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Hadron Production in Two-Photon Collisions

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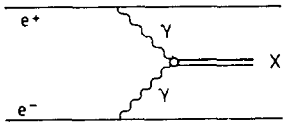
1 Introduction

This talk summarizes what two-photon physics has contributed to meson spectroscopy. The latest results have been reported at recent conferences [1,2].

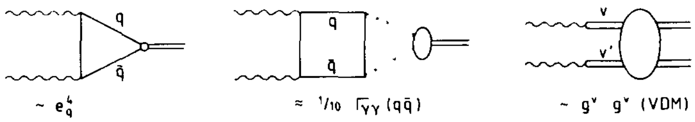
The formation of a C-even meson X can be observed in the two- photon process at e^+e^- colliders:

$$e^+e^- \rightarrow e^+e^-X.$$



The two electromagnetic currents in this reaction probe the charge content of the mesons. Within the quark model this implies a sensitivity to the flavours as far as they differ in their charge assignment. The two-photon results are in many respects complementary to those obtained in radiative J/ψ decays [3] or in hadroproduction experiments [4].

The basic goal of meson spectroscopy is a classification of the observed states - either as members of the standard $q\overline{q}$ multiplets or else as exotics, such as glueballs, hybrids or multiquark states. The two-photon couplings to such states are sketched below: the $\gamma\gamma$ coupling to the $q\overline{q}$ states is proportional to the fourth power of the quark charges, the coupling to glueballs - involving an additional quark loop - is expected to be OZI suppressed, and those 4-quark states which have superallowed decays into vector meson pairs should have, via VDM, large $\gamma\gamma$ couplings.



In the following we discuss the established (pseudoscalar and tensor) and less established (axial and scalar) meson multiplets, the observation of a D-wave meson, the $\gamma\gamma$ coupling of the η_c, the limits on the $\gamma\gamma$ couplings of glueball candidates, and the status of vector meson pair production and its connection to four-quark models.

2 Pseudoscalar Mesons

2.1 The light pseudoscalar

The groundstate pseudoscalar mesons (J^{PC}=0^{-+}) belong, together with the vector and tensor mesons, to the best established $q\overline{q}$ multiplets. The $\gamma\gamma$ width of the π^0 is calculable from basic

Meson	Decay Mode	$\Gamma_{\gamma\gamma}$ [keV]
π^0	$\gamma\gamma$	$(7.36 \pm 0.19) \cdot 10^{-3}$
η	$\gamma\gamma$	0.518 ± 0.028
η'	$\rho\gamma$, $\eta\pi\pi$	4.12 ± 0.18
$\eta_c(2980)$	$KK\pi$,$4K^\pm$,$4\pi^\pm$, $p\bar{p}$	$7.5 \pm 2\ 7$
$f_2(1270)$	$\pi\pi$	3.01 ± 0.12
$a_2(1320)$	$\rho\pi$, $\eta\pi$	0.97 ± 0.11
$f_2'(1525)$	$K\bar{K}$	$(0.078 \pm 0.011)/B(f_2' \to K\bar{K})$
$f_1(1285)$	$\eta\pi^+\pi^-$	$(2\ 3 \pm 0.4)/B(f_1 \to \eta\pi^+\pi^-)$
$f_1(1420)$	$KK\pi$	$(1\ 5 \pm 0.3)/B(f_1 \to K\bar{K}\pi)$
$f_0(975)$	$\pi\pi$	0.27 ± 0.12
$a_0(980)$	$\eta\pi$	$(0\ 23 \pm 0\ 09)/B(a_0 \to \eta\pi)$
$\pi_2(1680)$	$\pi^0\pi^0\pi^0$	1.4 ± 0.3

Table 1: Average values of measured two-photon widths (from [1,2]).

principles with the pion decay constant f_π as the only parameter The physical isoscalar states η and η' are mixtures of SU(3) singlet and octet states:

$$\begin{aligned} \eta &= \eta_8 \cos\Theta_P - \eta_1 \sin\Theta_P \\ \eta' &= \eta_8 \sin\Theta_P + \eta_1 \cos\Theta_P \end{aligned}$$

