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Interference effects in J (ψ) decay

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The direct hadronic decay amplitude $J(\psi)\rightarrow$hadrons can interfere with the decay amplitude via one photon, $J(\psi)\rightarrow 1\gamma\rightarrow$hadrons. We show how this might be useful. A definite pattern of coherence or incoherence of direct and 1γ decay amplitudes could test theoretical explanations for the small J (ψ) width. It should also prove possible to extract meson and baryon electromagnetic form factors at $Q^2 = m_J{}^2$.

There is evidence that the recently discovered J (ψ) (see Refs. 1 and 2) particle at 3.1 GeV has zero isospin, and that the presence of $I\neq 0$ final states (e.g., $4\pi^\pm$, $6\pi^\pm$) is due dominantly or entirely to the process $J\rightarrow 1\gamma\rightarrow$hadrons.[3] This is consistent with the picture of J and ψ'... as states built out of new heavy quarks ($J=Q\bar{Q}$). These states are probably also singlets under ordinary SU(3). Decays of J then require $Q\bar{Q}$ annihilation. Direct hadronic annihilation processes (or $Q\bar{Q}\rightarrow q\bar{q}$ mixing) are expected to conserve I; only $J\rightarrow 1\gamma\rightarrow$hadrons does not. In addition the "direct" decay should at least approximately conserve SU(3) and lead to predominantly SU(3) singlet final states. The decay $J\rightarrow 1\gamma\rightarrow$hadrons should lead to predominantly octet final states. Within this framework there are several possible explanations for the surprisingly small J width. One is that J contains a very small admixture of light quarks (already alluded to). Two possible quark pictures for this mixing term (for two-body final states) are shown in Fig. 1(a) and Fig. 1(b). The first is a simple real direct $Q\bar{Q}\rightarrow q\bar{q}$ mixing[4]; the second is mixing induced by the (virtual) process $Q\bar{Q}\rightarrow Q\bar{q}+\bar{Q}q\rightarrow q\bar{q}$.[5] In both cases the mixing is real relative to the $Q\bar{Q}\rightarrow 1\gamma\rightarrow q\bar{q}$ amplitude [Fig. 1(c)]. Another option is to suppose that J decay takes place through the incoherent annihilation $Q\bar{Q}\rightarrow$gluons$\rightarrow$hadrons.[6] Two-body final states such as those in Fig. 1 are then reached via $Q\bar{Q}\rightarrow$gluons$\rightarrow q\bar{q}$ as in Fig. 1(a), but with the important difference that the gluon lines can be cut to expose a multihadron state. There is then no reason to expect the direct decay amplitude $J\xrightarrow{d}$hadrons and the 1γ amplitude $J\rightarrow 1\gamma\rightarrow$hadrons to be relatively real. Is there any way of testing these pictures? In our view the study of two-body decays offers an opportunity. The amplitude for $J\rightarrow 1\gamma\rightarrow AB$ can be found via off-resonance measurements of $e^+e^-\rightarrow 1\gamma\rightarrow AB$, and used on-resonance as a probe of the direct decay amplitude, in particular of its phase relative to 1γ, which may allow us to check the models we mentioned. An alternative is to measure on resonance one channel which has $I=1$ and comes only via 1γ, using SU(3) to get the other 1γ amplitudes. Since this seems most practical at present, we shall discuss it here. Our aim is to show that the effects can be large.

First we want to make a simple observation. If SU(3) is exact, it is clear that the 1γ and direct decay amplitudes cannot interfere in the *total* rate. This is because the $\underline{8}$ and $\underline{1}$ final states are orthogonal. However, there can be interference effects in the rate for *specific* final states. This is self-evident for $J\rightarrow\pi^+\pi^-\pi^0$. Such interference cancels only on summing over a complete SU(3) set of final states. Interference can have drastic effects on relations such as $\Gamma(K^{*0}\bar{K}^0)=\Gamma(K^{*+}K^-)$ valid for J in the absence of 1γ.

