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Radiative decays of the δ(980) in a vector-dominance model

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A vector-dominance model is used to calculate the widths of the three- and four-body radiative decays of the δ(980).

I. INTRODUCTION

In recent experiments involving both K^-p interactions[1] and photoproduction,[2] clear evidence has been obtained for the existence of the δ(980) resonance with $I^G J^P = 1^- 0^+$ coupling to $\eta\pi$. Because of kinematics, the coupling of the δ to $K\bar{K}$ is seen only as an enhancement at threshold.[1]

Recently we have considered the δ meson as a possible intermediate state in the radiative decays of the η.[3] The work was motivated by our observation that the usual vector-dominance models, including the well-known one of Brown, Munczek, and Singer (BMS)[4] in which SU(3)-breaking effects are included in the *PVV* vertices, cannot reproduce the observed decay width $\Gamma(\eta \to \pi\gamma\gamma) = 26 \pm 9$ eV.[5] The BMS model gives the values 0.063 eV or 0.033 eV depending on the sign of the coupling constants,[3] two orders of magnitude smaller than the observed width. The decay widths for $\eta \to \gamma\gamma$ and $\eta \to \pi\pi\gamma$ are normally used as input in the vector-dominance models[6] and, therefore, cannot be thought of as stringent tests of these models for η radiative decays.

In our approach,[3] the main contribution to the decay $\eta \to \pi\gamma\gamma$ is assumed to be the δ-meson intermediate state as shown in Fig. 1. The δ-η-π coupling G is obtained from the decay width for $\delta \to \eta\pi$ which we take to be 55 ± 5 MeV.[1] The resulting value is $G = 2.1 \pm 0.1$ GeV.[7,8] Using this value of G in the diagram of Fig. 1 and fitting the result to the observed decay width $\Gamma(\eta \to \pi\gamma\gamma)$,[5] we obtain a value for the δ-γ-γ coupling of $g = 0.34 \pm 0.08$ GeV^{-1}. The large uncertainty in this number will cause uncertainties in our subsequent calculations of δ radiative decays. It is mainly due to the 35% uncertainty in the width for the decay $\eta \to \pi\gamma\gamma$. Using this value for g, we obtain

$$\Gamma(\delta \to \gamma\gamma) = 550 \pm 270 \text{ keV}. \quad (1.1)$$

In our previous work,[3] we assumed that the δ-γ-γ coupling occurs via vector mesons and proceeded to calculate the four-body radiative decays of the η. The results are in agreement with experimental upper limits,[5] and dominate the predictions of vector dominance by at least two orders of magnitude. In this paper, we again assume that vector mesons are coupled to the δ meson and using this model, calculate the three- and four-body radiative decays of the δ. If the δ couples to two photons via the ρ, ω, and ϕ, then

$$g = \frac{\alpha}{2} g_{\rho\omega\delta} \left(\frac{\gamma_\rho^2}{4\pi}\right)^{-1/2} \left[\left(\frac{\gamma_\omega^2}{4\pi}\right)^{-1/2} + \beta\left(\frac{\gamma_\phi^2}{4\pi}\right)^{-1/2}\right], \quad (1.2)$$

where $\beta = g_{\rho\phi\delta}/g_{\rho\omega\delta}$. Since the photons are real, we shall use the vector-meson-photon couplings obtained from photoproduction rather than e^+e^- colliding beams.[9] The values are[10]

$$\frac{\gamma_\rho^2}{4\pi} = 0.61\,, \quad \frac{\gamma_\omega^2}{4\pi} = 7.6\,, \quad \frac{\gamma_\phi^2}{4\pi} = 5.9\,, \quad (1.3)$$

where the V-γ coupling is given by $e\, m_V^2/2\gamma_V$. The value of β is assumed to be equal to the ratio $g_{\rho\phi\pi}/g_{\rho\omega\pi} = 0.073$.[3] This ratio is obtained from vector dominance and the ratio of the experimentally observed decay widths for $\phi \to \pi\gamma$ and $\rho \to \pi\gamma$. Using (1.2), the resulting value for the δ-ρ-ω coupling is[11]

$$g_{\rho\omega\delta} = 180 \pm 40 \text{ GeV}^{-1}. \quad (1.4)$$

In Sec. II we calculate the three-body radiative decays and in Sec. III the four-body radiative decays of the δ meson. Our results are summarized in Sec. IV.

