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Pseudoscalar mixing effects on hadronic and photonic decays of the new mesons*

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We calculate the mixing of η, η', and η_c in a cylinder-dominated model and apply our results to the hadronic decay $\psi' \to \psi\eta$ and a number of photonic decays, using vector-meson dominance. The results are in excellent agreement with all experimental data.

I. INTRODUCTION

In Refs. 1, we have discussed violation of the Okubo-Zweig-Iizuka (OZI) rule in the context of a model in which an intermediate state mediates the forbidden transitions. Unitarity requires this intermediate state; whether it is a cut (e.g., $\psi \to DD^* \to \rho\pi$ in ψ decay) or a real particle (a gluon bound state, an empty bag, an "O meson," a closed string), it seems to be rather well parametrized by a pole in the $J^P = 1^-$ and 0^+ channels we addressed in Refs. 1, which included some of the more interesting decays of ψ and ψ' as well as the classical $\phi \to \rho\pi$ rate.

This model will be extended here to OZI-rule-violating transitions in the 0^- channel, which has been treated by several other authors.[2-6] The strikingly large $\psi' \to \psi\eta$ rate, considering the small phase space, proves to be an interesting challenge for the model; furthermore, the model provides an interesting alternative to the treatment of Harari,[2] who finds a huge admixture of charm in η and η', and encounters some problems with photonic decays. (Our results are summarized in Table II.)

Rooted in dual models and dual diagrams, the model[7] correlates deviations from the ideal-mixing mass formula with deviation from ideal mixing in the states via an s-dependent interaction in the forbidden transition elements. In terms of dual diagrams the OZI-rule-forbidden process is one in which there is a U turn [Fig. 1(a)]. If one views the quarks as being at the ends of a string, then this can be pictured as a closing of the string into a circle, which then reopens, with equal probability, into any quark-antiquark state, according to SU(4) symmetry of the basic interaction. The closed string, or flux ring, sweeps out a cylinder, whose moving-flux-line boundaries, when cut, form tears in the cylinder bounded by quark lines which propagate in time the now open flux lines [Fig. 1(b)].

Within the framework of the topological expansion,[8] the cylinder diagrams are of second order in a perturbation in higher and higher orders of the topology; the lowest-order diagrams are the conventional planar graphs.

In this framework one associates the cylinder with the Pomeron singularity. Freund and Nambu,[7] in the context of a string picture, point out that both senses of flux circulation allow for both charge conjugations, and associate the $2^{++}, 1^{--}, 0^{++}$ closed strings with the Pomeron trajectory or its daughters. We have used these objects in Refs. 1 to study a number of OZI-rule suppressions.

In all our previous work we have been careful not to restrict ourselves to a particular dynamical structure for the Pomeron and its associated singularities. It is our feeling that these objects are not simple poles even when we often treated them as such as a convenient approximation. In particular, the cylinder corrections may be Pomeron-Reggeon cuts, suggesting cylinders in all quantum-number states which have Reggeons.

Moreover, if cylinders are established in the 0^+ and 1^- channels, one can use a topoligical duality to infer the existence of a cylinder in the 0^- channel. By topological duality we mean that topologically equivalent diagrams are dual in the usual sense. Consider for example the $\psi \to \phi\eta$ diagram. This is doubly suppressed and requires two cylinders [see Figs. 1(c)]; it has the topology of a sphere with three holes with a particle attached at each hole. It is topologically equivalent to Fig. 1(d), which has a 0^+ cylinder. The line of argument is analogous to pinching an ordinary planar graph in different ways to infer existence of quark-model states in s and t channels.

II. MASS-DEGENERATE MATRIX

As a result of the cylinder correction in the 0^- channel, the ideally mixed "planar" states will be mixed and the masses will be shifted.

