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Tests of isospin symmetry breaking at $\phi(1020)$ meson factories

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In a model of isospin symmetry breaking we obtain the $(e^-e^+ \to \pi^-\pi^+)$ amplitude Q and the isospin $I = 0$ and $I = 1$ relative phase ψ at the $\phi(1020)$ resonance in approximate agreement with experiment. The model predicts $\Gamma(\phi \to \omega\pi^0) \approx 4 \times 10^{-4}$ MeV. We have also obtained $\Gamma(\phi \to \eta'\gamma) = 5.2 \times 10^{-4}$ MeV. Measuring this partial width would strongly constrain η-η' mixing. The branching ratios $\mathcal{B}$ of the isospin violating decays $\rho^+ \to \pi^+\eta$ and $\eta' \to \rho^\pm\pi^\mp$ are predicted to be $\mathcal{B}(\rho^+ \to \pi^+\eta) = 3\times 10^{-5}$ and $\mathcal{B}(\eta' \to \rho^\pm\pi^\mp) = 4\times 10^{-3}$, respectively, leading to $\mathcal{B}[\phi \to \rho^\pm\pi^\mp \to (\pi^\pm\eta)\pi^\mp \to (\pi^\pm\gamma\gamma)\pi^\mp] = 10^{-6}$ and $\mathcal{B}[\phi \to \eta'\gamma \to (\rho^\pm\pi^\mp)\gamma] = 2 \times 10^{-6}$.

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I. INTRODUCTION

It is generally believed that electromagnetic interactions and the mass differences of u and d quarks are the sources of the breaking of isospin symmetry [1]. Both lead, among other things, to the mixing of the isospin $I = 0$ and $I = 1$ members of the $SU(3)_f$ flavor nonets. The present paper deals with isospin-symmetry-violating meson decays that proceed via π^0-η, π^0-η', ω-ρ^0, and ϕ-ρ^0 mixings. Well-known examples are the isospin-forbidden decays $\eta \to 3\pi$ [1] (the main decay channel of the η) and $\psi' \to \psi\pi^0$ [2]. We concentrate on the decays $\phi \to \pi^+\pi^-$, $\phi \to \omega\pi^0$, $\rho^\pm \to \pi^\pm\eta$, and $\eta' \to \rho^\pm\pi^\mp$ that can thoroughly be investigated at ϕ meson factories. This is obvious for $\phi \to \pi^+\pi^-$ and $\phi \to \omega\pi^0$. Since the ϕ decays into $\rho\pi$ with a branching of 13%, ρ mesons will be produced at ϕ meson factories with a rate that is sufficient for detecting and investigating $\rho^\pm \to \pi^\pm\eta$. The ϕ is furthermore expected to decay into $\eta'\gamma$ with a branching of approximately 10^{-4}. This will presumably be sufficient for detecting and investigating $\eta' \to \rho^\pm\pi^\mp$.

II. INPUT PARAMETERS

We will use the matrix element

$$\langle\eta|H'|\pi^0\rangle = -6000 \text{ MeV}^2. \tag{1}$$

We quote two determinations of this value. First, it follows from the recent determination [3]

$$\frac{m_d - m_u}{m_s} = 1/29 \tag{2}$$

of the quark mass ratios, together with the formula

$$\begin{aligned}\langle\eta|H'|\pi^0\rangle^{\text{tadpole}} &= -\frac{m_d - m_u}{m_s}(m_K^2 - m_\pi^2)x_P \\ &= -6350 \text{ MeV}^2.\end{aligned} \tag{3}$$

This assumes the Zweig rule formula

$$_{PS}\langle s\bar{s}|H'|\pi^0\rangle^{\text{tadpole}} = 0. \tag{4}$$

We assume [4] $\theta_P = -20°$ for the pseudoscalar meson mixing angle and have defined

$$|\eta\rangle = x_P\left|\frac{u\bar{u} + d\bar{d}}{\sqrt{2}}\right\rangle_{PS} + y_P|s\bar{s}\rangle_{PS}, \tag{5}$$

$$|\eta'\rangle = -y_P\left|\frac{u\bar{u} + d\bar{d}}{\sqrt{2}}\right\rangle_{PS} + x_P|s\bar{s}\rangle_{PS}, \tag{6}$$

such that $x_P = 1/\sqrt{3}(\cos\theta_P - \sqrt{2}\sin\theta_P) \approx 0.822$. We furthermore have