II. THREE-BODY RADIATIVE DECAYS OF THE δ MESON

In order to obtain the three-body radiative decay widths for the δ meson, it is first useful to calculate the decays $\delta \to \rho\gamma$ and $\delta \to \omega\gamma$ in vector dominance

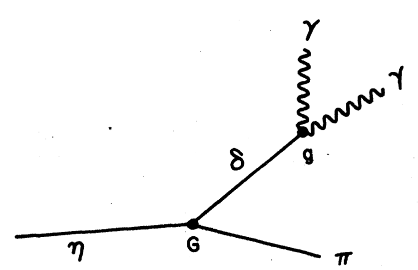

FIG. 1. Diagram for the decay $\eta \to \pi\gamma\gamma$ with the δ-meson intermediate state.

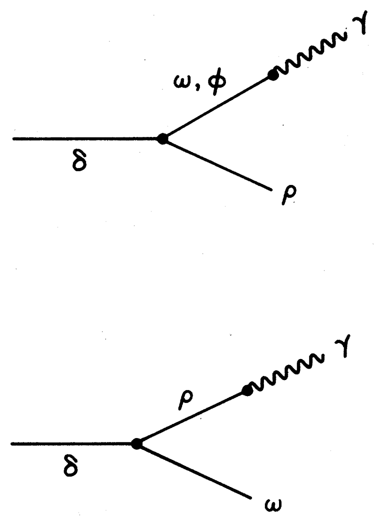

FIG. 2. Diagrams for the decays $\delta \to \rho\gamma$ and $\delta \to \omega\gamma$.

nance. The diagrams for these decays are shown in Fig. 2. Using the couplings given in Sec. I, we obtain

$$\Gamma(\delta \to \rho\gamma) = 4.7 \pm 2.1 \text{ MeV},$$
$$\Gamma(\delta \to \omega\gamma) = 43 \pm 18 \text{ MeV}. \tag{2.1}$$

The diagrams for the decay $\delta \to \pi\pi\gamma$ is shown in Fig. 3. Evaluating the decay width from this diagram gives the result

$$\Gamma(\delta \to \pi\pi\gamma) = 4.2 \pm 1.8 \text{ MeV}. \tag{2.2}$$

This width applies to $\delta^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ and $\delta^{0} \to \pi^{+}\pi^{-}\gamma$. In our model, the width for $\delta^{0} \to \pi^{0}\pi^{0}\gamma$ is zero. A simpler calculation for $\delta \to \pi\pi\gamma$ can be made using the narrow width approximation

$$\Gamma(\delta \to \pi\pi\gamma) = \Gamma(\delta \to \rho\gamma) B(\rho \to \pi\pi), \tag{2.3}$$

where $B(\rho \to \pi\pi)$ is the branching ratio of $\rho \to \pi\pi$ to $\rho \to$ all which is ≈ 1. The result using this approximation is $\Gamma(\delta \to \pi\pi\gamma) \simeq 4.7 \pm 2.1$ MeV which overestimates the exact result by ~10%. Since this overestimate is comparable with the accuracy of our calculation, we shall use the narrow width approximation wherever possible in all subsequent calculations.