We take the cylinder interaction to be

$$Q=\begin{bmatrix} 0 & 0 & 0 & \sqrt{2}f \\ 0 & 0 & 0 & f \\ 0 & 0 & 0 & f \\ \sqrt{2}f & f & f & 0 \end{bmatrix}, \tag{1}$$

where the channels are η, η', η_c, and O meson, respectively. In second order this generates the interaction

$$O=QPQ=\begin{bmatrix} \frac{2f^2}{s-m_{\bar{O}}^2} & \frac{\sqrt{2}f^2}{s-m_{\bar{O}}^2} & \frac{\sqrt{2}f^2}{s-m_{\bar{O}}^2} & 0 \\ \frac{\sqrt{2}f^2}{s-m_{\bar{O}}^2} & \frac{f^2}{s-m_{\bar{O}}^2} & \frac{f^2}{s-m_{\bar{O}}^2} & 0 \\ \frac{\sqrt{2}f^2}{s-m_{\bar{O}}^2} & \frac{f^2}{s-m_{\bar{O}}^2} & \frac{f^2}{s-m_{\bar{O}}^2} & 0 \\ 0 & 0 & 0 & \frac{2f^2}{s-m_{\bar{\eta}}^2}+\frac{f^2}{s-m_{\bar{\eta}'}^2}+\frac{f^2}{s-m_{\bar{\eta}_c}^2} \end{bmatrix}, \tag{2}$$

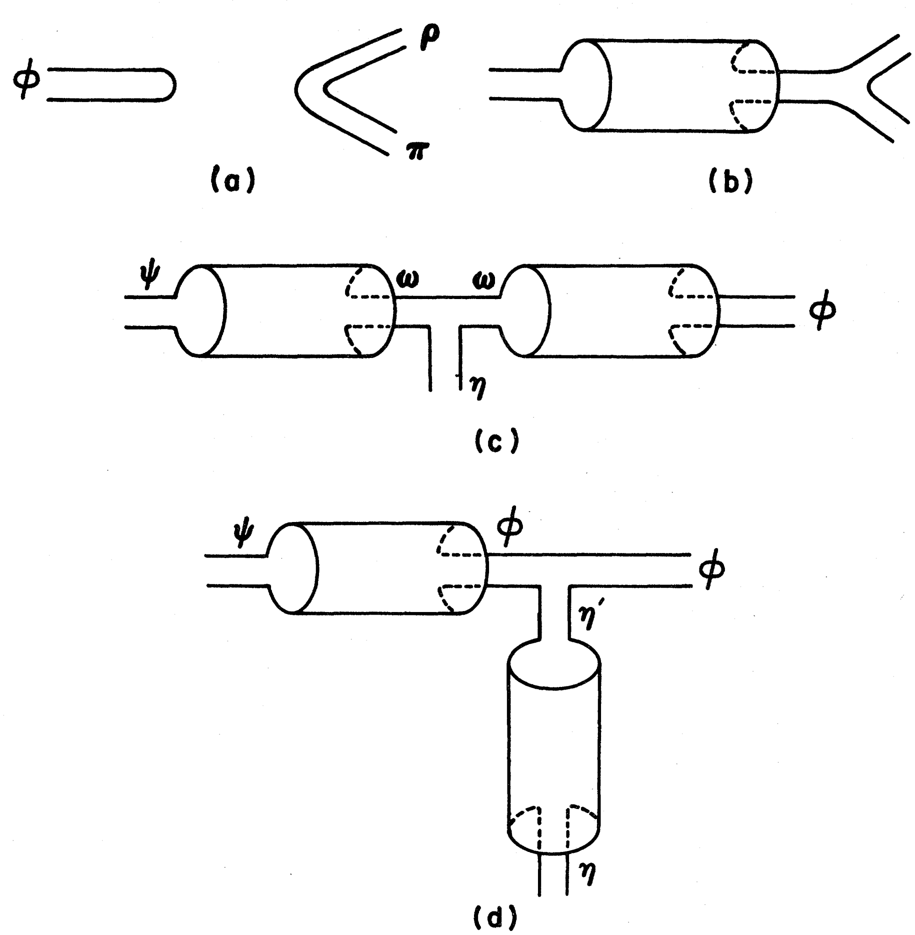

FIG. 1. (a) Dual diagram for $\phi \rightarrow \rho\pi$, (b) equivalent cylinder diagram, (c) and (d) equivalent topological diagrams for $\psi \rightarrow \phi\eta$.

with

$$P=\begin{bmatrix}(s-m_{\bar{\eta}}^2) & 0 & 0 & 0\\ 0 & (s-m_{\bar{\eta}'}^2)^{-1} & 0 & 0\\ 0 & 0 & (s-m_{\bar{\eta}_c}^2)^{-1} & 0\\ 0 & 0 & 0 & (s-m_{\bar{O}}^2)^{-1}\end{bmatrix}, \quad (3)$$

where the renormalized propagator is

$$\pi^{\alpha\beta}=(P^{-1}-Q)^{-1}=\sum_i \frac{V_i^{\alpha}V_i^{\beta}}{s-m_i^2}\equiv\sum_i\frac{\mathcal{R}_{\alpha\beta}^{\,i}}{s-m_i^2}, \quad (4)$$