As an example of the effects coming from interference we first consider $J\rightarrow$vector + pseudoscalar mesons. Some relations depend only on the fact that J and γ have $U=0$, e.g.,

$$\Gamma(\rho^\pm\pi^\mp)=\Gamma(K^{*\pm}K^\mp). \quad (1)$$

If this is violated, SU(3) is broken in either the

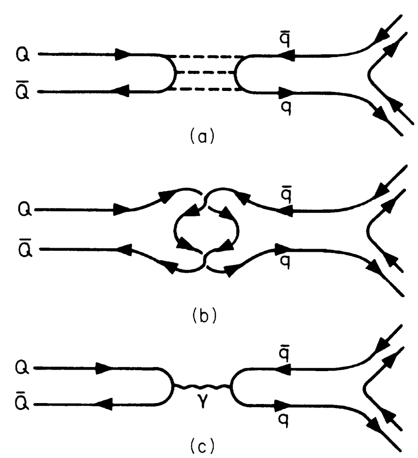

FIG. 1. (a) A simple mixing model for the transition $J\rightarrow AB$ using a quark picture with new heavy quarks $Q\bar{Q}$ for the J. The dashed lines denote a (real) gluon mixing term. (b) Mixing via the virtual transition $Q\bar{Q}\rightarrow Q\bar{q}+\bar{Q}q\rightarrow q\bar{q}$. This is real below the $Q\bar{q}+\bar{Q}q$ threshold. (c) The 1γ amplitude in the same picture.

1γ, the direct amplitude, or both. We write the matrix element for $J \xrightarrow{d} V_i P_j$ plus $J \to 1\gamma \to V_i P_j$ as

$$A\,\frac{\delta_{ij}}{2} + (d_{3ij} + d_{8ij}/\sqrt{3}\,)\,D + d_{8ij}\,D' , \tag{2}$$

and get rates proportional to the entries in Table I (modulo phase-space factors), e.g.,

$$\Gamma(\rho\pi) \propto 3\,|\tfrac{1}{2}A + \tfrac{1}{3}D + \tfrac{1}{3}D'\,|^2 . \tag{3}$$

In doing this we took a pure octet SU(3)-breaking term D' (consistent with the $Q\bar{Q} \to q\bar{q}$ mixing models of Fig. 1), octet η, and ideally mixed ω and ϕ.

It is easy to verify that with $D' = 0$ the direct and 1γ amplitudes do not interfere in the total $J \to VP$ rate, summed over all vector and pseudoscalar mesons.

The rates in Table I depend on three parameters: A, D, and D'. Because of limited experimental information, we cannot carry out a complete analysis. In order to get a feeling for the effects which interest us we will parametrize the rates in terms of the ratios

$$\Gamma(\rho\eta)/\Gamma(\rho\pi) \text{ and } \Gamma(K^{*\pm}K^{\mp})/\Gamma(\rho\pi)$$

(on resonance). The first ratio measures the size of the 1γ term, since $\rho\eta$ has $I=1$ and cannot arise from isospin-conserving direct decays; the second ratio measures SU(3) breaking. There is as yet no data on $J \to \rho\eta$. In the following we will assume that A and D' are relatively real. As support for this we note in advance that $|D'|/|A| \sim 0.4 - 0.6$ for zero relative phase. This ratio seems reasonable. As the relative phase increases $|D'|/|A|$ increases rapidly, and large values for this ratio do not seem so reasonable. Of course, it should be possible to extract this relative phase from data—e.g. once $\Gamma(\phi\eta)$ becomes available.

With this input assumption and the measured ratio[7]

$$\frac{\Gamma(K^{*\pm}K^{\mp})}{\Gamma(\rho\pi)} = \frac{0.31 \pm .07}{1.3 \pm 0.3}\,, \tag{4}$$

TABLE I. Vector + pseudoscalar decay rates in terms of singlet (A), one-photon (D), and octet SU(3)-breaking (D') parameters. Phase space is not included.

