41\pm0.38\text{ eV})\,, \tag{8a}$$

$$\Gamma(\delta^\pm\to\pi^\pm\pi^0\pi^0\gamma)=\frac{1}{(\gamma_\phi/\gamma_\omega+\beta)^2}(120\pm60\text{ keV})\,, \tag{8b}$$

$$\Gamma(\delta^0\to\pi^0\pi^+\pi^-\gamma)=\frac{1}{(\gamma_\phi/\gamma_\omega+\beta)^2}(34\pm15\text{ MeV})\,, \tag{8c}$$

$$\Gamma(\delta\to\pi\pi\gamma\gamma)=\frac{1}{(\gamma_\phi/\gamma_\omega+\beta)^2}(0.98\pm0.80\text{ eV})\,. \tag{9}$$

In (9), the rate applies to both $\delta^\pm\to\pi^\pm\pi^0\gamma\gamma$ and $\delta^0\to\pi^0\pi^0\gamma\gamma$. In the model used in Ref. 2, the decay rates for $\delta^0\to\pi^0\pi^0\pi^0\gamma$ and $\delta^0\to\pi^+\pi^-\gamma\gamma$ are both zero.

In Table I, the results (5)–(9) are evaluated for two values of β, one from the vector-dominance-model analogy used in Ref. 2 and the other based on assuming the δ is a four-quark state and invoking the OZI rule. The large value of β reduces many of the calculated decay rates by about two orders of magnitude. In Ref. 2 it was pointed out that a measurement of $\Gamma(\delta\to\eta\gamma\gamma)$ would help to resolve the uncertainty in the relative phase between the amplitudes for $\rho\to\eta\gamma$ and $\omega\to\eta\gamma$. However, if the δ is a four-quark state, the different values of the relative phase give nearly equal values for the decay rate for $\delta\to\eta\gamma\gamma$, and it appears that a measurement of this decay would not resolve the phase problem.

The expressions for the rates for the three-body radiative decays of vector mesons obtained in Ref. 8 are also modified to contain an arbitrary value of β. The results are

$$\Gamma(\rho\to\eta\pi\gamma)=100\pm50\text{ eV}\,, \tag{10}$$

$$\Gamma(\omega\to\eta\pi\gamma)=\frac{1}{(\gamma_\phi/\gamma_\omega+\beta)^2}(1.6\pm0.8\text{ keV})\,, \tag{11}$$

$$\Gamma(\phi\to\eta\pi\gamma)=\frac{\beta^2}{(\gamma_\phi/\gamma_\omega+\beta)^2}(140\pm70\text{ keV})\,, \tag{12}$$

TABLE I. Vector-dominance estimates of the radiative decay rates of the δ for two values of $\beta=g_{\delta\rho\phi}/g_{\delta\rho\omega}$. The values for $\delta\to\eta\gamma\gamma$ depend on the choice of relative phase Φ between the amplitudes for $\rho\to\eta\gamma$ and $\omega\to\eta\gamma$.

Decay	Vector-dominance analogy $\beta\simeq0.07$	$\delta=u\bar{d}s\bar{s}$ OZI rule $\beta\approx10$
$\delta^0\to\pi^+\pi^-\gamma$	4.2 ± 1.8 MeV	4.2 ± 1.8 MeV
$\delta^0\to\pi^0\gamma\gamma$	3.8 ± 1.8 MeV	29 ± 14 keV
$\delta^0\to\eta\gamma\gamma(\Phi=0°)$	14 ± 14 keV	6.0 ± 6.0 keV
$\delta^0\to\eta\gamma\gamma(\Phi=180°)$	120 ± 80 keV	7.6 ± 5.3 keV
$\delta^0\to\pi^+\pi^-\pi^0\gamma$	38 ± 17 MeV	280 ± 120 keV
$\delta^0\to\pi^0\pi^0\gamma\gamma$	1.1 ± 0.9 eV	(8.3 ± 6.8) $\times10^{-3}$ eV
$\delta^\pm\to\pi^\pm\pi^0\gamma$	4.2 ± 1.8 MeV	4.2 ± 1.8 MeV
$\delta^\pm\to\pi^\pm\gamma\gamma$	1.1 ± 0.8 keV	1.1 ± 0.8 keV
$\delta^\pm\to\pi^\pm\pi^0\pi^0\gamma$	130 ± 60 keV	1.0 ± 0.5 keV
$\delta^\pm\to\pi^\pm\pi^+\pi^-\gamma$	0.45 ± 0.42 eV	(3.5 ± 3.2) $\times10^{-3}$ eV
$\delta^\pm\to\pi^\pm\pi^0\gamma\gamma$	1.1 ± 0.9 eV	(8.3 ± 6.8) $\times10^{-3}$ eV

TABLE II. Scalar-meson-dominance values for the radiative decay rates of vector mesons for two values of $\beta = g_{\delta\rho\phi}/g_{\delta\rho\omega}$.

Decay	Vector-dominance analogy $\beta \simeq 0.07$	$\delta = u\bar{d}s\bar{s}$ OZI rule $\beta \approx 10$
$\rho \to \eta\pi\gamma$	100 ± 50 eV	100 ± 50 eV
$\omega \to \eta\pi\gamma$	1.8 ± 0.9 keV	14 ± 7 eV[a]
$\phi \to \eta\pi\gamma$	760 ± 380 eV	120 ± 60 keV
$\phi \to K^+K^-\gamma$	20 ± 11 eV	3.1 ± 1.7 keV
$\phi \to K^0\bar{K}^0\gamma$	3.0 ± 1.6 eV	460 ± 250 eV

[a] This value is comparable to the contribution to this decay from vector dominance; therefore, both must be included in the total rate. See text.

$$\Gamma(\phi \to K^+K^-\gamma) = \frac{\beta^2}{(\gamma_\phi/\gamma_\omega + \beta)^2}(3.7 \pm 2.0 \text{ keV}), \quad (13)$$

$$\Gamma(\phi \to K^0\bar{K}^0\gamma) = \frac{\beta^2}{(\gamma_\phi/\gamma_\omega + \beta)^2}(550 \pm 300 \text{ eV}). \quad (14)$$

In Table II, (10)–(14) are evaluated for the two values of β. The value $\beta \simeq 0.07$ reproduces the results of Ref. 8. The four-quark δ value decreases the ω decay rate by two orders of magnitude and increases the ϕ decays by two orders of magnitude. The $\omega \to \eta\pi\gamma$ rate is now comparable to the estimated contribution to this decay from vector dominance, where $\omega \to \eta\omega \to \eta\pi\gamma$. Therefore, if the δ is a four-quark state, our prediction for the total rate for the decay $\omega \to \eta\pi\gamma$ is in the range 0–56 eV. This is well within the experimental upper limit[12]

$$\Gamma(\omega \to \eta + \text{neutrals}) < 150 \text{ keV}.$$

The other results in the last column of Table II are many orders of magnitude larger than the vector-dominance estimates for these decays.

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