$$\langle\eta|H'|\pi^0\rangle = \langle\eta|H'|\pi^0\rangle^{\text{tadpole}} + \langle\eta|H'|\pi^0\rangle^{\text{el}} \tag{7}$$

with [5] $\langle\eta|H'|\pi_0\rangle^{\text{el}} = 520 \text{ MeV}^2$ leading to

$$\langle\eta|H'|\pi^0\rangle = -5800 \text{ MeV}^2. \tag{8}$$

Second, Ref. [6] has found

$$\langle\eta|H'|\pi^0\rangle = (-5900 \pm 600) \text{ MeV}^2. \tag{9}$$

In view of the large errors, we neglect the electromagnetic contribution and use the round number in Eq. (1), i.e.,

$$\langle\eta|H'|\pi^0\rangle \approx \langle\eta|H'|\pi^0\rangle^{\text{tadpole}} \approx -6000 \text{ MeV}^2. \tag{10}$$

In the same way we assume[1]

[1]We also note that [6] has found $\langle\eta'|H'|\pi^0\rangle = (-5500 \pm 500) \text{ MeV}^2$ for $\theta_P = -13°$. Using Eq. (9) together with these numbers one finds that $_{PS}\langle s\bar{s}|H'|\pi^0\rangle \approx 0$ also in the approach of that reference.

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$$\langle\eta'|H'|\pi^0\rangle \approx -y_p \left\langle \frac{u\bar{u}+d\bar{d}}{\sqrt{2}} \middle| H' \middle| \pi_0 \right\rangle^{\text{tadpole}} = -\frac{y_p}{x_p}\langle\eta|H'|\pi^0\rangle = -4200\ \text{MeV}^2. \quad (11)$$

We will also use [7]

$$\langle\omega|H'|\rho^0\rangle = (-4520 \pm 600)\ \text{MeV}^2. \quad (12)$$

For the ω-ϕ mixing angle the Gell-Mann–Okubo value [4] $\theta_V = 39°$ will be used.

The couplings f_V of the vector mesons ρ, ω, ϕ to the photon are defined such that

$$\Gamma(V \to e^+e^-) = \frac{\pi m_V \alpha^2}{3} f_V^{-2}. \quad (13)$$

where $\alpha = 1/137$ is the fine structure constant. Numerically $f_\rho^{-2} = 0.16$, $f_\omega^{-2} = 0.014$, $f_\phi^{-2} = 0.024$ in satisfactory agreement with the quark model relation 9:1:2 for these couplings. As also suggested by the quark model the f_V are assumed to be positive relative to each other.

One of the main ingredients of this work is the vector-vector-pseudoscalar meson coupling constant g defined by the effective Lagrangian

$$L_I = g/2\epsilon_{\alpha\beta\gamma\delta} \sum_{a,b,c=0}^{8} (\partial^\alpha V_a^\beta) V_b^\gamma (\partial^\delta P_c) d_{abc} \quad (14)$$

involving vector meson fields V_a^α with Lorentz index α, $SU(3)_f$ index a, and the pseudoscalar fields P_a. The d_{abc} are the well-known symmetric SU(3) Clebsch-Gordan coefficients, $\epsilon_{\alpha\beta\gamma\delta}$ is the four-dimensional antisymmetric ϵ tensor, and ∂^α is a differentiation symbol. The experimental value of $\Gamma(\rho^0 \to \pi^0\gamma)$ and the width formula

$$\Gamma(\rho^0 \to \pi^0\gamma) = \frac{\alpha g^2}{96 f_\omega^2}\left(\frac{m_\rho^2 - m_{\pi^0}^2}{m_\rho}\right)^3 \quad (15)$$

imply $|g| = 0.0164\ \text{MeV}^{-1}$. This value will be used below.

From the above, widths of the types $P \to \gamma\gamma$, $P \to V\gamma$, $V \to P\gamma$, and $V \to PV$ can be computed in overall agreement with experiment [8–10]. Details of the results depend on the assumed values of the meson mixing angles and $SU(3)_f$-symmetry-breaking corrections and will not concern us here. As examples of straightforward checks of our mixing assumptions, we calculate

$$\Gamma(\rho^0 \to \eta\gamma) = \frac{\alpha g^2}{96 f_\rho^2}\left(\frac{m_\rho^2 - m_\eta^2}{m_\rho}\right)^3 (x_P)^2 = 0.174 (x_P)^2\ \text{MeV} = 0.119\ \text{MeV}, \quad (16)$$

