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RADIATIVE TRANSITIONS FROM THE $\psi(3095)$ AND $\psi'(3684)$ TO ORDINARY HADRONS*

Daniel L. Scharre
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

Mark II results from SPEAR on radiative transitions from the $\psi(3095)$ and $\psi'(3684)$ to ordinary hadrons (i.e., hadrons which do not contain charmed quarks to first order) are reviewed.

I. INCLUSIVE ψ RADIATIVE TRANSITIONS

First order QCD calculations predict that a significant fraction of the hadronic decays of heavy quark-antiquark $^3S_1$ resonances (such as the ψ) result in the production of direct photons (i.e., photons not coming from secondary decays of π^0's and η's).[1] The direct hadronic decay of the ψ must proceed via an intermediate state consisting of at least three color-octet gluons. The dominant contribution to direct photon production arises by replacement of one of the outgoing gluon lines by a photon. It is expected that approximately 8% of all ψ decays should contain a direct photon. This direct photon production is expected to peak at $x = 1$, where x is the fraction of the beam energy taken by the photon, and hence should be experimentally observable.

Figure 1 shows the inclusive γ momentum distribution at the ψ (solid circles) compared with the γ distribution predicted from the measured π^0 and η momentum distributions (open circles).[2] Whereas π^0 and η decays can account for the measured γ spectrum at low x, there is clearly an excess in the spectrum for $x \gtrsim 0.5$. The direct photon contribution, which was obtained by subtracting the predicted distribution from the measured distribution, is shown in Fig. 2. Also shown in the figure is the theoretical distribution (convoluted with the Mark II photon energy resolution) from lowest order in QCD. The observed integrated rate of direct photon

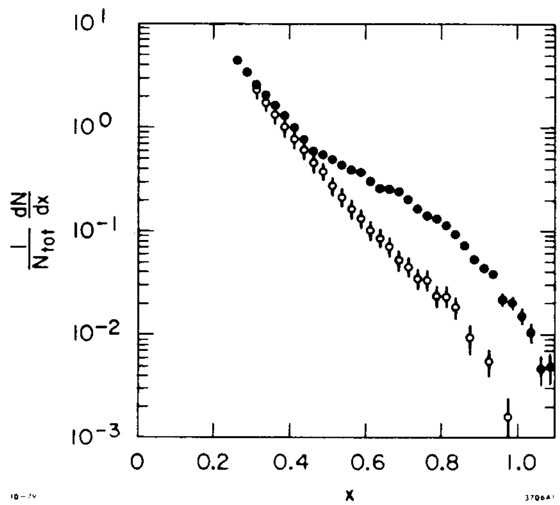

Fig. 1. Solid circles show the inclusive γ momentum distribution at the ψ, normalized to the total number of produced ψ events. Open circles show the expected distribution from π^0 and η decays.

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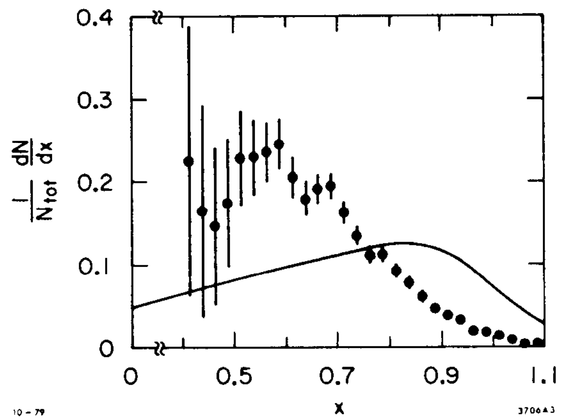

Fig. 2. Direct photon momentum distribution. Curve shows the leading-order QCD prediction.

production ($4.1 \pm 0.8\%$ for $x \geq 0.6$) agrees well with the theoretical estimate (5% for $x \geq 0.6$), but the observed distribution is softer than expected. However, the leading-order calculation ignores the effects of the masses of the final-state hadrons and radiative and second-order QCD effects. These are expected to soften the momentum distribution.