$m_i=(m_\eta, m_{\eta'}, m_{\eta_c}, m_O)$ are solutions of $|\pi|=0$, (5)

and

$$V_i=\frac{[\sqrt{2}f(m_i-m_{\bar{\eta}}^2)^{-1}, f(m_i^2-m_{\bar{\eta}'}^2)^{-1}, f(m_i^2-m_{\bar{\eta}_c}^2)^{-1}, 1]}{\left(1+\frac{2f^2}{(m_i^2-m_{\bar{\eta}}^2)^2}+\frac{f^2}{(m_i-m_{\bar{\eta}'}^2)^2}+\frac{f^2}{(m_i^2-m_{\bar{\eta}_c}^2)}\right)^{1/2}} \quad (6)$$

The fourth O channel represents a quarkless state which mediates the OZI-rule violation, and is here approximated by a pole. As implemented, probability leaks into this state and we have 4×4 orthogonality and completeness. It is possible to reformulate this problem in a *physically inequivalent* form with a general interaction

$$O=h(s)\begin{pmatrix}2 & \sqrt{2} & \sqrt{2}\\ \sqrt{2} & 1 & 1\\ \sqrt{2} & 1 & 1\end{pmatrix}. \quad (7)$$

Since this is an energy-dependent interaction, orthogonality and completeness hold at a given value of s. Thus, in evaluating the residues orthogonality is lost but completeness is realized in a 3×3 sense. The procedure is technically complicated by subsidiary conditions on $h(s)$ which guarantee the stability of the physical masses and the 3×3 completeness. This will be described in detail elsewhere.[9] The main result of this calculation is that *there exists an alternative to the* 4×4 *system we describe whose numerical output is the* 3×3 *submatrix of the* 4×4 *residue matrix, renormalized so that the diagonal residues sum to unity in the* 3×3 *channel space.*

Continuing with the 4×4 theory, with $m_{\bar{\eta}}^2=m_\pi^2$ and $m_{\bar{\eta}}^2=2m_K^2-m_\pi^2$ specified by the ideal-mixing formula, and m_η^2, $m_{\eta'}^2$, and $m_{\eta_c}^2$ determined by experiment (we take $m_{\eta_c}^2$ to be recently discovered state at 2.80 GeV), we find that the theory is completely determined, yielding

$$f_{OP}^2=0.1916,$$
$$m_{\bar{\eta}_c}^2=2.79\text{ GeV}, \quad (8)$$

and the residue matrices of Table I.

With reference to the alternative 3×3 theory discussed above, the practical effect is to drop the O sector, leave the $\mathcal{R}^\eta$ and $\mathcal{R}^{\eta_c}$ residues essentially unchanged, and increase all $\mathcal{R}^{\eta'}$ residues by ~70%. Effects of this difference on our results will be noted below, where MI refers to the 4×4 model and MII to the 3×3 model. When the differences are small the particular model will not be identified.

III. HADRONIC RATES

We have, referring to Fig. 2(a),

$$\Gamma_{\psi'\psi\eta}=\frac{P_\psi^3}{3}\frac{G_{V'VP}^2}{4\pi}\mathcal{R}^{\eta}_{\bar{\eta}_c\bar{\eta}_c}. \quad (9)$$

Guided by the experience[1,6] with the vector-vector-scalar vertex which indicates $G_{V'VS}\approx G_{VVS}$, we assume that $G_{V'VP}\approx G_{VVP}$, and determine G_{VVP} from (i) $\omega\to\pi^0\gamma$ via vector dominance, (ii) $\omega\to3\pi$ via the Gell-Mann–Sharp–Wagner[10] intermediate-ρ-pole method, (iii) the SU(6) relation $G_{\omega\rho^0\pi^0}^2=4G_{\rho\pi\pi}^2/m_\rho^2$, and (iv) $\phi\to\rho\pi$, as in Ref. 1. All methods are consistent with $\frac{1}{2}G_{\omega\rho^0\pi^0}^2/4\pi=G_{VVP}^2/4\pi\approx9\pm2$. Then

$$\Gamma_{\psi'\psi\eta}\approx(9\pm2)\text{ keV (experiment[11]: 9.6 keV)}. \quad (10)$$