$$\Gamma(\eta' \to \rho^0\gamma) = \frac{\alpha g^2}{32 f_\rho^2}\left(\frac{m_{\eta'}^2 - m_\rho^2}{m_{\eta'}}\right)^3 (y_P)^2 = 0.392 (y_P)^2\ \text{MeV} = 0.127\ \text{MeV}, \quad (17)$$

$$\Gamma(\phi \to \rho\pi) = 3\Gamma(\phi \to \rho^0\pi^0) = \frac{g^2}{4\pi}[q(\phi \to \rho^0\pi^0)]^3 (x_V)^2 = 136 (x_V)^2\ \text{MeV} = 0.55\ \text{MeV}, \quad (18)$$

and

$$\Gamma(\phi \to \eta\gamma) = \frac{\alpha g^2}{48 f_\phi^2}\left(\frac{m_\phi^2 - m_\eta^2}{m_\phi}\right)^3 (y_P)^2 = 0.38 (y_P)^2\ \text{MeV} = 0.122\ \text{MeV}. \quad (19)$$

A comparison with the experimental values $\Gamma(\rho^0 \to \eta\gamma) = 0.058$ MeV, $\Gamma(\eta' \to \rho^0\gamma) = 0.059$ MeV, $\Gamma(\phi \to \rho^0\pi^0) = 0.57$ MeV, and $\Gamma(\phi \to \eta\gamma) = 0.057$ MeV indicates the quality of agreement to be expected *without corrections*. In particular, the poor agreement in the only case where $SU(3)_f$ is applied to $s\bar{s}$ states (i.e., $\phi \to \eta\gamma$) invites an $SU(3)_f$-symmetry-breaking correction [9]. Overall fits [8–10] of course also improve the apparent agreement. Theoretical and experimental $\Gamma(\phi \to \rho\pi)$ compare surprisingly well, lending support to our choice of θ_V.

The width $\Gamma(\phi \to \eta'\gamma)$ can be written in terms of $\Gamma(\phi \to \eta\gamma)$ as

$$\Gamma(\phi \to \eta'\gamma) = \left(\frac{x_P}{y_P}\right)^2 \left(\frac{m_\phi^2 - m_{\eta'}^2}{m_\phi^2 - m_\eta^2}\right)^3 \Gamma(\phi \to \eta\gamma) = 5.2 \times 10^{-4}\ \text{MeV}. \quad (20)$$

The numerical value follows from assuming that η and η' do not mix with mesons outside their $SU(3)_f$ nonet.

III. THE DECAY $\phi \to \pi^+\pi^-$

The observed decays of the $\phi(1020)$ into purely hadronic final states are $\phi \to K\bar{K}$ (fraction: 0.83), $\rho\pi$ (0.13), $\pi^+\pi^-\pi^0$ (0.024), and $\pi^+\pi^-$ (8×10^{-5}). This pattern can be understood if the physical ϕ is an almost ideally mixed $s\bar{s}$ vector meson (i.e., $I^G = 0^-$) that decays into $\pi^+\pi^-$ electromagnetically [Fig. 1(c)] as well as hadronically via an isospin-symmetry-violating mixing with ρ^0 [Fig. 1(b)]. More specifically, we assume the resonant part A_ϕ of the invariant $\langle\gamma|\pi^+\pi^-\rangle$ ampli-

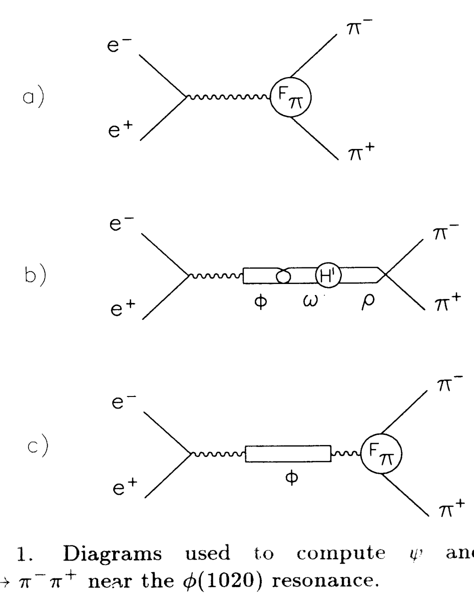

FIG. 1. Diagrams used to compute φ and Q of $e^-e^+ \to \pi^-\pi^+$ near the $\phi(1020)$ resonance.