We have compared some properties of the hadronic system recoiling against direct photons (presumably resulting from fragmentation of a 2-gluon system) and the hadronic system produced directly in e^+e^- annihilations (presumably resulting from fragmentation of a quark-antiquark system) at comparable invariant mass. Figure 3 shows the mean produced charged particle multiplicity as a function of the invariant mass of the hadronic system (M_X) from this experiment[2] and two low-energy e^+e^- annihilation experiments.[3] Also shown are mean multiplicities extrapolated from higher-energy e^+e^- annihilation data.[4] The data indicate that multiplicities from gluon and quark fragmentation are similar at these energies. A similar comparison of K^0 multiplicities in our data and e^+e^- annihilation data shows no evidence for an enhanced kaon yield from gluon fragmentation.[2]

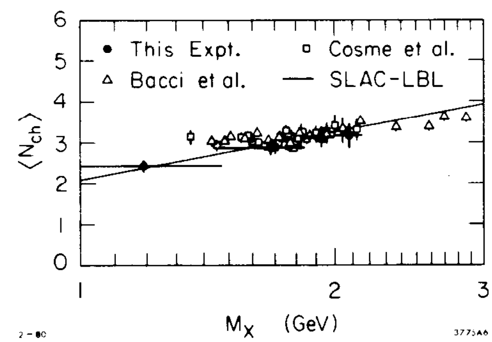

Fig. 3. Mean charged particle multiplicity as a function of the invariant mass of the hadronic system. Also shown are e^+e^- annihilation data (Refs. 3,4).

II. EXCLUSIVE ψ RADIATIVE TRANSITIONS

Transitions from the ψ to ordinary hadrons[5] are expected to proceed via emission of a photon from the initial-state charmed quark line as discussed in the previous section. The coupling to the ordinary quark-antiquark system is via a two-gluon system (in the case of the even C-parity states to be discussed here). Based on this model and the assumption of SU(3) invariance, a prediction for the relative widths of the $\gamma\eta$ and $\gamma\eta'$ transitions can be made. Unfortunately, this prediction does not agree with experimental measurements. However, if one allows for SU(3) symmetry breaking, these results are modified. Fritzsch and Jackson[6] have calculated the relative widths of the $\gamma\eta$ and $\gamma\eta'$ transitions by considering gluon-mediated mixing between the three isoscalar states η, η', and $\eta_c(2980)$. Based on the experimental masses of these states, they find a 1% admixture of η and a 2% admixture of η' in the η_c. This leads to the prediction $\Gamma(\psi\to\gamma\eta')/\Gamma(\psi\to\gamma\eta) \simeq 3.9$.

Figure 4 shows the $\pi^+\pi^-\gamma$ invariant mass distribution for events which satisfy constrained fits to the process

$$\psi \to \pi^+\pi^-\gamma\gamma \qquad . \qquad (1)$$

We observe a peak at the η' mass and determine the branching fraction $B(\psi\to\gamma\eta') = (3.4 \pm 0.7) \times 10^{-3}$. In order to measure the η branching fraction, it was necessary to analyze the process

$$\psi' \to \pi^+\pi^-\psi \quad , \quad \psi \to 3\gamma \ . \qquad (2)$$

(The Mark II trigger requirement does not allow direct observation of the 3γ decay of the ψ.) Of the ten events which satisfy constrained fits to (2), eight have a $\gamma\gamma$ combination with invariant mass consistent with the nominal value of the η mass. We determine $B(\psi\to\gamma\eta') = (0.9 \pm 0.4) \times 10^{-3}$. Based on these two measurements, we find $B(\psi\to\gamma\eta')/B(\psi\to\gamma\eta) = 3.8 \pm 1.9$, which agrees with the theoretical prediction of Fritzsch and Jackson.[6] These measurements are also in general agreement with previous measurements.[5]