A number of other predictions follow easily:

$$\frac{\Gamma_{\psi\eta\omega}}{\Gamma_{\psi\rho\pi}}=\frac{1}{3}\frac{G_{\omega\omega\bar{\eta}}^2}{G_{\omega\rho\pi}^2}\left|\frac{P_\omega}{P_\rho}\right|^3\mathcal{R}^{\eta}_{\bar{\eta}\bar{\eta}}\approx0.03, \quad (11)$$

TABLE I. Residue matrices for η, η', and η_c poles in the 4×4 model (MI).

$$\mathcal{R}^{\eta}=\begin{bmatrix}0.39 & -0.45 & -0.010 & 0.18\\ & 0.53 & 0.012 & -0.21\\ & & 2.8\times10^{-4} & 4.7\times10^{-3}\\ & & & 8.1\times10^{-2}\end{bmatrix}$$

$$\mathcal{R}^{\eta'}=\begin{bmatrix}0.19 & 0.28 & -0.018 & 0.28\\ & 0.40 & -0.026 & 0.40\\ & & 0.16\times10^{-2} & -0.026\\ & & & 0.41\end{bmatrix}$$

$$\mathcal{R}^{\eta_c}=\begin{bmatrix}2.03\times10^{-5} & 1.5\times10^{-5} & 4.5\times10^{-3} & 2.6\times10^{-4}\\ & 1.1\times10^{-5} & 3.4\times10^{-3} & 1.9\times10^{-4}\\ & & 0.997 & 5.7\times10^{-2}\\ & & & 3.2\times10^{-3}\end{bmatrix}$$

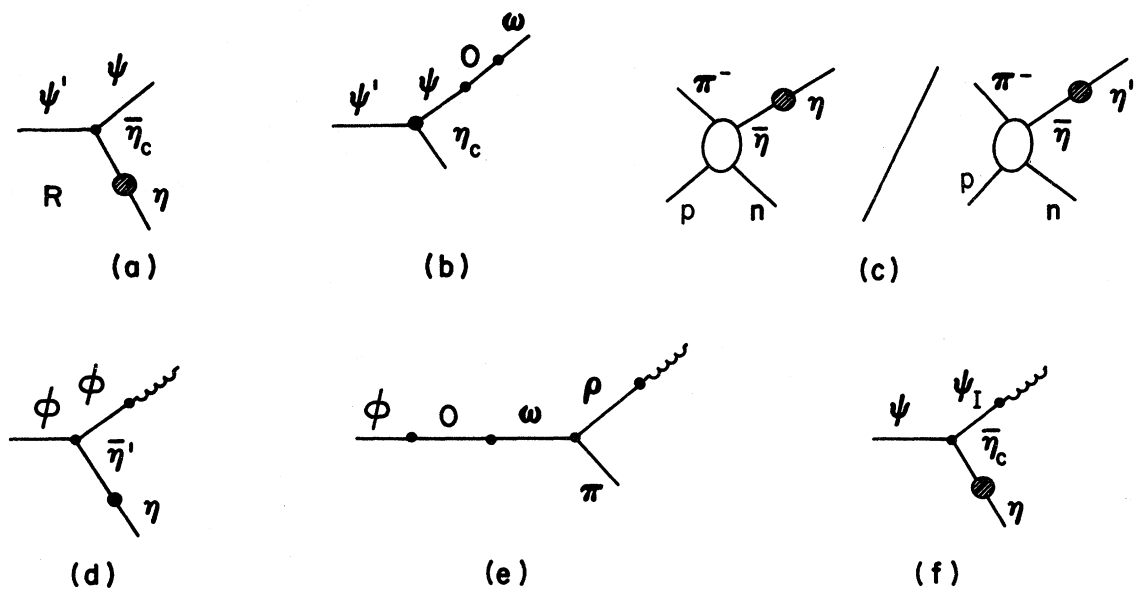

FIG. 2. Diagrams for various OZI-rule-forbidden processes.