tude [Fig. 1(a)] around $\sqrt{s} = 1020$ MeV to be given by Figs. 1(b) and 1(c). The total amplitude

$$A(s) = F_\pi(s) + A_\phi(s) \tag{21}$$

also contains a nonresonant smooth interpolation $F_\pi(s)$ of the total form factor A of the π over the ϕ resonance region. As an illustrative example we will saturate $F_\pi(s)$ by the Breit-Wigner propagator of the ρ in the normalization $F_\pi(m_\rho^2) = 1/i\Gamma_\rho m_\rho$ such that

$$F_\pi(s) = \frac{1}{s - m_\rho^2 + i\Gamma_\rho m_\rho}. \tag{22}$$

Since $A_\phi(m_\rho^2) \approx 0$, we also have $A(m_\rho^2) \approx F_\pi(m_\rho^2) = 1/i\Gamma_\rho m_\rho$. From Figs. 1(b) and 1(c) we read

$$A(s) = F_\pi(m_\phi^2) + \frac{f_\rho}{f_\phi}\frac{m_\phi^2}{m_\rho^2}\frac{1}{s - m_\phi^2 + i\Gamma_\phi m_\phi} \times \left(\frac{x_V\langle\omega|H'|\rho^0\rangle}{s - m_\rho^2 + i\Gamma_\rho m_\rho} + \frac{\alpha\pi}{f_\phi f_\rho}F_\pi(m_\phi^2)\right) \tag{23}$$

for $s \approx m_\phi^2$. In analogy with the pseudoscalar case we have defined $x_V = 1/\sqrt{3}(\cos\theta_V - \sqrt{2}\sin\theta_V)$.

A few comments are in order. Since the hadronic isospin-symmetry-breaking Hamiltonian is proportional to $(u\bar{u} - d\bar{d})$, the ϕ couples hadronically to the ρ via ϕ-ω mixing only. This yields the factor x_V. The contribution of $\omega \to \gamma \to \rho^0$ is contained in $\langle\omega|H'|\rho^0\rangle$. The contribution of the ρ^0 at $\sqrt{s} \approx m_\phi$ is then parametrized by the Breit-Wigner propagator. This is entirely correct for the hadronic ω-ρ^0 transition. For the photonic transition $\omega \to \gamma \to \rho^0$ it may be argued that the coupling is to $F_\pi(m_\phi^2)$ rather than to the Breit-Wigner propagator of the ρ^0. It is however easy to see that the photonic contribution to $\langle\omega|H'|\rho^0\rangle$ is small. Namely, the contribution of $\omega \to \gamma \to \pi^-\pi^+$ to $\omega \to \pi^-\pi^+$ can be obtained from an obvious modification of Eq. (23). If there were no other contribution, $\Gamma(\omega \to \pi^-\pi^+) = 0.005$ MeV (whereas the experimental width is 0.19 MeV). We follow [11] in factorizing the $\langle\gamma|\pi^+\pi^-\rangle$ amplitude in the neighborhood of the $\phi(1020)$ such that the s-dependent factor containing the ϕ resonance reads

$$1 + Q\frac{e^{i\psi}m_\phi\Gamma_\phi}{s - m_\phi^2 + im_\phi\Gamma_\phi} = 1 + \frac{f_\rho}{f_\phi}\frac{m_\phi^2}{m_\rho^2}\frac{Y}{s - m_\phi^2 + im_\phi\Gamma_\phi}, \tag{24}$$

where Y is given by

$$Y = \frac{\alpha\pi}{f_\rho f_\phi}m_\rho^2 + \left|\frac{F_\pi(m_\rho^2)}{F_\pi(m_\phi^2)}\right|\frac{m_\rho\Gamma_\rho x_V\langle\omega|H'|\rho^0\rangle}{m_\phi^2 - m_\rho^2 + i\Gamma_\rho m_\rho}e^{iR}, \tag{25}$$

with R the phase of $F_\pi(m_\phi^2)$ at the ϕ resonance:

$$F_\pi(m_\phi^2) = |F_\pi(m_\phi^2)|e^{-iR}. \tag{26}$$

Assuming for m_ϕ and Γ_ϕ the values of (Ref. [4]) $m_\phi = 1019.4$ MeV and $\Gamma_\phi = 4.43$ MeV, the observables to be determined experimentally are ψ and

$$Q = \left(\frac{36B(\phi \to \pi^-\pi^+)B(\phi \to e^-e^+)}{\alpha^2(1 - 4m_\pi^2/m_\phi^2)^{3/2}|F_\pi|^2}\right)^{1/2}. \tag{27}$$

