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Invited paper presented at the Workshop on Glueballs,  
Hybrids, and Exotic Hadrons, Upton, NY,  
August 29–September 1, 1988

### Resonance Formation in Photon-Photon Collisions

G. Gidal

August 1988



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RESONANCE FORMATION IN PHOTON-PHOTON COLLISIONS\*

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Invited talk presented at the  
Workshop on Glueballs, Hybrids and Exotic Hadrons  
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# RESONANCE FORMATION IN PHOTON-PHOTON COLLISIONS

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## ABSTRACT

Recent experimental progress on resonance formation in photon-photon collisions is reviewed with particular emphasis on the pseudoscalar and tensor nonets and on the  $\gamma\gamma^*$  production of spin-one resonances.

The radiative widths of the meson resonances have traditionally been considered the most direct measure of their quark content. In a model where the photons couple directly to quarks with charge  $e_q$ , the matrix element  $\langle q\bar{q}/\gamma\gamma \rangle \sim e_q^2 \Psi(0)$  in the  $s$ -wave and  $\langle q\bar{q}/\gamma\gamma \rangle \sim e_q^2 \Psi'(0)$  in the  $p$ -wave, so the radiative width  $\Gamma_{\gamma\gamma} \sim (\sum_q c_q e_q^2)^2$ . For example, for the pseudoscalar and tensor nonets

$$\begin{array}{lll} \pi^0(A_2) & \sqrt{\frac{1}{2}}(d\bar{d} - u\bar{u}) & \langle e_q^2 \rangle = \frac{-1}{3\sqrt{2}} \\ \eta_8(f_8) & \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s}) & \frac{1}{3\sqrt{6}} \\ \eta_1(f_1) & \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} - s\bar{s}) & \frac{2}{3\sqrt{3}} \end{array}$$

$$\begin{array}{ll} \text{where} & \eta = \cos\theta\eta_8 - \sin\theta\eta_1 \\ & \eta' = \sin\theta\eta_8 - \cos\theta\eta_1 \quad (\text{same for } f, f') \end{array}$$

In the case of ideal mixing ( $\theta = 35.3^\circ$ ), the  $\theta$  and  $f$  are pure  $(u\bar{u} + d\bar{d})$ , while the  $\eta'$  and  $f'$  are pure  $s\bar{s}$ . Thus the radiative width of the  $s\bar{s}$  member of a nonet is extremely sensitive to small admixtures of  $u\bar{u}$  and  $d\bar{d}$  components, i.e., to a small deviation from ideal mixing.

In this review I first discuss the status of the pseudoscalar, scalar and tensor mesons, and then briefly review the current information on the  $c\bar{c}$   $\eta_c$ , and finally summarize the exciting new results concerning the spin 1 mesons.

We now have measurements of the basic two photon reaction  $\gamma\gamma \rightarrow \gamma\gamma$  from both the CRYSTAL BALL<sup>1</sup> and ASP<sup>2</sup> groups (Figure 1). As was already clear from earlier results, the reaction is totally dominated by the pseudoscalars  $-\pi^0$ ,  $\eta$  and  $\eta'$ . The same is true of the  $\pi^0\pi^0\pi^0$ ,  $\eta\pi^0\pi^0$  and  $\eta\pi^+\pi^-$  final states and CRYSTAL BALL<sup>3</sup>, CELLO<sup>4</sup> JADE<sup>5</sup> and MARK II<sup>33</sup> have reported their data in these channels (Figure 2). The non resonant background is extremely small in all these channels and there is no evidence that this is

continuum  $\eta\pi\pi$  production rather than background. By relaxing the usual  $\Sigma P_T$  cut, the MARK II also observes a sizeable  $\eta'$  signal in the  $\pi^+\pi^+\pi^-\pi^-$  final state from  $\gamma\gamma \rightarrow \eta' \rightarrow \eta\pi^+\pi^-$ , with the  $\eta$  decaying into  $\pi^+\pi^-$  ( $\pi^0$ ) and  $\pi^+\pi^-(\gamma)$  (Figure 2d). The CRYSTAL BALL group has actually translated the absence of other signals into upper limits on  $\Gamma_{x\gamma\gamma} \cdot B(x \rightarrow \eta\pi\pi)$  and  $\Gamma_{x\gamma\gamma} \cdot B(x \rightarrow \gamma\gamma)$  for the whole available range of masses (Figure 3).

Table I displays these new results and the world averages of previous data (mostly from  $\eta' \rightarrow \rho\gamma$ ) from Kolanoski and Zerwas<sup>6</sup>. It is interesting that the new measurements, as most previous measurements of the  $\eta'$  width, have a spread beyond the statistical error, but are consistent within the systematic errors, indicating the difficulty in obtaining measurements more accurate than 10-20%. From  $\frac{\Gamma(\eta \rightarrow \gamma\gamma)}{\Gamma(\pi^0 \rightarrow \gamma\gamma)}$  and  $\frac{\Gamma(\eta' \rightarrow \gamma\gamma)}{\Gamma(\pi^0 \rightarrow \gamma\gamma)}$  one can determine the mixing angle  $\theta_p \simeq -20^\circ$  and  $F_0/F_\pi \simeq 1$ .  $SU(3)$  breaking gives  $F_8/F_\pi = 1.25$  (Donahue, Holstein, Lin<sup>7</sup>) giving a corrected  $\theta_p = -23^\circ \pm 3^\circ$  (Gilman, Kauffman<sup>8</sup>). This agrees with the quadratic GMO mass formula and with other measurements. No glueball admixtures are necessary!

Table I

	$\Gamma_{\gamma\gamma}(\pi^0)$ KeV	$\Gamma_{\gamma\gamma}(\eta)$ KeV	$\Gamma_{\gamma\gamma}(\eta')$ KeV
$\gamma\gamma \rightarrow \gamma\gamma$			
CRYSTAL BALL	$7.7 \pm 0.5 \pm 0.5$ ( $\times 10^{-3}$ )	$0.51 \pm 0.02 \pm 0.04$	$4.7 \pm 0.5 \pm 0.5$
ASP	—	$0.498 \pm 0.009 \pm .055$	—
$\gamma\gamma \rightarrow \eta\pi\pi, 3\pi^0$			
JADE	—	$0.53 \pm 0.05 \pm 0.10$	$3.8 \pm 0.13 \pm 0.50$
CELLO	—	—	$4.7 \pm 0.2 \pm 1.0$
MARK II	—	—	$4.7 \pm 0.6 \pm 0.9$
Kolanoski and Zerwas			
Former weighted mean	$7.48 \pm 0.33 \pm 0.31$ ( $\times 10^{-3}$ )	$0.53 \pm 0.04$	$4.3 \pm 0.3$

The PLUTO<sup>9</sup>, CELLO<sup>4</sup>, and ARGUS<sup>10</sup> groups have recently reported new measurements of the predominantly  $s\bar{s}$   $f'_2(1510)$  radiative width, nearly doubling the available measurements. It is particularly noteworthy that the PLUTO spectrometer is sensitive in the forward direction, so that no assumption regarding the helicity structure of the  $f'_2(1510)$  is required to extract  $\Gamma_{f'_2\gamma\gamma}$ . Some of the measurements are shown in Figure 4. The new world average is then  $\Gamma_{f'_2\gamma\gamma} B(f'_2 \rightarrow K\bar{K}) = 0.097 \pm 0.0016$ .