The two diagrams which contribute to the decay $\delta \to \pi\gamma\gamma$ are shown in Fig. 4. The contribution from Fig. 4(a) is

$$\Gamma_a(\delta \to \pi\gamma\gamma) = \Gamma(\delta \to \rho\gamma) B(\rho \to \pi\gamma) = 1.1 \pm 0.8 \text{ keV} \tag{2.4}$$

and the contribution from Fig. 4(b) is

$$\Gamma_b(\delta \to \pi\gamma\gamma) = \Gamma(\delta \to \omega\gamma) B(\omega \to \pi\gamma) = 3.8 \pm 1.8 \text{ MeV}, \tag{2.5}$$

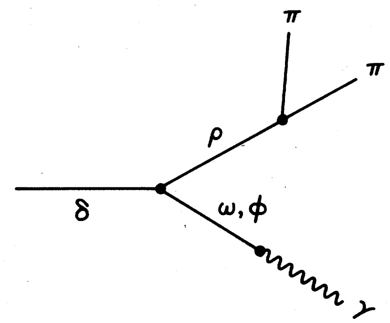

FIG. 3. Diagram for the decay $\delta \to \pi\pi\gamma$.

Only the diagram in Fig. 4(a) contributes $\delta^{\pm} \to \pi^{\pm}\gamma\gamma$ so that $\Gamma(\delta^{\pm} \to \pi^{\pm}\gamma\gamma) = 1.1 \pm 0.8$ keV. Both diagrams contribute to the neutral δ decay and, therefore, $\Gamma(\delta^{0} \to \pi^{0}\gamma\gamma) = 3.8 \pm 1.8$ MeV. The three orders of magnitude difference between these two results can be traced to the difference in the branching ratios for $\rho \to \pi\gamma$ and $\omega \to \pi\gamma$ which are $(0.24 \pm 0.07) \times 10^{-3}$ and $(88 \pm 5) \times 10^{-3}$, respectively.[5]

As a final example of a three-body radiative decay of the δ meson, we consider $\delta^{0} \to \eta\gamma\gamma$. The three diagrams for this decay are shown in Fig. 5. The diagram in Fig. 5(c) included because, although $\delta \to \phi\gamma$ is not kinematically allowed and, therefore, a large contribution is not possible due to a pole contribution in the ϕ resonance denomi-

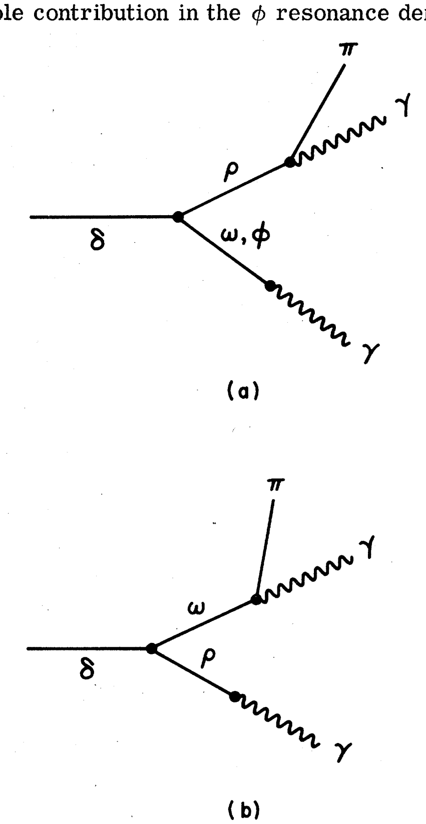

FIG. 4. Diagrams for the decay $\delta \to \pi\gamma\gamma$.