$$\frac{\Gamma_{\psi\eta'\phi}}{\Gamma_{\psi\eta\omega}} \approx \left|\frac{P_\phi}{P_\omega}\right|^3 \left(\frac{m_\psi{}^2 - m_\omega{}^2}{m_\psi{}^2 - m_\phi{}^2}\right)^2 \frac{\mathcal{R}^{\eta'}_{\bar\eta'\bar\eta'}}{\mathcal{R}^{\eta}_{\bar\eta\bar\eta}} \approx \begin{cases} 0.7\ (\mathrm{MI}) \\ 1.1\ (\mathrm{MII}) \end{cases}, \tag{12}$$

$$\frac{\Gamma_{\psi\eta'\omega}}{\Gamma_{\psi\eta\omega}} \approx \left|\frac{P_{\eta'}}{P_\eta}\right|^3 \frac{\mathcal{R}^{\eta'}_{\bar\eta\bar\eta}}{\mathcal{R}^{\eta}_{\bar\eta\bar\eta}} \approx \begin{cases} 0.38\ (\mathrm{MI}) \\ 0.59\ (\mathrm{MII}) \end{cases}. \tag{13}$$

An interesting way of looking for η_c is in the decay $\psi' \to \eta_c\omega$. Rosenzweig[4] predicts that this rate is only slightly ($\frac{1}{3}$) suppressed relative to $\psi' \to \psi\eta$. However, within our framework [see Fig. 2(b)], since the 0^+ OZI transitions are more copious than the 1^- OZI transitions (which *can* be handled perturbatively) we have

$$\frac{\Gamma_{\psi'\omega\eta_c}}{\Gamma_{\psi'\psi\eta}} = \left|\frac{P_{\eta_c}}{P_\eta}\right|^3 \frac{2 f_{OV}{}^4}{(m_\omega{}^2 - m_O{}^2)^2 (m_\omega{}^2 - m_\psi{}^2)^2} \frac{1}{\mathcal{R}^{\eta}_{\bar\eta_c\bar\eta_c}} \approx 0.084. \tag{14}$$

This model makes predictions, of course, for OZI-rule-violating production processes as well. Referring to Fig. 2(c), we have

$$\frac{d\sigma(\pi^- p \to \eta n)}{d\sigma(\pi^- p \to \eta' n)} = \frac{\mathcal{R}^{\eta}_{\bar\eta\bar\eta}}{\mathcal{R}^{\eta'}_{\bar\eta\bar\eta}} \approx \begin{cases} 2.05\ (\mathrm{MI}) \\ 1.3\ (\mathrm{MII}) \end{cases}, \tag{15}$$

where both cross sections are evaluated at the same s, t, and q^2. One hopes that the extrapolation in q^2 from $m_\eta{}^2$ to $m_{\eta'}{}^2$ is not too serious. However, comparisons should be made at the same s and t. We expect the predicted ratio to be much more accurate at $t=0$, since production processes at high momentum transfer depend more strongly on the mass of the produced object. Extensive data on this reaction will be available shortly.[12]

It is interesting to note that in our formalism we are able to account for the masses *and* the OZI suppression with physical η and η' that have extremely small admixture of charm. In particular, referring to Table I, we find 0.028% charm in η and 0.16% charm in η'. This is in sharp contrast with the Harari[2] treatment. The origin of this is clear: In our treatment the OZI-rule violation contributes to both diagonal and off-diagonal terms in the mass matrix. Thus we are freed from the constraint

$$m_{\bar\eta}{}^2 + m_{\bar\eta'}{}^2 + m_{\bar\eta_c}{}^2 = m_\eta{}^2 + m_{\eta'}{}^2 + m_{\eta_c}{}^2 \tag{16}$$

which forces Harari's large charm admixture.

IV. PHOTONIC RATES

Also in contrast with Harari, we find no serious problems with γ decays in the context of the vector-dominance model. The new ingredient here, apart from a different mixing, is the use of ψ' as another intermediate state in decays involving ψ as an intermediate state.[6] We choose a judicious relative phase. We do not believe that this is artificial, because there is no reason why (consistent with the assumption $G_{V'VP}{}^2 \approx G_{VVP}{}^2$) we cannot have $G_{V'VP} \approx -G_{VVP}$. Moreover, alternating signs considerably enhance the possibility of a convergent generalized-vector-dominance-model sum. This addition of radial excitations, interestingly enough, does not spoil rates such as $\omega \to \pi^0\gamma$ since the ρ' electronic width is expected to be *considerably* smaller than the ρ electronic width,[13] in contrast with the ψ' vs ψ electronic widths. With these preliminaries, consider the rates [referring to Figs. 2(d) and 2(e)]

$$\Gamma_{\phi\to\eta\gamma} = \frac{|P\gamma|^3}{3}\frac{G_{VVP}^2}{4\pi}\frac{3\Gamma_{\phi\to e^+e^-}}{\alpha m_\phi}\mathcal{R}^{\eta}_{\bar{\pi}\bar{\pi}}, \qquad (17)$$

which yields a partial width of (44.5 ± 10) keV consistent with recent data[14] indicating an experimental partial width of 65 ± 15 keV. (Our quoted error is determined by the uncertainty in G_{VVP}.)