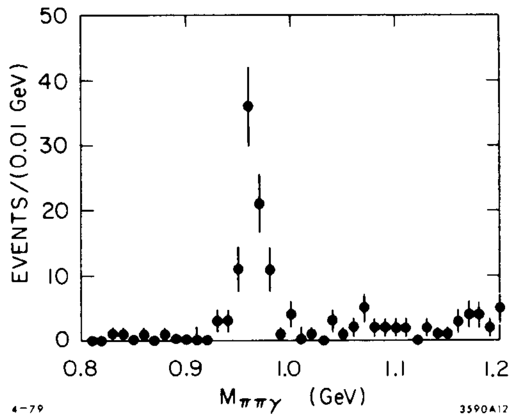

Fig. 4. $\pi^+\pi^-\gamma$ invariant mass distribution for events which satisfy (1).

Figure 5(a) shows the $\pi^+\pi^-$ invariant mass distribution for events which satisfy constrained fits to

$$\psi \to \pi^+\pi^-\gamma \qquad . \qquad (3)$$

A significant amount of background is expected from the $\pi^+\pi^-\pi^0$ decay mode (predominantly $\rho\pi$) of the ψ, as shown by the histogram in the figure. Figure 5(b) shows the $\pi^+\pi^-$ mass distribution after subtraction of this background. The fitted parameters of the peak in this distribution (with mass $M = 1280 \pm 20$ MeV and width $\Gamma = 180 \pm 50$ MeV) are consistent with those of the f. We find $B(\psi\to\gamma f) = (1.3 \pm 0.3) \times 10^{-3}$. We have looked for evidence of the transition $\psi\to\gamma f'$ in the $K^+K^-\gamma$ final state, but observe no signal. We set a 90% confidence level (c.l.) upper limit of $B(\psi\to\gamma f') \times B(f'\to K\bar{K}) < 10^{-3}$. This limit is not inconsistent with the naive theoretical calculation $B(\psi\to\gamma f')/B(\psi\to\gamma f) = 0.5$ based on SU(3) invariance.

Figure 6(a) shows the $K_S K^\pm\pi^\mp$ invariant mass distribution for events which satisfy 5-constraint (5C) fits (a K_S mass constraint is imposed in addition to the normal energy-momentum constraints) to