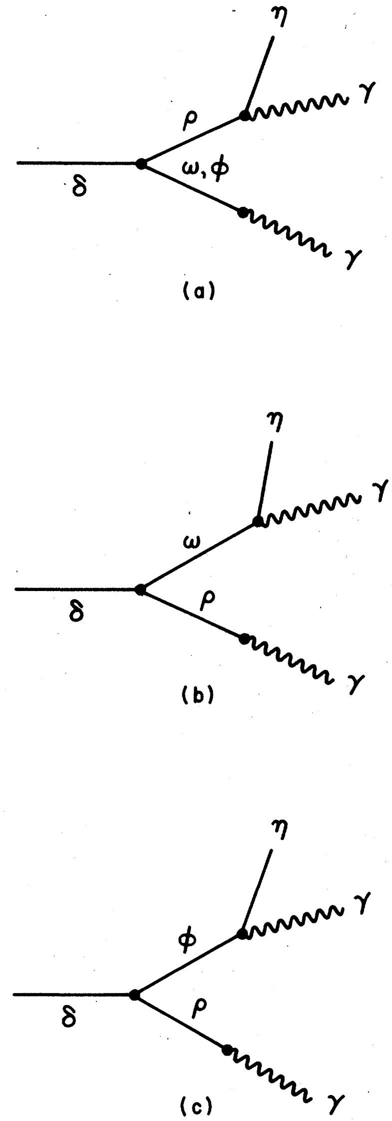

FIG. 5. Diagrams for the decay $\delta \to \eta\gamma\gamma$.

nator in the amplitude, the $\phi \to \eta\gamma$ branching ratio[5] is two orders of magnitude larger than the recently measured branching ratios for $\rho \to \eta\gamma$ and $\omega \to \eta\gamma$.[12] An exact calculation of the contribution to the decay from Fig. 5(c) gives

$$\Gamma_c(\delta \to \eta\gamma\gamma) = 30 \pm 13 \text{ eV}, \tag{2.6}$$

which is three orders of magnitude smaller than the contributions from the other two diagrams in Fig. 5.

Using the narrow-width approximation for Figs. 5(a) and 5(b)

$$\begin{aligned} \Gamma_a(\delta \to \eta\gamma\gamma) &= \Gamma(\delta \to \rho\gamma)\, B(\rho \to \eta\gamma), \\ \Gamma_b(\delta \to \eta\gamma\gamma) &= \Gamma(\delta \to \omega\gamma)\, B(\omega \to \eta\gamma). \end{aligned} \tag{2.7}$$

In the data of Andrews *et al.*,[12] there is an overlap of the contributions of the ρ and ω to the $\eta\gamma$ mass spectrum. A model is used to separate the two contributions with the relative phase between the two amplitudes left as a variable parameter. Best fits are obtained for relative phases of approximately 0° and 180°, either of which is allowed by time-reversal invariance, each corresponding to a different set of branching ratios.

For 0° relative phase, the branching ratios are

$$\begin{aligned} B(\rho \to \eta\gamma) &= (3.6 \pm 0.9) \times 10^{-4}, \\ B(\omega \to \eta\gamma) &= (3.0 \pm 2.2) \times 10^{-4}. \end{aligned} \tag{2.8}$$

When these values are used in (2.7), the resulting decay width is $\Gamma(\delta \to \eta\gamma\gamma) = 15 \pm 14$ keV. For 180° relative phase, the branching ratios are

$$\begin{aligned} B(\rho \to \eta\gamma) &= (5.4 \pm 1.1) \times 10^{-4}, \\ B(\omega \to \eta\gamma) &= (29 \pm 7) \times 10^{-4}, \end{aligned} \tag{2.9}$$

which, when substituted into (2.7), give a decay width of $\Gamma(\delta \to \eta\gamma\gamma) = 130 \pm 90$ keV. Since the two calculated decay widths for $\delta \to \eta\gamma\gamma$ differ by an order of magnitude, there exists the possibility of resolving the phase uncertainty by experimentally measuring the direct decay width for $\delta \to \eta\gamma\gamma$.

III. FOUR-BODY RADIATIVE DECAYS OF THE δ MESON

The diagrams for the decay $\delta \to \pi\pi\pi\gamma$ are shown in Fig. 6. Using the narrow-width approximation, the contribution from Fig. 6(a) is

$$\Gamma_a(\delta \to \pi\pi\pi\gamma) = \Gamma(\delta \to \omega\gamma)\, B(\omega \to 3\pi) = 38 \pm 17 \text{ MeV}. \tag{3.1}$$

The contribution from Fig. 6(b) cannot be obtained using the narrow-width approximation and, in principle, must be calculated exactly. We obtain an estimate by assuming that the ϕ decays to three pions via $\phi \to \rho\pi$ with the subsequent decay $\rho \to \pi\pi$. A calculation is then done in the ρ-pole approximation where the decay width for $\delta \to \rho\pi\gamma$ is obtained, using the ϕ intermediate state, and multiplied by the branching ratio for $\rho \to \pi\pi$. The result gives

$$\Gamma_b(\delta \to \pi\pi\pi\gamma) \simeq 5.1 \pm 2.6 \text{ eV}. \tag{3.2}$$

This result is much smaller than (3.1) and indicates that the contribution of Fig. 6(b) can be ignored.