Similarly we have

$$\Gamma_{\phi\to\pi^0\gamma} = \frac{|P\gamma|^3}{3}\frac{2G_{VVP}^2}{4\pi}\frac{3\Gamma_{\rho e^+e^-}}{\alpha m_\rho} \times\frac{2f_{OV}^4}{(m_\phi^2-m_0^2)^2(m_\phi^2-m_\omega^2)^2}, \qquad (18)$$

which yields a partial rate of (10.8 ± 3) keV compared with the experimental[14] partial rate of 5.9 ± 2.1 keV.

Referring to Fig. 2(f), with $\psi_{\rm I}$ now ψ and ψ', we have for $\psi\to\eta\gamma$

$$\Gamma_{\psi\eta\gamma} = \frac{1}{4\pi}\frac{|P\gamma|^3}{3}\mathcal{R}^{\eta}_{\bar{\eta}_c\bar{\eta}_c}\left|\frac{eF_\psi}{m_\psi^2}G_{VVP}+\frac{eF_{\psi'}}{m_{\psi'}^2}G_{V'VP}\right|^2,$$

$$= \frac{|P\gamma|^3}{3}\frac{G_{VVP}^2}{4\pi}\mathcal{R}^{\eta}_{\bar{\eta}_c\bar{\eta}_c}\frac{3\Gamma_{\psi e^+e^-}}{\alpha}\frac{1}{m_\psi}B, \qquad (19)$$

where

$$B = \left[1+\frac{G_{VV'P}}{G_{VVP}}\left(\frac{\Gamma_{\psi' e^+e^-}}{\Gamma_{\psi e^+e^-}}\frac{m_\psi}{m_{\psi'}}\right)^{1/2}\right]^2. \qquad (20)$$

Using $\Gamma_{\psi\eta\gamma}=100$ eV (Ref. 15) we find that

$$\frac{G_{VV'P}}{G_{VVP}} = -1.24, -1.98; \qquad (21)$$

the first root is consistent with our earlier assumption[16] $G_{VV'P}^2 \approx G_{VVP}^2$. Using this new determination we have

$$\Gamma_{\psi\eta_c\gamma} = \frac{|P\gamma|^3}{3}\frac{G_{VVP}^2}{4\pi}\mathcal{R}^{\eta_c}_{\bar{\eta}_c\bar{\eta}_c}\frac{3\Gamma_{\psi e^+e^-}}{\alpha}\frac{1}{m_\psi}B$$
$$= 2.2 \text{ keV}, \qquad (22)$$

which is now a prediction based on $\Gamma_{\psi\eta\gamma}$.

Similarly we find

$$\frac{\Gamma_{\psi\eta'\gamma}}{\Gamma_{\psi\eta\gamma}} = \begin{cases}4.6 \text{ (MI)}\\ 7.5 \text{ (MII)}\end{cases} \quad (\text{data}^{14}\text{: } 4\pm2.5). \qquad (23)$$

Treating the $\psi'\to\eta_c\gamma$ decay in analogy to the $\psi\to\eta_c\gamma$ decay we find

$$\Gamma_{\psi'\eta_c\gamma} = \frac{|P\gamma|^3}{3}\frac{G_{VV'P}^2}{4\pi}\mathcal{R}^{\eta_c}_{\bar{\eta}_c\bar{\eta}_c}\frac{3\Gamma_{\psi e^+e^-}}{\alpha}\frac{1}{m_\psi}B', \qquad (24)$$

where

$$B' = \left|1+\frac{G_{V'V'P}}{G_{VV'P}}\left(\frac{\Gamma_{\psi' e^+e^-}m_\psi}{\Gamma_{\psi e^+e^-}m_{\psi'}}\right)^{1/2}\right|^2. \qquad (25)$$