$$\psi \to K_S K^\pm\pi^\mp\gamma \qquad . \qquad (4)$$

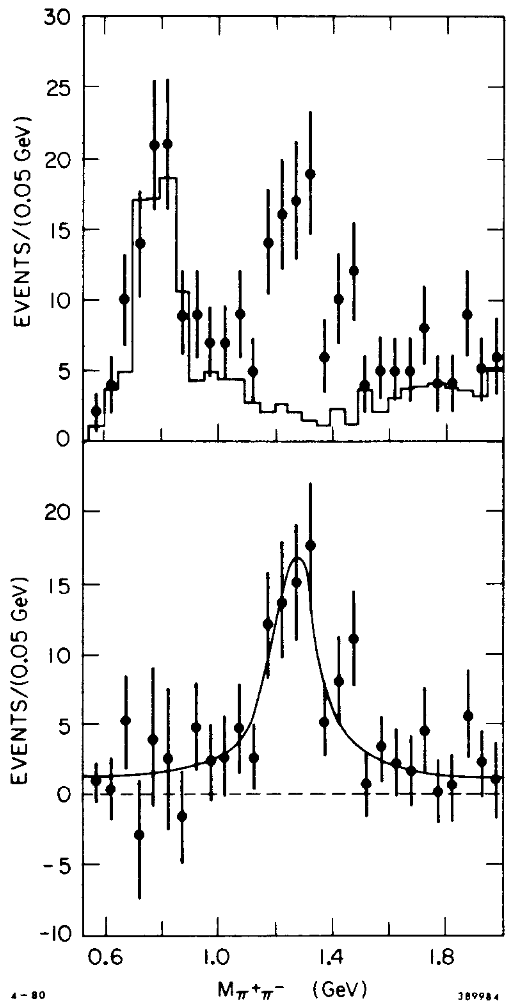

Fig. 5. (a) $\pi^+\pi^-$ invariant mass distribution for events which satisfy (3). Histogram shows the expected feeddown from the $\pi^+\pi^-\pi^0$ final state. (b) $\pi^+\pi^-$ invariant mass distribution after subtraction of the $\pi^+\pi^-\pi^0$ feeddown. Curve shows fit to data.

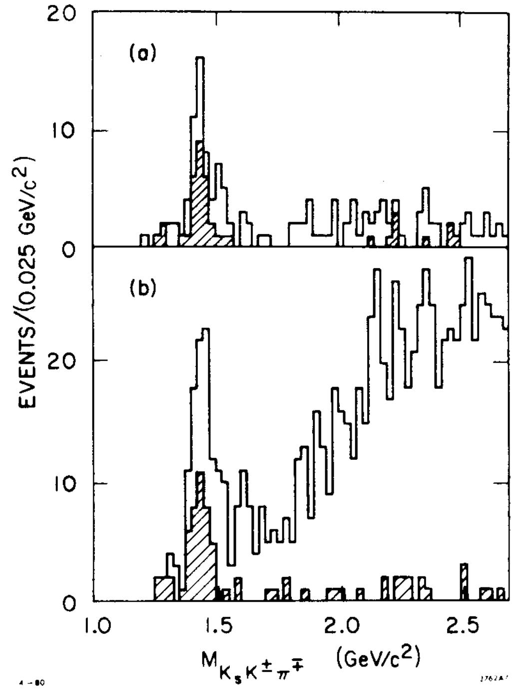

Fig. 6. $K_S K^\pm \pi^\mp$ invariant mass distributions for events which satisfy (a) 5C fits and (b) 2C fits to (4). Shaded regions have the additional requirement $M_{K\bar{K}} < 1.05$ GeV.

Figure 6(b) shows the same distribution for events which satisfy 2C fits (observation of the γ is not required) to (4). We observe a state near 1.4 GeV which we intepret as the E(1420).[7] From a fit to the distribution in Fig. 6(a), we determine $M = 1440^{+10}_{-15}$ MeV, $\Gamma = 50^{+30}_{-20}$ MeV, and $B(\psi \to \gamma E) \times B(E \to K\bar{K}\pi) = (3.6 \pm 1.4) \times 10^{-3}$. The Dalitz plot for the events shown in Fig. 6(b) with masses between 1.375 and 1.500 GeV (the signal region) is shown in Fig. 7. The data is inconsistent with a phase space distribution and we observe evidence for an excess of events in the region of the plot corresponding to low values of the $K_S K^\pm$ invariant mass. Figure 8 shows the $K_S K^\pm$ invariant mass projection for events in the signal region compared with the expected phase space distribution. There is an excess at low mass which we associate with the $\delta(980)$. As shown by the shaded region in Fig. 6 (which requires $M_{K\bar{K}} < 1.05$ GeV), this enhancement is associated with events in the signal region.

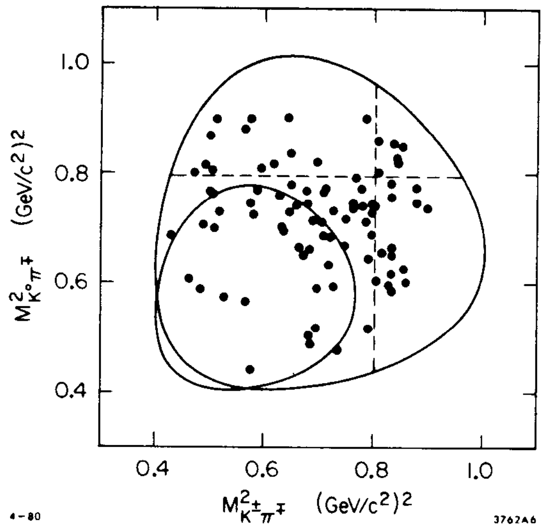

Fig. 7. Dalitz plot for events with $1.375 \leq M_{K\bar{K}\pi} < 1.500$ GeV. Curves show low-mass kinematic boundaries. Dashed lines show nominal K^* mass values.