The  $f(1270)$  radiative width has been measured many times, but there are now new  $\pi^+\pi^-$  measurements from CELLO<sup>4</sup> and MARK II<sup>11</sup>, and new

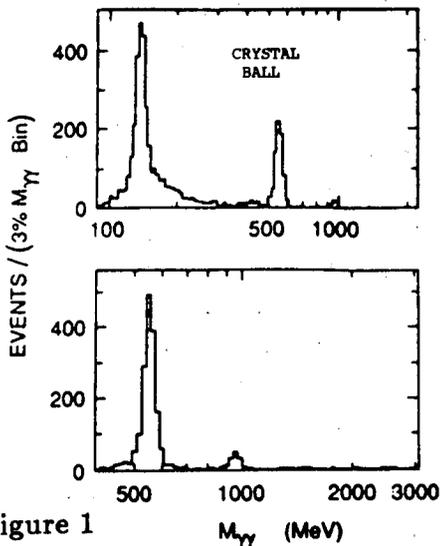


Figure 1

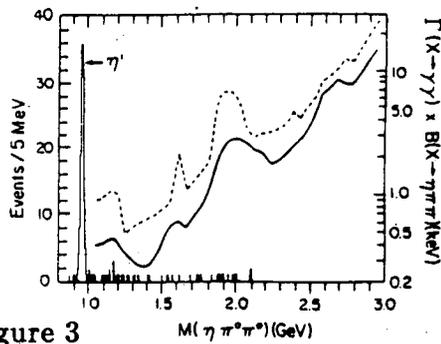
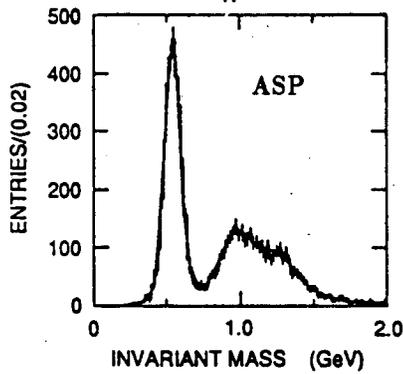


Figure 2

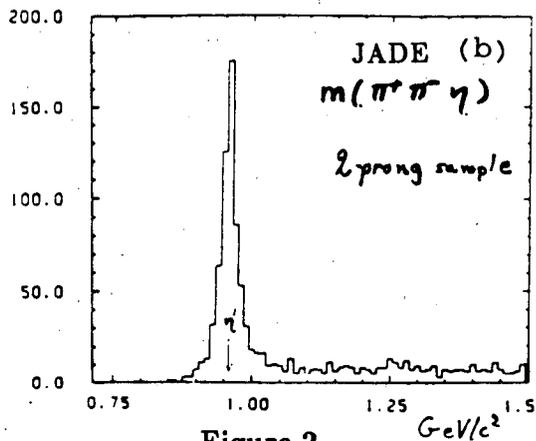
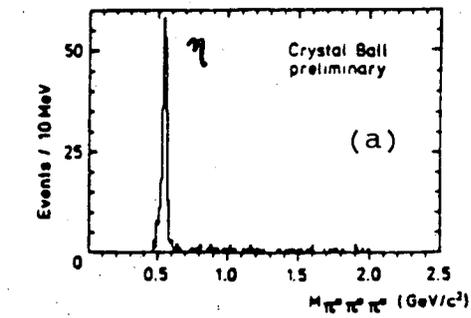
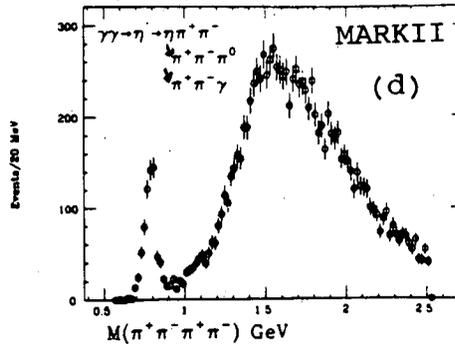
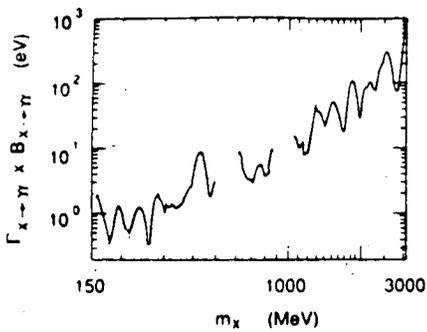


Figure 3



$\pi^0\pi^0$  measurements from both CRYSTAL BALL<sup>14</sup> and JADE<sup>5</sup>. In Figure 5 we show the  $\pi^0\pi^0$  spectrum obtained by JADE and CRYSTAL BALL, and the  $\pi^+\pi^-$  spectrum obtained by MARK II. The dominant feature is the  $f_2(1270)$ . The  $\pi^+\pi^-$  data is fit with a background consisting of the Born amplitude for each helicity state and scalar resonances at the high and low end. Mennessier<sup>12</sup> and more recently, Morgan and Pennington<sup>13</sup> have pointed out the necessity of taking final state interactions into account in such fits, and in particular the importance of requiring consistency between the fitted  $\pi\pi$  phase shifts and those independently measured in peripheral  $\pi N$  interactions. As in the case of all the  $2^{++}$  nonet members, the value of  $\Gamma_{f_2\gamma\gamma}$  is sensitive to the assumed helicity structure. Although most experiments do not sample the entire  $\cos\theta$  interval, the most precise measurements are able to get limits on the helicity 0 contribution from the shape of the angular distribution. An example is the JADE measurement for the  $f_2(1270)$  in Figure 5. The resulting widths are given in Table II and are all somewhat higher than the previous world average.

The  $a_2(1230)$  is usually identified by its  $\rho\pi$  decay but a rather clear signal has now been observed by both the CRYSTAL BALL<sup>14</sup> and JADE<sup>5</sup> groups in the  $\pi^0\eta$  decay mode as shown in Figure 6.