The $\gamma\gamma$ widths are then given by

$$\begin{aligned} \Gamma_{\gamma\gamma}(\pi^0) &= \left(\frac{\alpha^2}{64\pi^3}\right) \frac{M_{\pi^0}^3}{f_\pi^2} \\ \Gamma_{\gamma\gamma}(\eta) &= \left(\frac{\alpha^2}{64\pi^3}\right) \frac{M_\eta^3}{3f_\pi^2} \left[\frac{f_\pi}{f_8}\cos\Theta_P - \sqrt{8}\frac{f_\pi}{f_1}\sin\Theta_P\right]^2 \\ \Gamma_{\gamma\gamma}(\eta') &= \left(\frac{\alpha^2}{64\pi^3}\right) \frac{M_{\eta'}^3}{3f_\pi^2} \left[\frac{f_\pi}{f_8}\sin\Theta_P + \sqrt{8}\frac{f_\pi}{f_1}\cos\Theta_P\right]^2, \end{aligned}$$

f_1, f_8 are the singlet and octet decay constants. In [6] these equations have been solved using the measured $\gamma\gamma$ widths in Table 1 and the theoretically motivated ratio f_π/f_8=0.8:

$$\begin{aligned} f_\pi &= 94 \pm 2\ MeV, \\ \Theta_P &= -22.2^\circ \pm 1\ 2^\circ, \\ f_\pi/f_1 &= 0\ 95 \pm 0.03 \end{aligned}$$

The pseudoscalar mixing angle differs from that obtained by the quadratic mass formula (about -10°) but is consistent with that obtained from hadronic reactions [7].

2.2 Search for other light pseudosclare states

The Crystal Ball Group searched for resonances, in the $\eta\pi^0\pi^0$ and $\pi^0\pi^0\pi^0$ final states [8] Except for the η and η' no signals were observed. The upper limits for the $\gamma\gamma$ couplings of

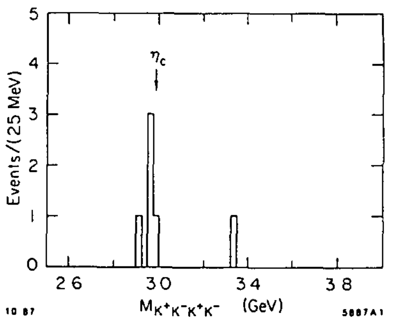


Figure 1:

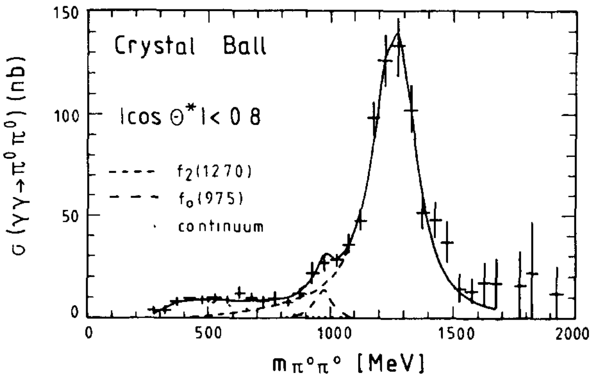


Figure 2:

radially excited η's or π's, which are well below 1 keV up to masses of 1.5 GeV, contradict expectations from the quark potential model, see e.g. [9]. The small $\gamma\gamma$ coupling of such states could recently be explained by chiral symmetry effects [10].