Reference [11] finds

$$\psi = (20 \pm 13)^\circ \tag{28}$$

together with

$$Q = 0.07 \pm 0.02. \tag{29}$$

Using $|F_\pi|^2 = 2.9 \pm 0.2$ and $B(\phi \to e^-e^+) = 3 \times 10^{-4}$ (as has also been obtained in [11]), this yields

$$\Gamma(\phi \to \pi^+\pi^-) = 2.8 \times 10^{-4}\ \text{MeV}. \tag{30}$$

The value $\Gamma(\phi \to \pi^+\pi^-) = (3.5^{+2.2}_{-1.8}) \times 10^{-4}$ MeV [4] combines this result with the much higher $\Gamma(\phi \to \pi^+\pi^-) = 8 \times 10^{-4}$ MeV of Ref. [12].

Using R as a parameter, we present our results in Table I. Approximate agreement with experiment is obtained for R between -170° and 15°. A more meaningful test will hopefully be provided by DAΦNE.

IV. THE DECAY $\phi \to \omega\pi^0$

The amplitude $\langle\phi|\omega\pi^0\rangle$ is determined by the contributions of Fig. 2. We emphasize that, in contrast to Fig. 1(c), we have in Fig. 2(c) *only to take the contribution of the* $\rho^0(770)$ into account, i.e., *not* the full $F_\pi(M_\phi^2)$. Namely interpreting $F_\pi(s)$ in the neighborhood of the $\phi(1020)$ as the *sum* of the contributions of the $(I = 1)$ vector mesons $\rho(770)$, $\rho(1450)$, and $\rho(1700)$, the meson full listings of Ref. [4] suggest that *only the* $\rho(770)$ *considerably couples to* $\omega\pi^0$. Thus we may write, for the amplitude (taking the $\rho^0\omega\pi^0$ coupling from Sec. II rather than directly from the Gell-Mann–Sharp–Wagner calculation [10,13] of $\omega \to 3\pi$),

$$A = \sum_{j=a}^{e} A^{(j)} \tag{31}$$

TABLE I. With the use of R of Eq. (26) as a parameter, the predicted values of ψ and Q [Eq. (27)] are listed and compared to experiment [11].

Condition	R (degree)	ψ (degree)	Q
Experiment		−20±13	0.07±0.02
Destructive interference	−165.7	0	0.089
	−150	−6.4	0.091
	−120	−15	0.10
Phase ψ minimal	−93	−17	0.12
Constructive interference	14.3	0	0.16
Phase ψ maximal	122	17	0.12

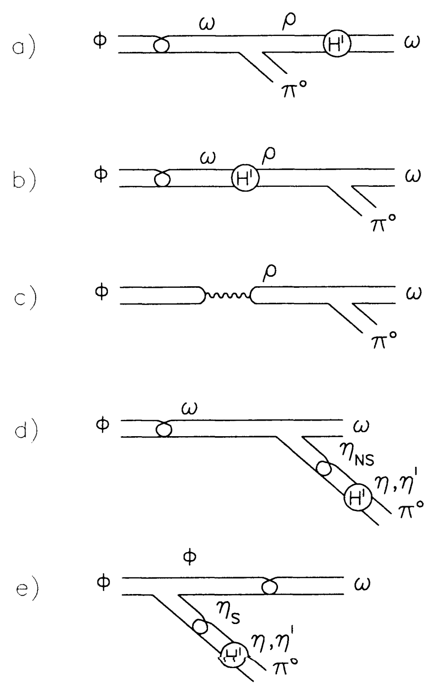

FIG. 2. Diagrams used to compute the width $\Gamma(\phi \to \omega\pi^0)$.

with

$$A^{(a)} = \frac{g x_V \langle\omega|H'|\rho^0\rangle}{m_\omega^2 - m_\rho^2 + i m_\rho \Gamma_\rho}, \tag{32}$$

$$A^{(b)} = \frac{g x_V \langle\omega|H'|\rho^0\rangle}{m_\phi^2 - m_\rho^2 + i\Gamma_\rho m_\rho}, \tag{33}$$

$$A^{(c)} = \frac{\alpha g \pi m_\rho^2}{f_\phi f_\rho} \frac{1}{m_\phi^2 - m_\rho^2 + i\Gamma_\rho m_\rho}, \tag{34}$$

$$A^{(d)} = x_V g \left(x_P \frac{\langle\eta|H'|\pi^0\rangle}{m_{\pi^0}^2 - m_\eta^2} - y_P \frac{\langle\eta'|H'|\pi^0\rangle}{m_{\pi^0}^2 - m_{\eta'}^2} \right), \tag{35}$$

and

$$A^{(e)} = \sqrt{2} x_V g \left(y_P \frac{\langle\eta|H'|\pi^0\rangle}{m_{\pi^0}^2 - m_\eta^2} + x_P \frac{\langle\eta'|H'|\pi^0\rangle}{m_{\pi^0}^2 - m_{\eta'}^2} \right). \tag{36}$$