With helicity 2 dominance, the radiative widths of the  $2^{++}$  mesons can be used to evaluate the mixing angle and coupling ratio  $R = F_8/F_1$  with the relations:

$$\frac{\Gamma(f_2' \rightarrow \gamma\gamma)}{\Gamma(a_2 \rightarrow \gamma\gamma)} = \frac{1}{3} \left( \frac{m_{f_2'}}{m_{a_2}} \right)^3 (\cos\theta - 2\sqrt{2} R \sin\theta)^2$$

$$\frac{\Gamma(f_2 \rightarrow \gamma\gamma)}{\Gamma(a_2 \rightarrow \gamma\gamma)} = \frac{1}{3} \left( \frac{m_{f_2}}{m_{a_2}} \right)^3 (\sin\theta - 2\sqrt{2} R \cos\theta)^2$$

The resulting values remain consistent with nonet symmetry ( $R \simeq 1$ ) and with the mixing angle given by the Gell-Mann-Okubo mass formula ( $\theta \sim 28^\circ$ ).

Table II

		$\Gamma_{\gamma\gamma} f_2(1270)$	$\Gamma_{\gamma\gamma} a_2(1320)$
CRYSTAL BALL	$\pi^0\pi^0$	$3.26^{+0.16}_{-0.15}$ KeV	$\pi^0\eta$ $1.14 \pm 0.20 \pm 0.26$ KeV
JADE	$\pi^0\pi^0$	$3.09 \pm 0.10 \pm 0.38$ ( $\lambda_0 < 0.15$ )	$\pi^0\eta$ $1.09 \pm 0.14 \pm 0.25$
CELLO	$\pi^+\pi^-$	$2.99 \pm 0.10 \pm$	—
MARK II	$\pi^+\pi^-$	$3.21 \pm 0.09 \pm 0.40$ ( $\lambda_0 < 0.15$ )	—

The scalar mesons remain a puzzle, although some new results have recently been reported. JADE<sup>5</sup> has now confirmed the previous observation of

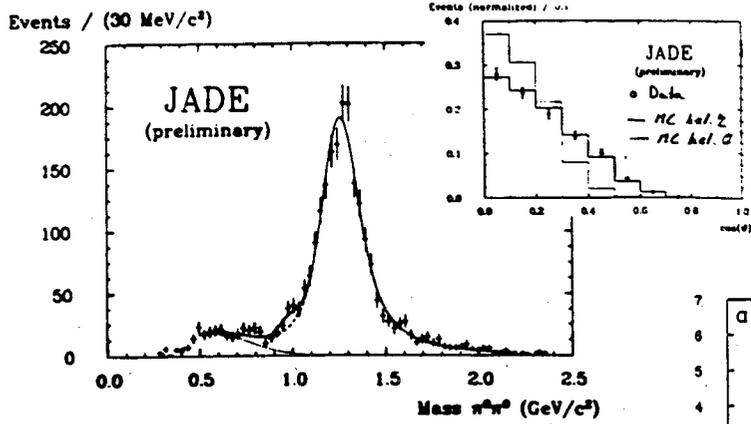


Figure 4

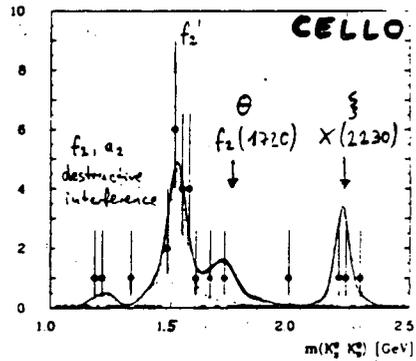
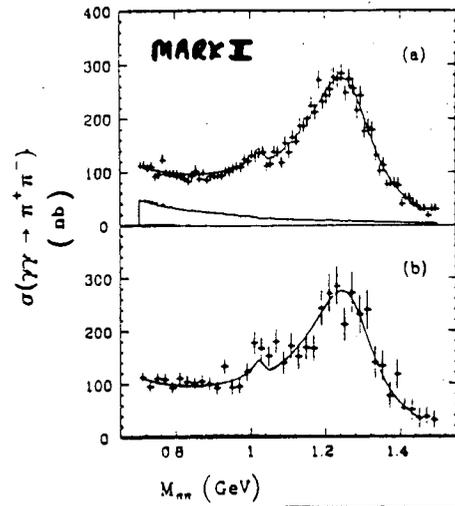
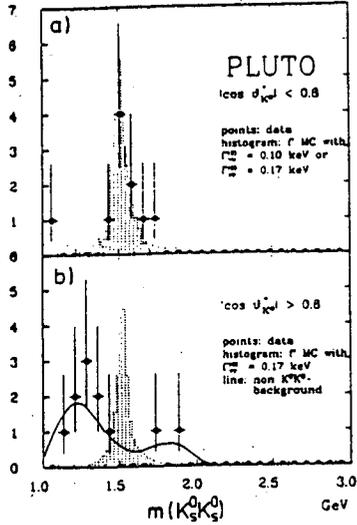
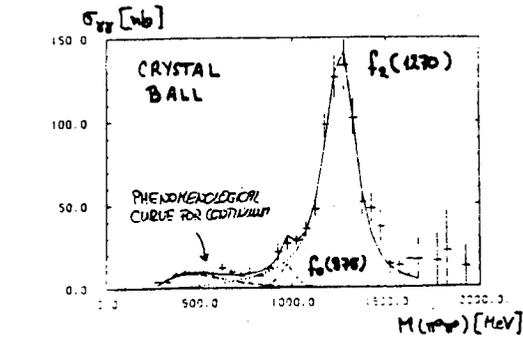


Figure 5

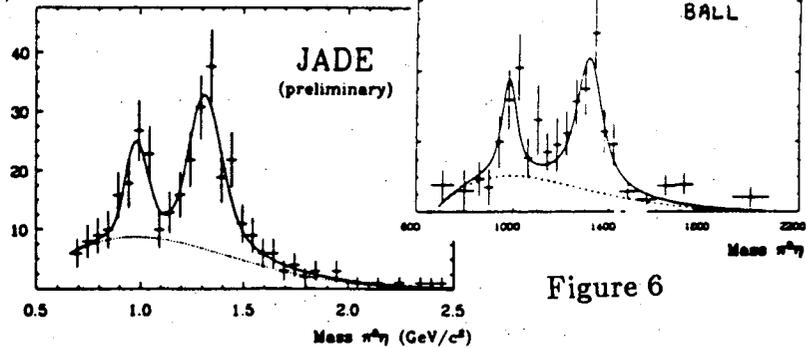


Figure 6

the  $a_0(980)$  by the CRYSTAL BALL<sup>14</sup> group in the  $\pi^0\eta$  channel. Both  $\pi^0\eta$  mass spectra are shown in Figure 6 and give radiative widths,