The glueball candidate state $\eta(1440)$ which is abundantly produced in radiative J/ψ decays is not observed in $\gamma\gamma$ collisions. Limits on the $\gamma\gamma$ width times branching ratio have been given for the $KK\pi$, $\eta\pi\pi$, $\rho\rho$ and $\rho\gamma$ final states. E.g., the TPC/Two-Gamma collaboration finds [11]:

$$\Gamma_{\gamma\gamma} \cdot B(\eta(1440) \to K\overline{K}\pi) \; < \; 1.6 \; keV \quad (95\% \; c.l.).$$

Note that these limits hold for the couplings to two real photons. The resonant production of the $KK\pi$ final state in collisions of a virtual and a real photon is discussed in Sect. 4.

2.3 The $\gamma\gamma$ width of the η_c

The two-photon production of the pseudoscalar charmonium groundstate η_c has been searched for by several groups in the final states $KK\pi$, $4K^{\pm}$, $4\pi^{\pm}$ and in an inclusive measurement (double tag) [12]. None of the experiments observed a statistically really convincing signal

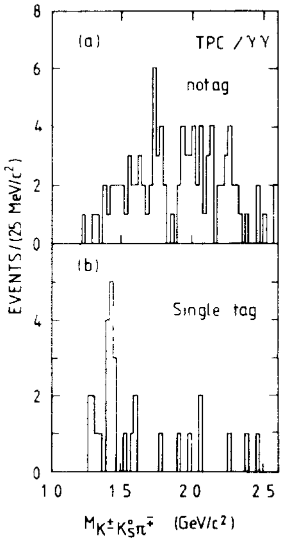
The smallest background seems to be in the 4 charged kaon channel as measured by the TPC/Two-Gamma group (Fig.1). The value of the $\gamma\gamma$ width of the η_c (Table 1) as obtained by averaging over the experiments with positive results (rather than upper limits) covers the range of most theoretical predictions. In particular it is consistent with the $\sim$ 6 keV expected from the leptonic width of the J/ψ if the η_c and the J/ψ have the same spatial wave functions

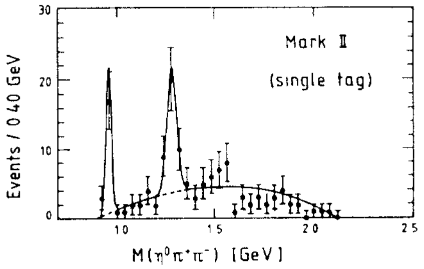
3 Tensor Meson Multiplet

The $q\bar{q}$ P-wave triplett $^3P_{0,1,2}$ consists of the tensor, axial vector and scalar meson multiplets. From those only the tensor multiplet can be considered as firmly established. The average values for the $\gamma\gamma$ widths of the $a_2(1320)$ the $f_2(1270)$ and the $f_2'(1525)$ are listed in Table 1 From these data one obtains a mixing angle of

$$\Theta_T \;\approx\; +28^\circ.$$

The exact value is somewhat model dependent, but in any case it is close to the ideal mixing angle of 35.3°. The exclusive $\pi\pi$ and $K\overline{K}$ mass distributions are dominated by tensor meson





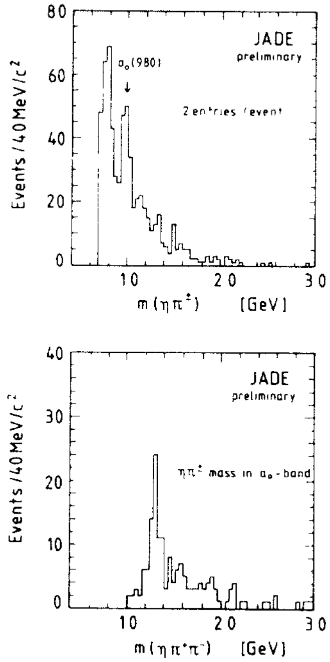


Figure 3. (left)

Figure 4· (top)

Figure 5. (right)

formation. Due to extensive analyses by many groups the essential features of these mass spectra seem to be well understood·