The width is

$$\Gamma(\phi \to \omega\pi^0) = |A|^2 \frac{[q(\phi \to \omega\pi^0)]^3}{12\pi}. \tag{37}$$

The input parameters we use yield $\Gamma(\phi \to \omega\pi^0) = 4 \times 10^{-4}$ MeV.

V. THE DECAYS $\rho^\pm \to \pi^\pm\eta$ AND $\eta' \to \rho^\pm\pi^\mp$

Finally we consider the decays $\rho^\pm \to \pi^\pm\eta$ and $\eta' \to \rho^\pm\pi^\mp$. They obviously violate G parity and thus isospin symmetry (since charge conjugation symmetry holds for these strong and/or electromagnetic decays). The strong isospin-symmetry-conserving matrix element leading to the proposed decays via $\pi^0\eta$ and $\pi^0\eta'$ mixing, is in both cases $\langle\rho^\pm\pi^\mp\pi^0\rangle$.

With q the decay momenta of the P-wave decays we thus obtain

$$\begin{aligned}\Gamma(\rho^+ \to \pi^+\eta) &= \left(\frac{q(\rho \to \pi\eta)}{q(\rho \to \pi\pi)}\right)^3 \left(\frac{\langle\eta|H'|\pi^0\rangle}{m_\pi^2 - m_\eta^2}\right)^2 \\ &\quad \times\Gamma(\rho^+ \to \pi^+\pi^0) \\ &= 4 \times 10^{-3} \text{ MeV}\end{aligned} \tag{38}$$

and, taking both final charge states together,

$$\begin{aligned}\Gamma(\eta' \to \rho^\pm\pi^\mp) &= 2 \times 3 \left(\frac{q(\eta' \to \rho\pi)}{q(\rho \to \pi\pi)}\right)^3 \left(\frac{\langle\eta'|H'|\pi^0\rangle}{m_\pi^2 - m_{\eta'}^2}\right)^2 \\ &\quad \times\Gamma(\rho^+ \to \pi^+\pi^0) \\ &= 7 \times 10^{-4} \text{ MeV}.\end{aligned} \tag{39}$$

The factor of 3 in the second formula is due to the summation (rather than averaging) over the spin orientations of the ρ. The results for the branching ratios $\mathcal{B}$ are $\mathcal{B}(\rho^+ \to \pi^+\eta) = 3 \times 10^{-5}$ and $\mathcal{B}(\eta' \to \rho^\pm\pi^\mp) = 4 \times 10^{-3}$, leading to branchings $\mathcal{B}[\phi \to \rho^\pm\pi^\mp \to (\pi^\pm\eta)\pi^\mp \to (\pi^\pm\gamma\gamma)\pi^\mp] = 10^{-6}$ and $\mathcal{B}[\phi \to \eta'\gamma \to (\rho^\pm\pi^\mp)\gamma] = 2 \times 10^{-6}$. Thus meaningful conclusions on these decays can be obtained at ϕ meson factories [14].

VI. CONCLUSIONS

In conclusion, we note that our understanding of the processes considered here and those connected to them by $SU(3)_f$ symmetry, vector meson dominance, and isospin symmetry breaking will be strongly enhanced by accurate e^-e^+ annihilation experiments in the $\phi(1020)$ resonance region. As to orders of magnitude, mainstream low-energy phenomenology can accommodate the observed $\psi = (-20 \pm 13)^\circ$ and $Q = 0.07 \pm 0.02$ within the large experimental errors. Our input data favor a ψ that is negative and nearer to 0° and/or a larger Q [implying a larger $\Gamma(\phi \to \pi^-\pi^+)$]. The width $\Gamma(\phi \to \omega\pi^0)$ is predicted to be approximately 4×10^{-4} MeV. Our predictions concerning $\rho^\pm \to \pi^\pm\eta$ and $\eta' \to \rho^\pm\pi^\mp$ are stated at the end of the preceding section.

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