	$\Gamma_{\gamma\gamma}(a_0(980)) \cdot B(a_0 \rightarrow \pi^0\eta)$
JADE	$0.29 \pm 0.05 \pm 0.14$ KeV
CRYSTAL BALL	$0.19 \pm 0.07 \pm_{-0.07}^{+0.10}$ KeV

Both the MARK II<sup>11</sup> and CRYSTAL BALL<sup>15</sup> require an  $f_0(975)$  to fit a shoulder in their respective  $\pi^+\pi^-$  and  $\pi^0\pi^0$  spectra, although the fitted mass and width are somewhat different. A simple Breit Wigner fit results in preliminary values of the radiative width

	$\Gamma_{\gamma\gamma}(f_0(975))$
MARK II	$0.24 \pm 0.06 \pm 0.15$ KeV
CRYSTAL BALL	$0.31 \pm 0.14 \pm 0.11$ KeV (or $< 0.55$ KeV at 90% C.L.)

although such a naive parametrization is certainly inadequate. Most ( $q\bar{q}$ ) models predict  $\Gamma_{\gamma\gamma f_0} \sim 2 - 5$  KeV and  $\Gamma_{\gamma\gamma f_0}/\Gamma_{\gamma\gamma a_0} \simeq \frac{25}{9}$  while  $q\bar{q}q\bar{q}$  and ( $K\bar{K}$ ) molecule models<sup>16</sup> predict  $\Gamma_{\gamma\gamma f_0} \sim 0.3 - 0.6$  KeV and  $\Gamma_{\gamma\gamma f_0}/\Gamma_{\gamma\gamma a_0} \sim 1$ .

The CRYSTAL BALL group has reported<sup>17</sup> the first evidence for the  $\gamma\gamma$  production of a radial excitation; the  $J^{PC} = 2^{-+}\pi_2(1680)$ . It is observed in the reaction  $e^+e^- \rightarrow e^+e^-\pi_2(1680); \pi_2(1680) \rightarrow f_2(1270)\pi^0; f_2(1270) \rightarrow \pi^0\pi^0$  where one  $\pi^0$  is rather fast and hence both of its decay gammas are "merged" into a single shower. The efficiency corrected  $3\pi^0$  spectrum is shown in Figure 7 and a fit gives  $\Gamma_{\pi_2\gamma\gamma} = 1.4 \pm 0.3$  KeV. The CELLO<sup>18</sup> group has now confirmed the  $\pi_2(1680)$  in the  $\pi^+\pi^-\pi^0$  final state.

The  $\eta_c$  has been a long sought prize of  $\gamma\gamma$  physics. Its high mass and many decay modes have meant that only the highest luminosity experiments would be capable of observing it. Most experiments chose the  $K_s^0 K^\pm \pi^\mp$  decay and PLUTO<sup>19</sup> first reported a measurement  $\Gamma_{\eta_c\gamma\gamma} \cdot B(\eta_c \rightarrow K_s^0 K^\pm \pi^\mp) = 0.5_{-0.15}^{+0.2} \pm 0.1$  KeV which, when taken with the average branching ratio<sup>20</sup> gave  $\Gamma_{\eta_c\gamma\gamma} = 28 \pm 15$  KeV. MARK II<sup>21</sup> and CELLO<sup>4</sup> see considerably smaller signals in the same decay mode. A TPC/ $2\gamma$  result<sup>22</sup> using the decay mode  $K^+K^+K^-K^-$ , and the R704 experiment<sup>23</sup> at the ISR which utilized the  $\bar{p}p$  formation of the  $\eta_c$  and its subsequent decay into  $\gamma\gamma$ , also gave smaller values. TASSO has recently presented<sup>24</sup> the results of a global fit to three decay modes:  $K^0 K^\pm \pi^\mp$ ,  $K^+ K^- \pi^+ \pi^-$ , and  $\pi^+ \pi^+ \pi^- \pi^-$ , giving  $\Gamma_{\eta_c\gamma\gamma} = 19.9 \pm 6.1 \pm 8.6$  KeV. These results are summarized in Table III. All are consistent with the range of theoretical predictions.

A topic currently of great interest is the  $\gamma\gamma^*$  production of spin 1 resonances. Although Yang's theorem prohibits the formation of spin 1 mesons