- The $\pi\pi$ mass spectra are well described by unitarized amplitudes for background and resonances
- The $\pi^0\pi^0$ mass spectrum is dominated by f_2 formation which is well described by standard resonance parameters (Fig.2) In particular, the previously seen mass shift has disappeared
- The KK final state is characterized by an isoscalar-isovector interference which is most pronounced for the nearly degenerate states a_2 and f_2. This interference is constructive in the K^+K^- channel and destructive in the $K^0\overline{K^0}$ channel

No other light tensor states have been observed especially not the glueball candidate state $f_2(1720)$, for which the most restrictive upper limit is [14]

$$\Gamma_{\gamma\gamma} \; B(f_2(1720) \rightarrow K^+K^-) \; < \; 0.10 \; keV \quad (95\% \; c.l.)$$

4 The Axial Vector Mesons

A vector state of either parity cannot be formed by two real photons according to the Landau-Yang theorem [13] Therefore, a state which is only seen in two-photon collisions with at least one off-mass-shell photon but not in collisions of two real photons, is likely to be a vector state. Furthermore, if it is a $q\bar{q}$ state even charge conjugation ties the parity down to be also even, i.e. $J^{PC}=1^{++}$.

Two such states have been observed in collisions of a quasi-real and a virtual photon The virtual photon is tagged by detecting the corresponding scattered electron at small but non-zero angle.

4.1 The $KK\pi$ final state

Searching for the glueball candidate $\eta(1440)$ in the $KK\pi$ final state no signal was found in the notag data samples, i.e. in quasi-real photon scattering (e.g. Fig.3a). Thus it was quite a surprise when the TPC/Two-Gamma group, and subsequently also other groups, observed a relatively strong signal in the nearby mass region in a single-tag data sample (Fig 3b) [15]. The signal is consistent with being due to the axial vector state $f_1(1420)$, formerly called E(1420). The axial vector assignment is suggested by the data but an exotic $J^{PC}=1^{-+}$ assignment is statistically not yet excluded. The Dalitz-plot distributions observed by TPC/Two-Gamma and Mark II suggest a dominance of the K^*K final state which is however, not so clear in the JADE data.

4.2 The $\eta\pi\pi$ final state

The $\eta\pi\pi$ final state produced by two quasi-real photons is dominated by η' resonance formation. No other states, like a radially excited η, have been observed [8] (see sect 2). In single-tag data Mark II observed in addition to the η' a signal around 1280 MeV (Fig.4). The observation has been confirmed by other experiments [16]. The measured mass and width is consistent with the axial vector state $f_1(1285)$, formerly called D(1285). In this case negative parity is definitely excluded by the JADE observation that the $\eta\pi^\pm$ mass distribution shows a clear signal in the $a_0(980)$ region correlated with the $\eta\pi\pi$ signal at 1285 MeV (Fig 5) The argument is that the decay chain

$$f_1(1285) \rightarrow a_0(980)\pi^\pm \rightarrow \eta\pi^+\pi^-$$

involves a scalar plus a pseudoscalar intermediate state which cannot form a $J^P=1^-$ state. This excludes in particular a $q\bar{q}$-gluon hybrid state as proposed in [17].

4.3 The two-photon coupling of axial vector mesons

The cross section for the scattering of one real photon ($Q_1^2 = 0$) and one virtual photon ($Q_2^2 = Q^2 \neq 0$) is given by

$$\sigma_{\gamma\gamma}(W_{\gamma\gamma}, 0, Q^2) = \sigma^{TT} + \epsilon \cdot \sigma^{LT}.$$

For $J^{PC}=1^{++}$ production the transverse photon cross section vanishes in the $Q^2=0$ limit like Q^4 and the transverse-longitudinal part like Q^2. For resonance production two couplings can be defined analogously to the real photon case, $\Gamma_{\gamma\gamma}^{TT}$, $\Gamma_{\gamma\gamma}^{LT}$, which are however not constants but Q^2 dependent. Up to now, statistics do not allow to separate σ^{TT} and σ^{LT}. A reduction of the couplings to a single, measurable number is model dependent. The experiments used a non-relativistic quark model for 1^{++} mesons by R.Cahn [18] which predicts a Q^2 dependence and connects the two, in principle independent, couplings:

$$\Gamma_{\gamma\gamma^*}^{LT} = \frac{4X}{W^4}\frac{Q^2}{W^2}F^2(Q^2)\,\tilde{\Gamma}$$
$$\Gamma_{\gamma\gamma^*}^{TT} = \frac{4X}{W^4}\left(\frac{Q^2}{W^2}\right)^2 F^2(Q^2)\,\tilde{\Gamma}$$