If we assume that $G_{VVP}G_{V'V'P} \approx G_{VV'P}^2$, we have

$$\Gamma_{\psi'\eta\gamma} \approx 50 \text{ keV}. \qquad (26)$$

Continuing in this spirit, we have

$$\Gamma_{\eta_c\to\gamma\gamma} = \frac{G_{VVP}^2}{4\pi}\frac{|P\gamma|^3}{2}\left(\frac{3\Gamma_{\psi e^+e^-}}{\alpha m_\psi}\right)^2 \times\left[1+\frac{\Gamma_{\psi'}m_\psi G_{VV'P}^2}{\Gamma_\psi m_{\psi'}G_{VVP}^2}+2\frac{G_{VV'P}}{G_{VVP}}\left(\frac{\Gamma_{\psi' e^+e^-}m_\psi}{\Gamma_{\psi e^+e^-}m_{\psi'}}\right)^{1/2}\right]^2$$
$$\cong 15 \text{ eV}. \qquad (27)$$

(This width should be taken with caution since it depends on the square of the difference of two large numbers; a factor-of-2 variation in the coupling ratio can result in a factor-of-50 increase in the rate.)

Taking Γ_{η_c} full width to be 100 keV, which is certainly a lower limit, we find

$$\frac{\Gamma_{\psi'\eta_c\gamma}}{\Gamma_{\psi'}}\frac{\Gamma_{\eta_c\gamma\gamma}}{\Gamma_{\eta_c}} \le 4\times10^{-5}, \qquad (28)$$

TABLE II. Table of various rates involving OZI-rule-forbidden transitions. MI is the 4×4 model and MII is the 3×3 model.

Rates	Theory	Exp.
$\Gamma(\psi'\to\psi\eta)$	9 ± 2 keV	9.6 ± 1.8 keV
$\Gamma(\psi\to\eta\omega)/\Gamma(\psi\to\rho\pi)$	0.03	
$\Gamma(\psi\to\eta'\varphi)/\Gamma(\psi\to\eta\omega)$	0.7 (MI) 1.1 (MII)	
$\Gamma(\psi'\omega\eta_c)/\Gamma(\psi'\psi\eta)$	0.38 (MI) 0.59 (MII)	
$\Gamma(\psi'\omega\eta_c)/\Gamma(\psi'\psi\eta)$	0.084	
$\frac{d\sigma(\pi^-p\to\eta n)}{d\sigma(\pi^-p\to\eta' n)}$	2.05 (MI) 1.3 (MII)	
$\Gamma(\varphi\to\eta\gamma)$	44.5 ± 10 keV	65 ± 15 keV
$\Gamma(\varphi\to\pi^0\gamma)$	10.8 ± 3 keV	5.9 ± 2.1 keV
$\Gamma(\psi\eta\gamma)$	normalization	100 ± 25 eV
$\Gamma(\psi\eta_c\gamma)$	2.2 keV	
$\Gamma(\psi\eta'\gamma)/\Gamma(\psi\to\eta\gamma)$	4.6 (MI) 7.5 (MII)	4 ± 2.5
$\Gamma(\psi'\eta_c\gamma)$	50 keV	
$\Gamma(\eta_c\to\gamma\gamma)$	15 eV	
$\Gamma(\psi'\to\rho_0\rho_0\gamma)$	$<50B(\eta_c\to\rho_0\rho_0)$ keV	<7 keV

which is well within the experimental[15] bound.

Finally, consider $\psi' \to \rho_0\rho_0\gamma$, which Harari points out as a possible problem. We have

$$\Gamma_{\psi' \to \rho_0\rho_0\gamma} \leq \Gamma_{\psi' \to \gamma\eta_c} B_{\eta_c\rho_0\rho_0} = 50 \text{ keV}$$

$$(\text{experiment}^{17}\text{: } B_{\eta_c\rho_0\rho_0} \leq 7 \text{ keV}), \qquad (29)$$

which is consistent with a plausible branching ratio $B_{\eta_c\rho_0\rho_0}$ for $\eta_c \to \rho_0\rho_0$. Our decay rates are summarized in Table II.

V. SUMMARY AND CONCLUSIONS

(i) The mixing generated by O-meson or cylinder correction, controlled by the 0^- masses, yields a correct rate for $\psi' \to \psi\eta$ and results in predictions for a number of measurable hadronic rates, different from the predictions of Rosenzweig.[4]

(ii) The admixture of charm in η and η' is much smaller than the model of Harari indicates.

(iii) The photonic rates, calculated using this mixture and the extended vector-dominance-model, yield results consistent with experiment.

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