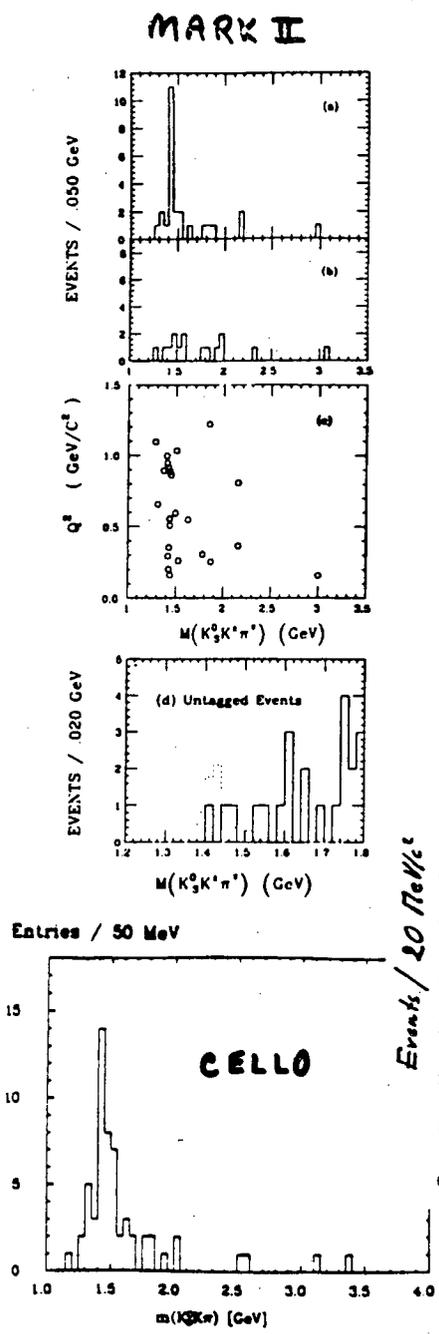


Figure 8

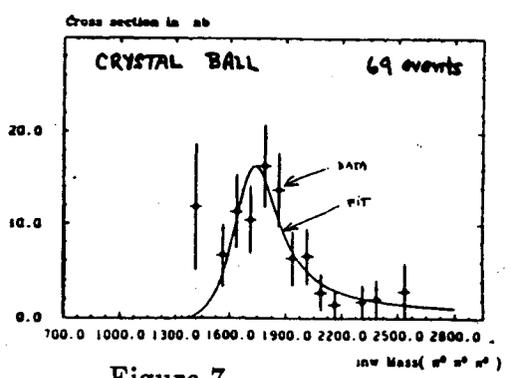
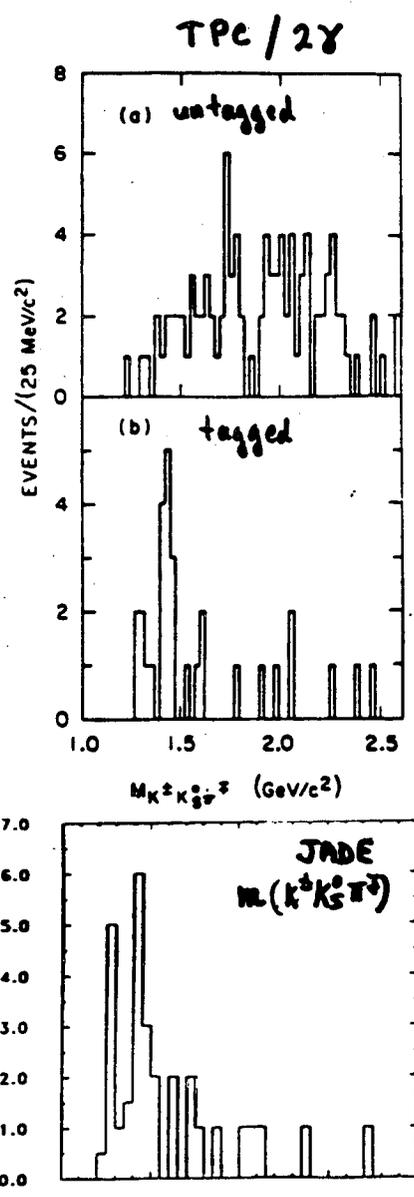


Figure 7

by real photons, taking one photon off the mass shell by a relatively small amount, immediately allows their production, as first suggested by Renard.<sup>25</sup>

Dramatic evidence<sup>26</sup> for production of such a spin 1 state at 1425 MeV in the tagged  $KK\pi$  channel was first presented by the TPC/2 $\gamma$  group. The nonobservation of such a peak in untagged formation confirms the spin 1 nature. This result was subsequently confirmed by MARK II<sup>21,27</sup>, who pointed out the  $K^*K$  dominance in its decay, and additional confirmation has now been presented by the CELLO<sup>4</sup> and JADE<sup>5</sup> groups. The experimental mass spectra are shown in Figure 8. We take the liberty of combining the data from all four experiments in Figure 9, even though the acceptances and backgrounds are certainly different. If we assume the acceptance to be slowly varying over the resonance region, then the sum indicates that the resonance is rather narrow. Most of the events are in one 50 MeV bin. A simple Gaussian fit gives a mass of 1433 MeV and a  $\sigma$  of 19 MeV, consistent with the typical experimental mass resolution.

One usually measures  $\frac{d\sigma}{dQ^2}$  with the other electron antitagged. Assuming a standard  $\rho$  dominance form for  $F(Q^2)$  and narrow resonances, one starts from the equations of Budnev et al.<sup>28</sup> or of Bonneau, Gourdin and Martin<sup>29</sup> with  $\frac{E_1 E_2 d^6\sigma}{dp_1^3 dp_2^3} = \sum L_{ij} \sigma_{ij}$  retaining  $\sigma_{TT}$  and  $\sigma_{TL}$ . It is convenient to define (Renard<sup>25</sup>, Cahn<sup>30</sup>) a  $\tilde{\Gamma}$ , which is nearly independent of  $Q^2$  at small  $Q^2$ .

$$\tilde{\Gamma}_{R\gamma\gamma^*} \equiv \Gamma_{R\gamma\gamma^*} \cdot \frac{M^2}{Q^2}$$

Relating  $\sigma_{TT}$  and  $\sigma_{TL}$  in a nonrelativistic quark model, Cahn<sup>30</sup> then finds a formula analogous to the Low formula (for  $J = 0, 2$ )

$$\sigma(ee \rightarrow eeR) \sim \frac{\tilde{\Gamma}_{R\gamma\gamma^*}}{M^3} \int \frac{dQ^2}{M^2} F^2(Q^2) \left\{ 1 + a_{model} \cdot \frac{Q^2}{M^2} \right\}.$$

One then compares this to the data to deduce  $\tilde{\Gamma}$ . Two conventions have now been used:

- (1) Cahn<sup>30,31</sup>: Takes into account the non identical nature of the  $T$  and  $L$  photons in relating  $\sigma$  to  $\tilde{\Gamma}_{TL}$ .
- (2) TPC/2 $\gamma$ <sup>26</sup>: Uses the same relation between  $\sigma$  and  $\tilde{\Gamma}_{TL}$  as between  $\sigma$  and  $\Gamma_{TT}$  for spin 0,2.

The radiative widths extracted from the measured cross sections are related by

$$\tilde{\Gamma}_{R\gamma\gamma^*}^{\text{Cahn}} = 2\tilde{\Gamma}_{R\gamma\gamma^*}^{\text{TPC}}.$$

The values obtained in the four experiments are given in Table IV. The agreement is excellent. The  $Q^2$  dependence for TPC/2 $\gamma$  and CELLO are shown in Figure 10.

Table III

$\Gamma_{\gamma\pi^0}$	
PLUTO	$28 \pm 15$ KeV
TASSO	$19.9 \pm 6.1 \pm 8.6$ KeV
TPC/2γ	$6.4^{+5.0}_{-3.5}$ KeV
CELLO	$<15.5$ KeV
Mark II	$8 \pm 6$ KeV
R704	$4.3^{+3.4}_{-3.7} \pm 2.4$