In order to estimate the contribution of Figs. 6(c) and 6(d), we again use ρ- and ω-pole dominance. This results in only three-body final states, instead of four, greatly simplifying the calculation. The accuracy of this method is presumably well

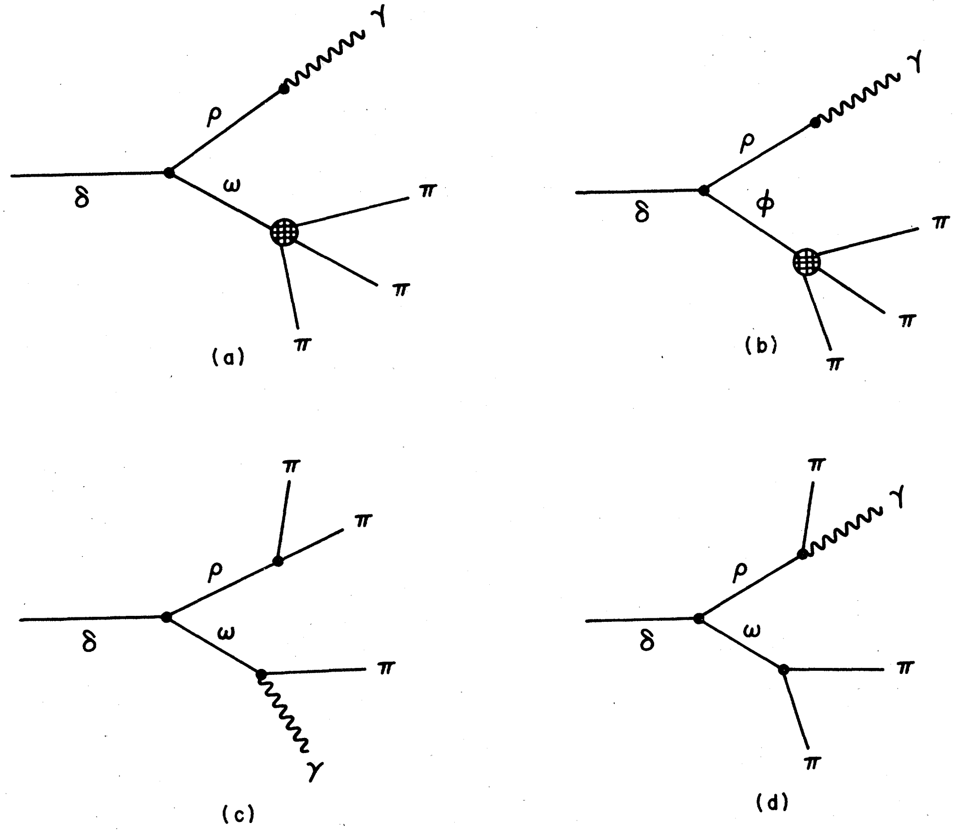

FIG. 6. Diagrams for the decay $\delta \to \pi\pi\pi\gamma$.

within the ultimate accuracy of our estimates of the δ radiative decays. For Figs. 6(c) and 6(d), we must calculate $\Gamma_\omega(\delta \to \rho\pi\gamma)$, $\Gamma_\rho(\delta \to \omega\pi\pi)$, $\Gamma_\omega(\delta \to \rho\pi\pi)$, and $\Gamma_\rho(\delta \to \omega\pi\gamma)$, where the subscript indicates the intermediate particle in the decay diagram. The results are

$$\begin{aligned} &\Gamma_\omega(\delta \to \rho\pi\gamma) = 400 \pm 200 \text{ eV},\\ &\Gamma_\rho(\delta \to \omega\pi\pi) = 1.5 \pm 0.6 \text{ MeV},\\ &\Gamma_\omega(\delta \to \rho\pi\pi) = 1.3 \pm 0.8 \text{ keV},\\ &\Gamma_\rho(\delta \to \omega\pi\gamma) = 11 \pm 8 \text{ eV}. \end{aligned} \tag{3.3}$$