It is expected that if gluonium states exist, they should be observed in radiative transitions from the ψ. I will comment on the possibility that the E is a gluonium state. First, the branching fraction for $\psi \to \gamma E$ is larger than the corresponding branching fractions for transitions to other ordinary hadrons, with the possible exception of the η'. This is in contrast to hadronic experiments where E production is small, in general, compared to the production of other resonant states. This indicates a connection between the E and the 2-gluon system associated with ψ radiative decays. However, it is possible that this is due only to the differences in the quantum numbers involved in the two types of processes.

Second, in most hadronic experiments in which an E is observed in the $K\bar{K}\pi$ channel, roughly comparable D(1285) production is also observed. We see no evidence for the transition $\psi \to \gamma D$ with 90% c.l. upper limit

$$\frac{B(\psi \to \gamma D) \times B(D \to K\bar{K}\pi)}{B(\psi \to \gamma E) \times B(E \to K\bar{K}\pi)} < 0.2.$$

This might be interpreted as evidence for a large gluonium component in the E but not the D. However, if one hypothesizes that the E is predominantly an SU(3) singlet state and the D is predominantly an SU(3) octet state, the transition to the D could be greatly suppressed relative to the E.

Finally, Dionisi et al.[8] recently reported a determination of the spin-parity of the E from a partial wave analysis of the $K_SK^\pm\pi^\mp$ system produced in the reaction $\pi^-p \to K_SK^\pm\pi^\mp n$ at 3.95 GeV/c. The spin-parity $J^P = 1^+$ was

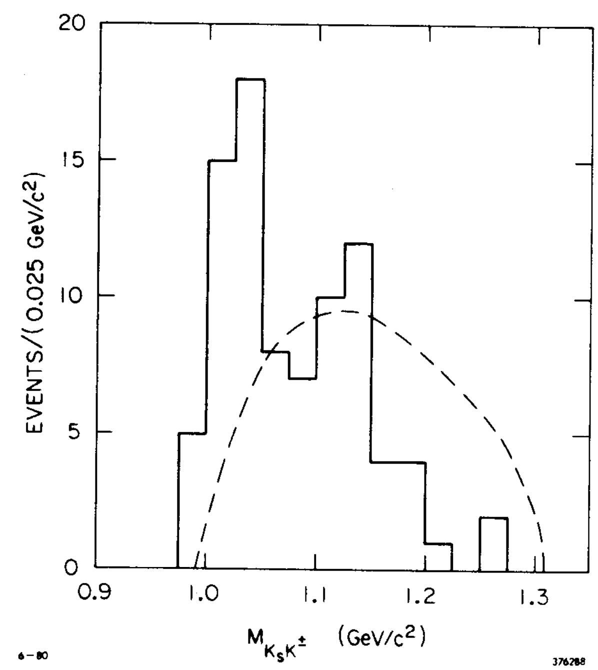

Fig. 8. $K_SK^\pm$ invariant mass distribution for events in the signal region. Curve shows expected phase space distribution.

determined from the $K^*\bar{K}$ (plus charge conjugate) decay mode of the E, which they find from their data to be the principal decay mode. This is inconsistent with Mark II results which find no evidence for a large $K^*\bar{K}$ decay mode, but rather require a significant fraction of the decay to go via $\delta\pi$. If the state observed by us and by Dionisi et al. are the same state, it is necessary to understand this inconsistency before the spin of the E can be considered as firmly established. (Unfortunately, our statistics are too limited to allow an independent determination of the spin.) If the E were finally established as an axial vector state, there would be no reason not to make the standard quark model interpretation and include it in the same nonet as the D(1285), A_1, and Q_A. If, on the other hand, the E were pseudoscalar, it would be difficult to interpret it within the standard quark model. The $J^P = 0^-$ nonet is complete, and one plausible interpretation of the E would be as a gluonium state.