Figure 9

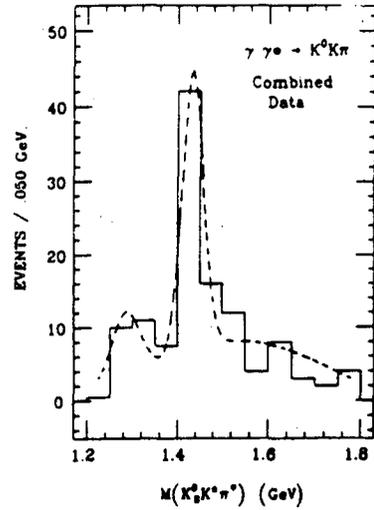
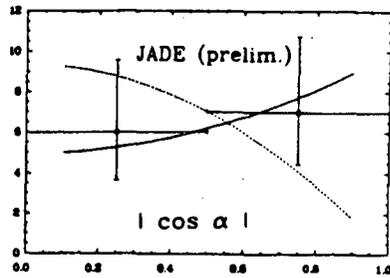
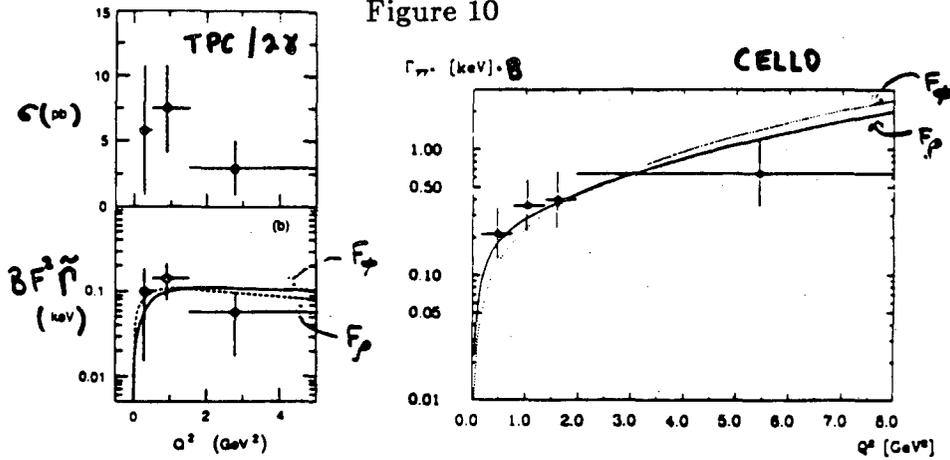


Figure 10



TPC/2γ		
$R = \sigma_{\pi\pi} / \sigma_{\pi\pi}$		
$P = +1,$	$R = 1,$	$C.L. = 69\%$
$P = -1,$	$R = 0$	$C.L. = 29\%$
$P = -1,$	$R = 1$	$C.L. = 1.4\%$

Figure 11

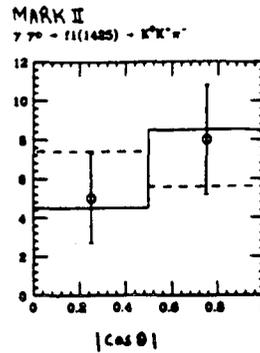
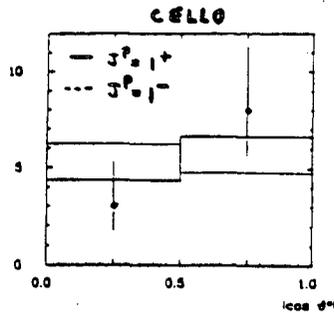


Table IV

$B(K\bar{K}\pi) \cdot \tilde{\Gamma}\gamma\gamma^*(f_1(1425))$		
	TPC/2 $\gamma$ Convention	Cahn Convention
TPC/2 $\gamma$	$1.3 \pm 0.5 \pm 0.3$ ( $\rho$ pole) $0.63 \pm 0.24 \pm 0.15$ ( $\phi$ pole)	$2.6 \pm 1.0 \pm 0.6$ ( $\rho$ pole) KeV $1.26 \pm 0.48 \pm 0.30$ ( $\phi$ pole)
MARK II	—	$3.2 \pm 1.4 \pm 0.6$ KeV ( $\rho$ pole) $2.1 \pm 1.0 \pm 0.4$ ( $\phi$ pole)
JADE	$1.9_{-0.7}^{+1.0} \pm 0.6$ ( $\rho$ pole) $1.5_{-0.5}^{+0.6} \pm 0.5$ ( $\phi$ pole)	$4.2_{-1.6}^{+1.8} \pm 1.2$ KeV ( $\rho$ pole) $3.0_{-1.0}^{+1.2} \pm 1.0$ KeV ( $\phi$ pole)
CELLO	—	$3.0 \pm 0.8 \pm 0.6$ KeV ( $\rho$ pole) $1.4 \pm 0.4 \pm 0.3$ KeV ( $\phi$ pole)
weighted		$3.0 \pm 0.6$ KeV ( $\rho$ pole)
mean		$1.6 \pm 0.3$ KeV ( $\phi$ pole)

The rather large radiative width measured for this particle has put into question its association with the predominantly  $s\bar{s}$   $f_1(1425)$  or “ $E$ ” meson. In particular Chanowitz<sup>32</sup> has suggested that it could be an “exotic”  $1^{-+}$  state. To test this, Cahn<sup>30</sup> has pointed out that for small  $Q^2/M^2$ , the distribution in the angle between the normal to the decay plane and the incident photon, in the rest frame of the produced resonance, is proportional to  $\sin^2 \theta$  for a  $1^{-+}$  resonance and to  $1 + \cos^2 \theta$  for a  $1^{++}$  resonance. Figure 11 shows this distribution in  $\cos \theta$  for the several experiments, together with the Monte Carlo expectations for each hypothesis. Clearly, no conclusion is possible at this level of statistics.

Having confirmed the spin 1 particle at 1425, the MARK II group also observed<sup>33</sup> the well known  $J^{PC} = 1^{++} f_1(1285)$  in the tagged  $\eta\pi^+\pi^-$  events. Again, the tagged events show the  $\eta'(958)$  and the  $f_1(1285)$  (Figure 12) while the untagged events show only the  $\eta'(958)$ . The TPC/2 $\gamma$ <sup>26</sup>, CELLO<sup>4</sup> and JADE<sup>5</sup> groups have all now confirmed the  $f_1(1285)$  and their observations are shown in Figures 13, 14, and 15. The  $f_1(1285)$  is observed to decay via  $a_0(980) \pi$  with the  $a_0(980) \rightarrow \eta\pi$ . The measured  $f_1(1285)$  radiative widths are given in Table V. No evidence has been seen for  $f_1(1425) \rightarrow \eta\pi\pi$  and limits of  $B(\eta\pi\pi)/B(K\bar{K}\pi)$  of 0.6 (MARK II)<sup>33</sup> and 0.5 (TPC/2 $\gamma$ )<sup>35</sup>