X is a kinematical factor, F(Q^2) is a form factor with the normalisation F(0) = 1, $\tilde{\Gamma}$ is the number to be determined by the experiments. Unfortunately different normalisations are used $\tilde{\Gamma}$ used by Mark II and CELLO is twice as large as that used by TPC/Two-Gamma and JADE. In Table 1 the average results are given using the Cahn-model with the TPC/Two-Gamma convention and the ρ form factor.

Assuming that the observed states belong to the same $^3P_1$ $q\bar{q}$ multiplet with the flavour neutral members $a_1(1270)$, $f_1(1285)$, $f_1(1420)$, a mixing angle can be derived in the context of the Cahn-model:

$$\frac{\tilde{\Gamma}(f_1(1285))}{\tilde{\Gamma}(f_1(1420))} = \frac{M_{f_1(1285)}}{M_{f_1(1420)}} \left(\frac{\sin\Theta_A + \sqrt{8}\cos\Theta_A}{-\cos\Theta_A + \sqrt{8}\sin\Theta_A} \right)^2$$

Using the average values for $\tilde{\Gamma}$ in Table 1 one obtains: $\Theta_A = (57.1 \pm 4.7)^\circ$ Using for the dominantly ss candidate $f_1(1420)$ a ϕ form factor the TPC/Two-Gamma group finds $\Theta_A = (45.4 \pm 6\ 4)^\circ$ This difference demonstrates the model dependence of the result.

From the quadratic mass formula one obtains $\Theta_A = 42.2^\circ$ Thus one can conclude that the measured f_1 states together with the $a_1(1270)$ consistently fit into a 1^{++} nonet However, there are at least two problems with this interpretation:

- The LASS experiment does not observe the production of the $f_1(1420)$ in the reaction $K^- p \to K_s K^\pm \pi^\mp \Lambda$, but rather another axial vector state at 1530 MeV [4]
- The Mark III group observes in J/ψ decays the $f_1(1420)$ recoiling against an ω but not against a ϕ [3].

Both observations contradict the interpretation of the $f_1(1420)$ being the mainly ss member of the axial vector nonet.

5 Scalar Mesons

The third member of the P wave triplet, the scalar meson multiplet, is known to be notoriously problematic. None of its members is firmly established Candidate states are the isovector $a_0(980)$ and the isoscalar $f_0(975)$. The second isoscalar is sometimes located around 700 MeV and sometimes around 1300 MeV. The measured two-photon couplings of the f_0 and a_0 (Table 1) are much smaller than expected for scalar $q\bar{q}$ mesons which should have similar $\gamma\gamma$ widths as the tensor mesons as they belong to the same P-wave triplet The small $\gamma\gamma$ widths are consistent with an interpretation of these states being four-quark states or $K\bar{K}$ molecules [19]. Note that the statistical significance of $f_0(975)$ production is marginal (e.g Fig.2).