III. EXCLUSIVE ψ' RADIATIVE TRANSITIONS

For a given exclusive decay of the ψ to some state X, the partial width is given by

$$\Gamma(\psi \to X) = |M_X|^2 |R(0)|^2 \quad ,$$

where M_X is the matrix element for the decay and R(0) is the wave function of the ψ at the origin. A similar expression can be written for the decay of the ψ' to some state X, where the wave function at the origin is expected to be different than for the ψ decay but the matrix element should be independent of the initial state. (All phase space factors are ignored in this discussion.) Thus, the ratio

$$R(X) = \frac{B(\psi' \to X)}{B(\psi \to X)} = \frac{B(\psi' \to e^+e^-)}{B(\psi \to e^+e^-)} \simeq 0.13$$

is expected to be independent of the state X. In addition to the e^+e^- final state (which was used in the determination of the value 0.13), the following measurements have been made:[9] $R(\pi^+\pi^-\pi^+\pi^-\pi^0) = 0.095 \pm 0.043$, $R(\pi^+\pi^-K^+K^-) = 0.19 \pm 0.08$, and $R(p\bar{p}) = 0.11 \pm 0.04$. These ratios are consistent with the expected value of 0.13.

Figure 9 shows the $\pi^+\pi^-\gamma$ invariant mass for events which satisfy constrained fits to the process

$$\psi' \to \pi^+\pi^-\gamma\gamma \quad . \qquad (5)$$

From the signal observed at the mass of the η', we determine $B(\psi' \to \gamma\eta') = (2.0 \pm 1.0) \times 10^{-4}$ and $R(\gamma\eta') = 0.06 \pm 0.03$. This value for R is somewhat smaller

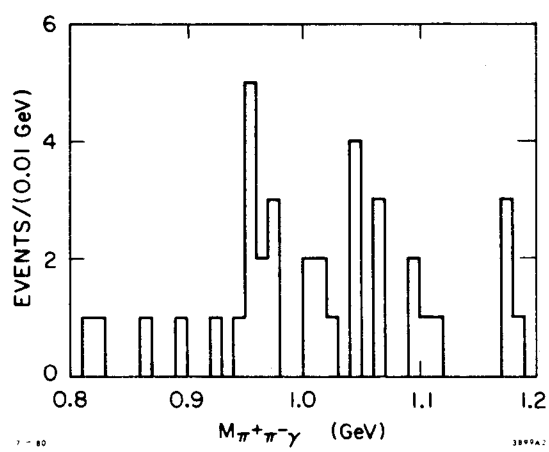

Fig. 9. $\pi^+\pi^-\gamma$ invariant mass distribution for events which satisfy (5).

than the expected value of 0.13.

No other radiative transitions from the ψ' have been observed, but 90% c.l. upper limits on two decay modes are significantly smaller than 0.13: $R(\eta\gamma) < 0.08$[10] and $R(\gamma E) < 0.03$[7]. However, since radiative transitions occur via photon emission from the charmed quark line, it is not correct to calculate partial widths in terms of the wave functions of the ψ or the ψ' at the origin. The calculation is more complicated because it involves intermediate $c\bar{c}$ states (resulting from the photon emission) which are different for each final state and also depend on whether the transition originated from the ψ or ψ'. To add confusion to the situation, we see no evidence for the decay $\psi' \to \rho^0\pi^0$ with 90% c.l. upper limit $R(\rho^0\pi^0) < 0.011$, which is an order-of-magnitude smaller than expected. Clearly, more ψ' data is required.

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