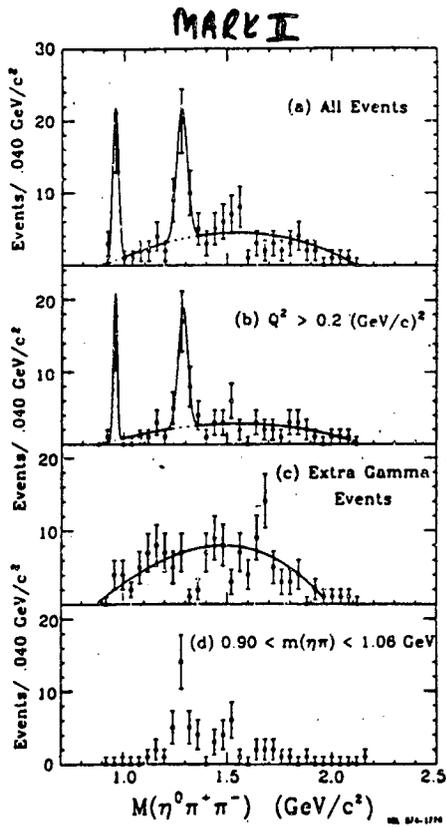


Figure 12

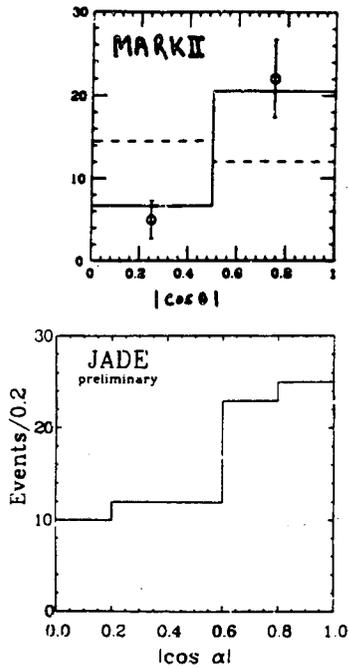


Figure 16

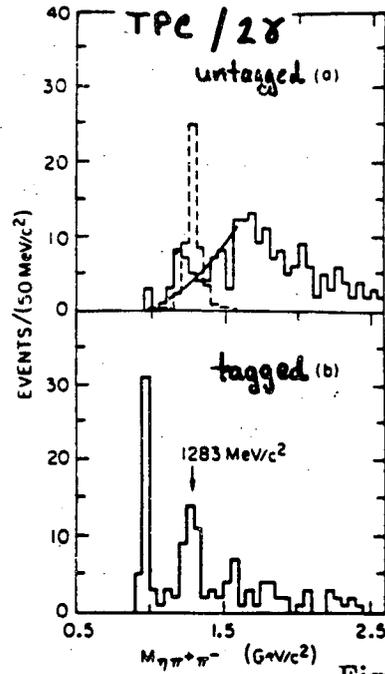


Figure 13

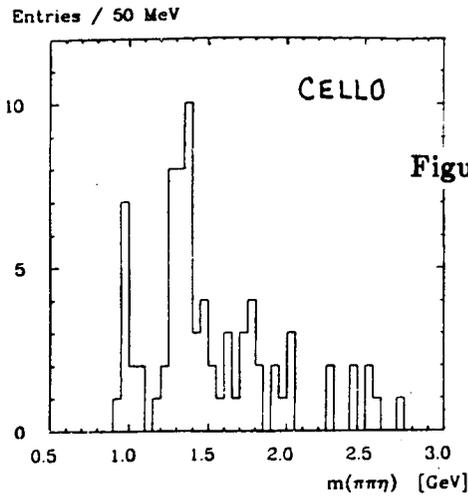


Figure 14

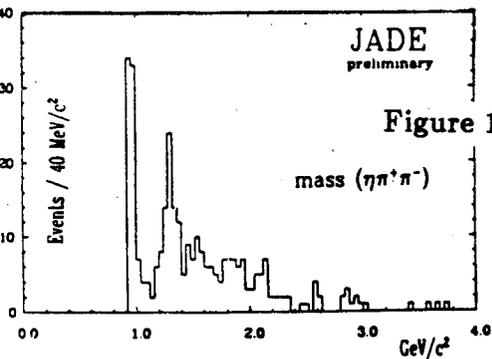


Figure 15

Table V

	$\tilde{\Gamma}(f_1(1285))$ (KeV)	$\tilde{\Gamma}(f_1(1285))/\tilde{\Gamma}(f_1(1425))$	
	Cahn Convention	$\rho$ pole	$\phi$ pole
TPC/2 $\gamma$	$4.8 \pm 1.0 \pm 1.0$	$1.8 \pm 0.8$ (stat. only)	$3.8 \pm 1.7$
MARK II	$9.4 \pm 2.5 \pm 1.7$	$2.9 \pm 1.5$	$4.5 \pm 2.5$
JADE	$3.6 \pm 0.6 \pm 0.8$	$0.9 \pm 0.5$	$1.2 \pm 0.5$
CELLO	$7.2 \pm 2.2 \pm 2.4$	$2.4 \pm 1.0$	$5.1 \pm 2.2$
Mean		$1.8 \pm 0.6$	$3.6 \pm 1.1$

In this case the higher statistics and greater acceptance allow a clearer measurement of the parity. Figure 16 shows the MARK II and JADE  $|\cos \theta|$  distribution for the  $f_1(1285)$  events and they clearly favor positive parity.

It is interesting that, by simply requiring a  $\Sigma P_T$  imbalance greater than 300 MeV/c, ARGUS<sup>37</sup> has observed both the  $f_1(1285)$  and the  $f_1(1425)$  in their untagged data. Their preliminary evidence is shown in Figure 17.

Several interpretations of the  $X(1425)$  have been proposed:

- (1) The expected mostly  $s\bar{s}$  member of the  $1^{++}$  nonet.
- (2) An extra state, assuming the  $f_1(1530)$  is the  $s\bar{s}$  partner of the  $f_1(1285)$ . It can then be interpreted as an exotic  $qqg$   $1^{-+}$  state (Chanowitz) or a four quark state (Caldwell<sup>35</sup>).
- (3) The  $\eta(1440)$  glueball candidate with a judicious suppression at  $Q^2 = 0$  (Achasov, Shestakov<sup>36</sup>).

In a non relativistic quark model with ideal mixing, the  $1^{++} {}^3P_1 q\bar{q}$  nonet contains the isoscalars  $|A\rangle = s\bar{s}$  and  $|B\rangle = (u\bar{u} + d\bar{d})/\sqrt{2}$  with squared charges  $1/9$  and  $5\sqrt{2}/18$  respectively. For an angle  $\lambda$  deviation from ideal mixing

$$R \equiv \frac{\tilde{\Gamma}(f_1(1285) \rightarrow \gamma\gamma^*)}{\tilde{\Gamma}(f_1(1425) \rightarrow \gamma\gamma^*)} = \frac{\frac{5}{\sqrt{2}} \cos \lambda + \sin \lambda}{\frac{5}{\sqrt{2}} \sin \lambda + \cos \lambda} = \frac{\sin^2(\lambda + \beta)}{\cos^2(\lambda + \beta)} = \tan^2(\lambda + \beta)$$

$$\text{where } \cos \beta \equiv \sqrt{\frac{2}{27}} \text{ and } \sin \beta = \frac{5}{\sqrt{27}}.$$

Following this simplest interpretation, Table V and Figure 18 show this ratio  $R$  in terms of  $\lambda$  together with the experimental results. The weighted mean defines a range of  $\lambda$  values between  $-10^\circ$  and  $-25^\circ$ .