The DM1 and DM2 experiments observed in the reaction $\gamma\gamma \to \pi^+\pi^-$ an excess over the Born contribution for $\pi\pi$ masses up to about 600 MeV. If this excess was due to the production of the ϵ resonance a similar signal should be observable in the channel $\gamma\gamma \to \pi^0\pi^0$. In the Crystal Ball data (Fig.2) no such excess is observed above the expected continuum production [8]. Until now no other experiment was able to directly scrutinize the DM1/2 results

6 Observation of a D-wave $q\bar{q}$ State

The Crystal Ball group observed the D-wave $q\bar{q}$ state $\pi_2(1680)$ (J^{PC}=2^{-+}) in the reaction [8]

$$\gamma\gamma \to \pi_2(1680) \to \pi^0\pi^0\pi^0 \to 6\gamma$$

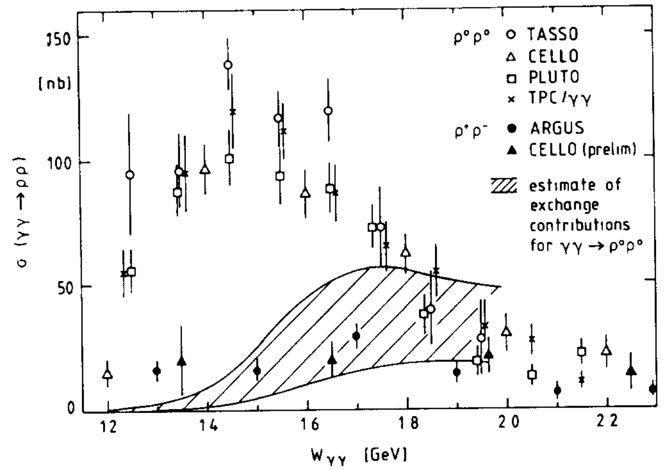


Figure 6:

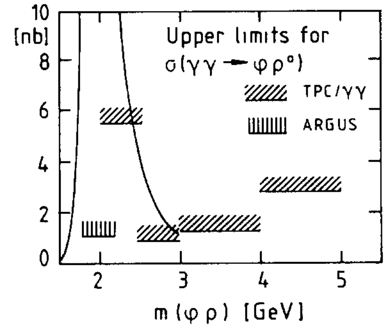


Figure 7:

The $\pi^0\pi^0$ invariant mass distribution suggests that the π_2 decays via $\pi^0 f_2(1270)$ Assuming s-wave dominance this quasi-twobody decay leads to a unique angular distribution since for $J^P = 2^-$ the $\gamma\gamma$ system can only be in an helicity state $J_z=0$. The angular distribution of the fastest π^0 was found to be in agreement with the $J^{PC}=2^{-+}$ assignment for the observed state. The measured $\gamma\gamma$ width (Table 1) indicates little suppression for the $\gamma\gamma$ couplings of D-wave $q\bar{q}$ states when compared to the S and P wave states.

7 Vector Meson Pair Production

Two-photon production of vector meson pairs,

$$\gamma\gamma \to VV',$$

has meanwhile been studied for all combinations of light vector mesons, V,V' = ρ, ω ϕ, K^* [1,2]. Signals have been found for all channels except for those involving ϕ-mesons.

This experimental program was started with the measurement of the reaction $\gamma\gamma \to \rho^0\rho^0$ which showed a strong enhancement near threshold (Fig.6). Recent measurements of the $\rho^+\rho^-$ cross section by the ARGUS and CELLO groups (Fig.6) and the old upper limit from JADE show that the enhancement cannot be due to a single I=0 resonance which would require a ratio $\rho^+\rho^-/\rho^0\rho^0 = 2$. The factorisation model suggested by [20] was recently reevaluated for the $\rho^0\rho^0$ channel [21] and was found not to be able to describe the data (Fig.6).

It remains the interesting possibility that the enhancement is due to four-quark states. The MIT bag model offers two degenerate states with I=0 and I=2 near the $\rho\rho$ threshold decaying dominantly into $\rho\rho$. It was predicted that the interference of these states is constructive for $\rho^0\rho^0$ and destructive for $\rho^+\rho^-$, yielding $\rho^+\rho^-/\rho^0\rho^0 \approx 0$ [22].

The prediction that these states have $J^{PC}=2^{++}$, unfortunately, could not be finally tested since the experimental analyses of the angular distributions are not yet conclusive [23] Safely, one can only say that the $\rho\rho$ channel is not dominated by negative parity states. Thus two-photon production of $\rho\rho$ seems not to be related to $\rho\rho$ production in radiative J/ψ decays where dominance of $J^P=0^-$ was observed [3].