Two pole contributions occur for each of the diagrams in Figs. 6(c) and 6(d). The resulting estimates are

$$\begin{aligned} \Gamma_c(\delta \to \pi\pi\pi\gamma) &\simeq \Gamma_\omega(\delta \to \rho\pi\gamma)B(\rho \to \pi\pi)\\ &\quad + \Gamma_\rho(\delta \to \omega\pi\pi)B(\omega \to \pi\gamma)\\ &= 130 \pm 60 \text{ keV},\\ \Gamma_d(\delta \to \pi\pi\pi\gamma) &\simeq \Gamma_\omega(\delta \to \rho\pi\pi)B(\rho \to \pi\gamma)\\ &\quad + \Gamma_\rho(\delta \to \omega\pi\gamma)B(\omega \to \pi\pi)\\ &= 0.46 \pm 0.43 \text{ eV}. \end{aligned} \tag{3.4}$$

Combining (3.1), (3.2), and (3.4), we obtain

$$\begin{aligned} &\Gamma(\delta^\pm \to \pi^\pm\pi^+\pi^-\gamma) = \Gamma_d \simeq 0.46 \pm 0.43 \text{ eV},\\ &\Gamma(\delta^\pm \to \pi^\pm\pi^0\pi^0\gamma) = \Gamma_c \simeq 130 \pm 60 \text{ keV},\\ &\Gamma(\delta^0 \to \pi^0\pi^+\pi^-\gamma) = \Gamma_a + \Gamma_b + \Gamma_c + \Gamma_d = 38 \pm 17 \text{ MeV},\\ &\Gamma(\delta^0 \to \pi^0\pi^0\pi^0\gamma) = 0. \end{aligned} \tag{3.5}$$

The diagram from $\delta \to \pi\pi\gamma\gamma$ is shown in Fig. 7. We again use the ρ- and ω-pole approximation and obtain

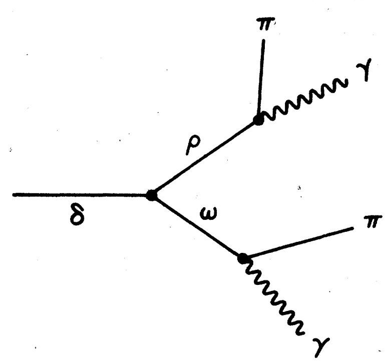

FIG. 7. Diagram for the decay $\delta \to \pi\pi\gamma\gamma$.

$$\Gamma(\delta\to\pi\pi\gamma\gamma)\simeq\Gamma_\omega(\delta\to\rho\pi\gamma)B(\rho\to\pi\gamma)+\Gamma_\rho(\delta\to\omega\pi\gamma)B(\omega\to\pi\gamma)=1.1\pm0.9\text{ eV}. \quad (3.6)$$

This decay width applies to the decays $\delta^\pm\to\pi^\pm\pi^0\gamma\gamma$ and $\delta^0\to\pi^0\pi^0\gamma\gamma$. In our model, the decay width for $\delta^0\to\pi^+\pi^-\gamma\gamma$ is zero.

IV. SUMMARY

The failure of vector-dominance models to account for the decay $\eta\to\pi\gamma\gamma$ has led us to propose a model for the radiative decays of the η involving the δ meson as an intermediate state. After fitting the model to the η radiative decay and obtaining the coupling of the δ meson to two photons, the vector-dominance assumption is made and used to calculate the three- and four-body radiative decays of the δ. The results are summarized in Table I. Of special interest are the two results for the decay $\delta\to\eta\gamma\gamma$. It appears that a measurement of the width for this decay could help resolve the phase uncertainty that exists in the data between the amplitudes for $\rho\to\eta\gamma$ and $\omega\to\eta\gamma$.