$\rho\pi = 3\lvert A/2 + D/3 + D'/3\rvert^2$
$K^{*\pm}K^{\mp} = 2\lvert A/2 + D/3 - D'/6\rvert^2$
$K^{*0}K^0 = 2\lvert A/2 - 2D/3 - D'/6\rvert^2$
$\phi\eta = \frac{2}{3}\lvert A/2 - 2D/3 - 2D'/3\rvert^2$
$\omega\eta = \frac{1}{3}\lvert A/2 + D/3 + D'/3\rvert^2$
$\omega\pi^0 = \lvert 0 + D + 0\rvert^2$
$\rho\,\eta = \lvert 0 + D/\sqrt{3} + 0\rvert^2$

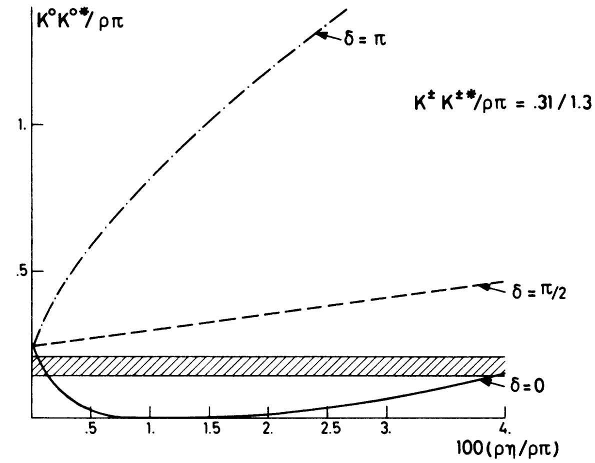

FIG. 2. The ratio $\Gamma(K^{*0}K_0)/\Gamma(\rho\pi)$ as a function of $\Gamma(\rho\mu)/\Gamma(\rho\pi)$ for three values of the relative phase of the direct and 1γ amplitudes, Phase-space corrections are not included. The shaded band is the experimental range.

we can calculate rates for other channels, and in Fig. 2 we show $\Gamma(K^{*0}K^0)/\Gamma(\rho\pi)$ as a function of $\Gamma(\rho\eta)/\Gamma(\rho\pi)$ for three values of the relative phase between A and D, $\delta = 0,\ \pi/2,\ \pi$. The effects are large for $\Gamma(\rho\eta)/\Gamma(\rho\pi) \gtrsim 0.5\%$. The measured ratio $\Gamma(K^{*0}K^0)/\Gamma(\rho\pi)$ is shown as a shaded band. The dependence on δ is striking. We can carry out the same sort of analysis for the baryon-antibaryon channels; again SU(3) gives U-spin equalities such as $\Sigma^+\bar{\Sigma}^+ = p\bar{p}$ independent of interference. Including a direct and a single decay term [plus a single octet SU(3)-breaking term] we have a matrix element

$$A\,\frac{\delta_{ij}}{2} + \left(d_{3ij} + \frac{d_{8ij}}{\sqrt{3}}\right) D + i\left(f_{3ij} + \frac{f_{8ij}}{\sqrt{3}}\right) F + \frac{d_{8ij}}{\sqrt{3}} D' + \frac{d_{8ij}}{\sqrt{3}} F' . \tag{5}$$

The rates are proportional to the entries in Table II (again modulo phase-space factors). For $B\bar{B}$ we measure the 1γ decay via $J \to \Sigma^0\bar{\Lambda}^0 + \Lambda^0\bar{\Sigma}^0$. It is more involved to incorporate SU(3) breaking here, and is not clearly required by data; so we will set $D' = F' = 0$. Now we can parametrize everything in terms of $\Gamma(\Sigma^0\bar{\Lambda}^0)/\Gamma(p\bar{p})$ and $\Gamma(\Lambda\bar{\Lambda})/\Gamma(p\bar{p})$. The measured value for the second ratio is 0.75 ±0.27;[8] for the first there is an upper bound of 0.1.[8] For the result see Fig. 3, where we give

$$\Gamma(\Sigma^-\bar{\Sigma}^- \text{ or } \Xi^-\bar{\Xi}^-)/\Gamma(p\bar{p}),$$

$$\Gamma(\Sigma^0\bar{\Sigma}^0)/\Gamma(p\bar{p}),$$

and

$$\Gamma(n\bar{n} \text{ or } \Xi^0\bar{\Xi}^0)/\Gamma(p\bar{p}).$$

TABLE II. Baryon-antibaryon decay rates in terms of singlet (A), one-photon (D,F), and octet SU(3)-breaking (D',F') parameters. Phase space is not included.