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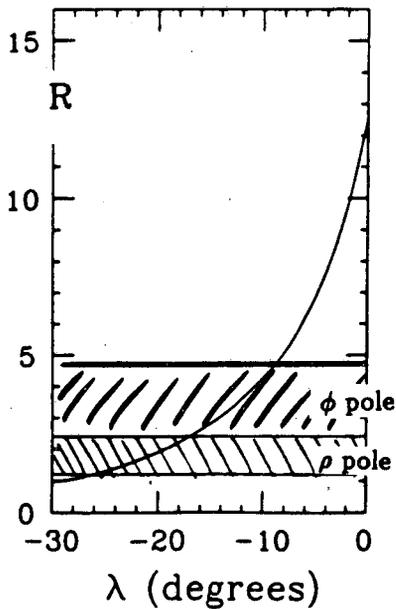


Figure 18

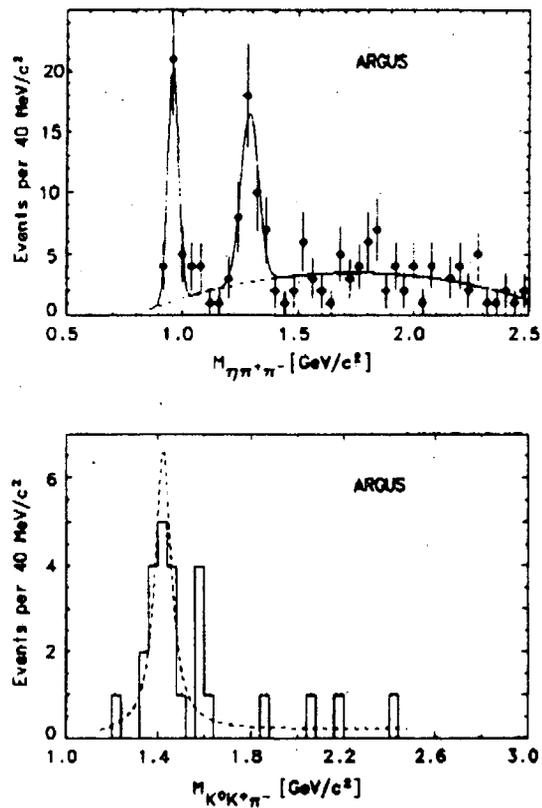
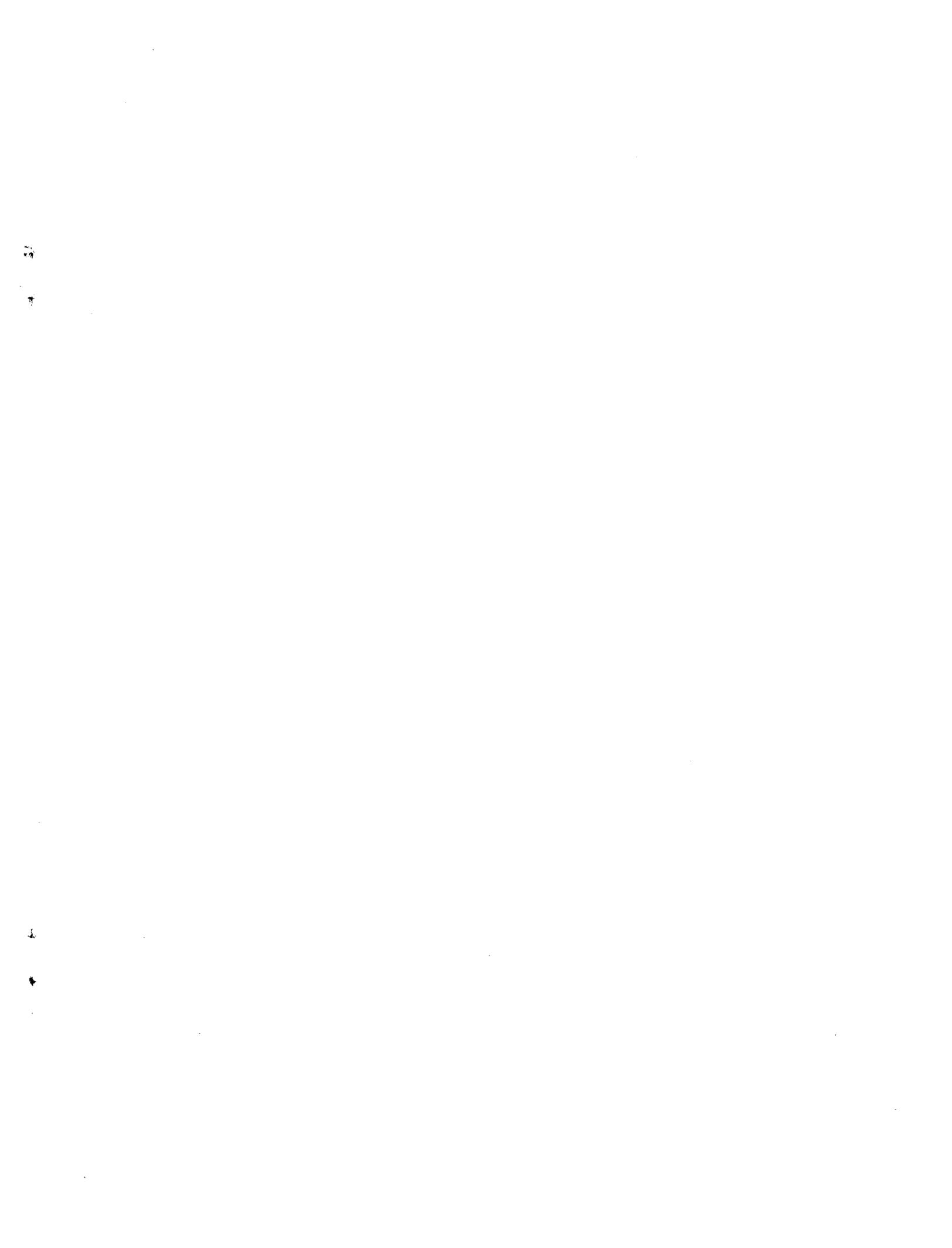


Figure 17



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