TABLE I. Vector-dominance estimates of the radiative decays of the δ meson. The two values for $\delta\to\eta\gamma\gamma$ correspond to two values for the relative phase of the amplitudes for $\rho\to\eta\gamma$ and $\omega\to\eta\gamma$ obtained in Ref. 12.

δ^0 decay	Width
$\delta^0\to\gamma\gamma$	550 ± 270 keV
$\delta^0\to\pi^+\pi^-\gamma$	4.2 ± 1.8 MeV
$\delta^0\to\pi^0\gamma\gamma$	3.8 ± 1.8 MeV
$\delta^0\to\eta\gamma\gamma$	15 ± 14 keV ($\Phi\simeq0°$) 130 ± 90 keV ($\Phi\simeq180°$)
$\delta^0\to\pi^+\pi^-\pi^0\gamma$	38 ± 17 MeV
$\delta^0\to\pi^0\pi^0\gamma\gamma$	1.1 ± 0.9 eV
$\delta^\pm$ decay	Width
$\delta^\pm\to\pi^\pm\pi^0\gamma$	4.2 ± 1.8 MeV
$\delta^\pm\to\pi^\pm\gamma\gamma$	1.1 ± 0.8 keV
$\delta^\pm\to\pi^\pm\pi^0\pi^0\gamma$	130 ± 60 keV
$\delta^\pm\to\pi^\pm\pi^+\pi^-\gamma$	0.46 ± 0.43 eV
$\delta^\pm\to\pi^\pm\pi^0\gamma\gamma$	1.1 ± 0.9 eV

[1]J. B. Gay *et al.*, Phys. Lett. 63B, 220 (1976).
[2]E. N. May *et al.*, Phys. Rev. D 16, 1983 (1977).
[3]G. K. Greenhut and G. W. Intemann, Phys. Rev. D 16, 776 (1977).
[4]L. Brown, H. Munczek, and P. Singer, Phys. Rev. Lett. 21, 707 (1968).
[5]Particle Data Group, Rev. Mod. Phys. 48, S1 (1976).
[6]L. M. Brown and P. Singer, Phys. Rev. D 15, 3484 (1977).
[7]We use a value of 981 ± 6 MeV for the mass of the δ as obtained in Ref. 1.
[8]We are ignoring the possibility discussed by S. M. Flatté [Phys. Lett. 63B, 224 (1976)] that the observed $\delta\to\eta\pi$ width may be quite reduced from its actual value due to the existence of the $\delta\to K\bar{K}$ channel and the combined effects of unitarity and analyticity. In any event, Flatté obtains a minimum χ^2 fit to the data in Ref. 1 for a value of $\Gamma(\delta\to\eta\pi)$ close to the experimentally reported value and for a ratio of the δ-*K*-*K* to δ-η-π couplings in approximate agreement with the predictions of SU(3).
[9]E. H. Thorndike, in *Proceedings of the Fifth International Conference on Experimental Meson Spectroscopy*, Northeastern University, Boston, 1977 (unpublished).
[10]A. Silverman, in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California*, edited by W. T. Kirk (SLAC, Stanford, 1976), p.355.
[11]In Ref. 9, it is shown that in the recent photoproduction data of D. E. Andrews *et al.* (unpublished), there is evidence that the relative phase between the amplitudes for $\rho\to\pi\gamma$ and $\phi\to\pi\gamma$ is ~ 180°. If this relative phase occurs in the ρ-ϕ-π and ρ-ω-π couplings in the vector-dominance expressions for these amplitudes, then the sign of β must be changed and we obtain $g_{\rho\omega\delta}=220\pm50$ GeV^{-1}. This has the effect of increasing all our calculated three- and four-body δ decay widths by a factor of ~ 1.5.
[12]D. E. Andrews *et al.*, Phys. Rev. Lett. 38, 198 (1977).