$p\bar{p} = \lvert A/2 + D/3 + F - D'/6 + F'/2 \rvert^2$
$n\bar{n} = \lvert A/2 - 2D/3 - D'/6 + F'/2 \rvert^2$
$\Sigma^+\bar{\Sigma}^+ = \lvert A/2 + D/3 + F + D'/3 \rvert^2$
$\Sigma^0\bar{\Sigma}^0 = \lvert A/2 + D/3 + D'/3 \rvert^2$
$\Sigma^-\bar{\Sigma}^- = \lvert A/2 + D/3 - F + D'/3 \rvert^2$
$\Sigma^0\bar{\Lambda} = \lvert 0 + D/\sqrt{3} + 0 \rvert^2$
$\Lambda\bar{\Lambda} = \lvert A/2 - D/3 - D'/3 \rvert^2$
$\Xi^-\bar{\Xi}^- = \lvert A/2 + D/3 - F - D'/6 - F'/2 \rvert^2$
$\Xi^0\bar{\Xi}^0 = \lvert A/2 - 2D/3 - D'/6 - F'/2 \rvert^2$

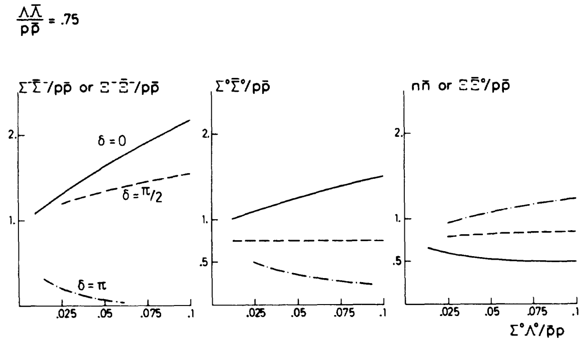

FIG. 3. Some ratios $\Gamma(B\bar{B})/\Gamma(p\bar{p})$ as a function of $\Gamma(\Sigma^0\bar{\Lambda})/\Gamma(p\bar{p})$ for three values of the phase δ. SU(3) has been assumed; phase-space corrections have not been included.

In all cases we kept $\Lambda\bar{\Lambda}/p\bar{p}$ fixed and varied $\Sigma^0\bar{\Lambda}/p\bar{p}$ from 0 to 0.1. Notice that the dependence on δ is again dramatic. Even including SU(3) breaking, it should prove possible to extract δ both for meson and $B\bar{B}$ channels. The analysis simply needs more data than now available.

As an alternative, one could get δ by measuring isospin-related channels such as $K^{*0}K^0, K^{*\pm}K^{\mp}$ and $p\bar{p}$, $n\bar{n}$ both on and off resonance. Experimentally harder, this no longer involves SU(3) in any way.

We have shown that it should be possible to extract the relative phase between the direct J decay and the decay via one photon, $J \rightarrow 1\gamma \rightarrow$hadrons, at least for two-body final states.[9] But is this of any use? After all, two-body decays are only a small fraction of the J width and need not reflect the dominant decay mechanism. Besides this, SU(3) breaking complicates the picture.[10]

We believe that interference effects can test models for the J decay mechanism. But there are conditions. A random pattern of relative phases (e.g., for VP and $B\bar{B}$) will probably mean that there is no fundamental connection between these decays and hypothesized J decay mechanisms. A dramatic pattern of maximal (expected in simple mixing models) or zero coherence of direct and 1γ decays, independent of decay channel, will surely mean the opposite and should teach us something about the physics behind the strikingly small J width.

Note added in proof. After this paper was submitted we learned of similar work by S. Rudaz [Phys. Ref. D 14, 298 (1976)].

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[8]G. Goldhaber *et al.*, SLAC Report No. SLAC-PUB-1622/LBL-4224, 1975 (unpublished); G. Goldhaber (private communication).
[9]It might be amusing to try this also for inclusive decays such as $J \rightarrow \bar{n} + X$, $\bar{p} + X$ or $K_S + X$, $K^+ + X$.
[10]If SU(3) breaking can be brought under control, it should be possible to extract meson and baryon electromagnetic form factors at the J mass, even for those cases where a direct J amplitude is present.