The measurements of the many other vector meson pair cross sections did not much contribute to checking the four-quark model. In most channels the predicted four-quark cross section is smaller than the measured one so that one can only conclude that there are also other contributions Such contributions can partly be well explained, like by one-particle exchanges in the case of $\omega\omega$ (π^0-exchange) and $K^0\overline{K^0}$ (K-exchange). The large $K^{*+}K^{*-}$ cross section (measured by ARGUS to reach about 60 nb at 2 GeV) is unexpected by all theoretical models (e.g.[24]).

The only experimental result which is so far in serious conflict with the four-quark model is the upper limit for $\gamma\gamma \rightarrow \rho\phi$ (Fig 7) Achasov et al [22] emphasized this channel as a particularly clean test reaction for the four-quark model The upper limits exclude at least some versions of the four-quark model However, it should be noted that sizeable $\phi\pi^+\pi^-$ production has been observed raising the question if $\phi\rho$ can be substituted in the models by $\phi\pi\pi$ As in the $\rho\rho$ case a spin-parity analysis is probably the best way to prove are disprove the four-quark model.

8 Summary

The contributions of two-photon physics to meson spectroscopy are first of all the measured $\gamma\gamma$ widths in Table 1. Further results and conclusions can be summarized as follows:

- Pseudoscalars: the pseudoscalar mixing angle is $\Theta_P = (-22.2 \pm 1.2)°$; non-$q\overline{q}$ admixtures, like gluonium, are not needed; no other light 0^- states, like radial excitations, are observed; the measured $\gamma\gamma$ width of the η_c is consistent with the charmonium model
- Tensor Mesons. Well measured, well understood multiplet, mixing angle $\approx 28°$
- Axial vectors: $f_1(1285)$ and $f_1(1420)$ could be members of the same nonet with mixing angle 45-57°, an exotic explanation is not required by the $\gamma\gamma$ data.
- Scalar Mesons: the measured $\gamma\gamma$ widths of $a_0(980)$ and $f_0(975)$ are smaller than expected for $q\overline{q}$ states, but consistent with four-quark or $K\overline{K}$ molecule models; no other I=0 state has been observed
- D-wave $q\overline{q}(2^{-+})$ $\gamma\gamma \rightarrow \pi_2(1680) \rightarrow \pi^0\pi^0\pi^0$ observed, $\Gamma_{\gamma\gamma} = (1.4 \pm 0.3)\ keV$
- Glueballs: Non-observation of $\eta(1440)$, $f_2(1720)$ in $\gamma\gamma$ reactions supports glueball hypotheses.
- Vector meson pairs. All channels involving ρ, ω, ϕ, K^* are studied, contributions from four-quark states not yet clear, no other good explanation for $\gamma\gamma \rightarrow \rho\rho$ near threshold

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Discussion

I.S. Shapiro (Lebedev Inst., Moscow): Comments: (1) The "Yang Theorem for $\gamma\gamma \to spin$ 1" was really obtained by L.D. Landau in 1947-48. (2) $\gamma\gamma^* \to spin$ 1 may be forbidden by gauge invariance. But I am not sure about this latter point.

H. K.: (1) The reference to Landau will be included in the write-up of the talk.

L. Montanet (CERN): If 0^{++} and 2^{++} are degenerated in mass and width, isn't it possible that the $\gamma\gamma$ width attributed to $a_2(1320)\to \eta\pi$ or $f_2(1270)\to \pi\pi$, $f_2'(1525)\to K\overline{K}$ is (in part) due to these 0^{++} ?

H. K.: In all cases the angular distributions have been analysed and no indication of isotropic contributions have been found. On a 20 to 30% level all mentioned decays show a dominance of helicity 2 for the $\gamma\gamma$ system.