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# Observed and Unobserved States —Crystal Ball Results on Two-Photon Physics—

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## Abstract

The Crystal Ball detector at the $e^+e^-$-storage ring DORIS-II has measured the $\gamma\gamma$-excitation of resonances decaying into final states with photons only. The results are presented by the partial widths $\Gamma_{\gamma\gamma}$ as well as by their helicity form factors. Upper limits on candidates for radially excited mesons as well as gluonia are reported and can easily be compared with values of observed resonances using the helicity form factors. Octet-singlet mixing angles are derived.

## 1. Introduction

Photons couple to charges and therefore $\gamma\gamma$-collisions probe the charge structure of resonances. Important information is gathered on the constituents of those mesons which are accessible to $\gamma\gamma$-reactions because of their quantum numbers (neutral mesons with charge conjugation $C = C(\gamma\gamma) = +1$ can be produced). The cross-section for production of a resonance R is

$$\sigma(\gamma\gamma \to R) \sim \Gamma_{\gamma\gamma} \sim \langle e_q^2 \rangle_R^2 \tag{1}$$

where $\Gamma_{\gamma\gamma}$ is the partial width of the decay $R \to \gamma\gamma$ and $\langle e_q^2 \rangle_R$ the mean squared quark charge of $R$.

The Crystal Ball experiment on which I will report is limited to

1. quasi-real photons (no-tag mode) which further restricts the states which can be produced (J = 1 resonances are excluded),
2. final states with photons only from which $\pi^\circ$'s etc. will be reconstructed.

## 2. The Crystal Ball Detector

The Crystal Ball detector [1] is a non-magnetic calorimeter for electromagnetically showering particles (photons in our case). The performance figures important for $\gamma\gamma$ experiments are:

1. The photon energy resolution of $\sigma_E/E = (2.7 \pm 0.2)\%/\sqrt[4]{E/GeV}$ together with the photon angular resolution of $\sigma_\theta = (1\text{–}3)^\circ$ (depending on the photon energy) gives a mass resolution of $\sigma_M(\pi^\circ) = (6.0 \pm 0.4)$ MeV, $\sigma_M(\eta) = (16 \pm 1)$ MeV and e.g. $\sigma(\pi^\circ\pi^\circ) = (28 \pm 2)$ MeV at $M = 1300$ MeV or $\sigma_M(\pi^\circ\pi^\circ\pi^\circ) = (45 \pm 2)$ MeV at $M = 1680$ MeV. This is needed not only for the final physics analysis, but especially for background rejection.

Talk given at the BNL Workshop on Glueballs, Hybrids and Exotic Hadrons, August 29–September 1, 1988



Table 1: Data sample and trigger settings.

| $\gamma\gamma$ trigger | trigger threshold [MeV] | luminosity [$pb^{-1}$] |
|---|---|---|
| standard trigger | 800 | 270 |
| Subsamples | | |
| $\pi^\circ$-trigger | 90 | 46 |
| $\eta$-trigger | 400 | 68 |
| $\pi^\circ\pi^\circ$-trigger | 200 | 51 |

2. The solid angle coverage of 93% of $4\pi$ (vetoes up to 98%) together with a low energy detection threshold for photons of $E_\gamma^{threshold} = 20$ MeV gives a high detection efficiency for $\pi^\circ$'s which otherwise is difficult to reach because the center of mass system for $\gamma\gamma$-production is moving.
3. The Crystal Ball detector allows very low energy trigger thresholds. Values down to 90 MeV ($\approx 0.9\% \times E_{c.m.}$) have been reached by using additional requirements (transverse symmmetry of events, vetoes against charged particles and vetoes in the forward direction).

The data samples collected in the years 1982–1986 by the Crystal Ball at DORIS-II (around 10 GeV c.m. energy) with their trigger thresholds are listed in Table 1.

## 3. Results

We go through the results according to the number of photons in the final state. In the channel $\gamma\gamma \to 2\gamma$ (Fig. 1a) [2] the $\pi^\circ$, $\eta$, and $\eta'$ are seen—and no other resonances. The results for $\Gamma_{\gamma\gamma}$ are given in Table 2. We derive upper limits on $\Gamma_{\gamma\gamma}$ of (hypothetical) resonances at other masses (see sect. 4).

The reaction $\gamma\gamma \to \pi^\circ\pi^\circ \to 4\gamma$ (Fig. 1b) [3] is dominated by the $f_2(1270)$ production. Crystal Ball observes $\pi^\circ\pi^\circ$'s down to threshold where a continuum of $\sigma \approx 10$ nb is measured in fair agreement with expectations (not further discussed in this talk). Limits on hyphothetical scalar resonances at masses between 270–800 MeV will be given. At the $f_0(975)$ a peak of 2.2 standard deviations shows up. The measurement of the angular distribution of the $\pi^\circ$'s shows spin 0 for the continuum and spin 2 with helicity 2 for the $f_2(1270)$. This allows to set a limit for the $\gamma\gamma$ production of the $f_0(1300)$. At 975 MeV a (statistically non-significant) change of the angular distributions is seen in agreement with the cross section enhancement.

In the $4\gamma$ final state also the reaction $\gamma\gamma \to \pi^\circ\eta$ is identified (Fig. 1c) [4]. The invariant mass distrubution shows the $a_2(1320)$ and the $a_0(980)$ which had been first observed in $\gamma\gamma$-reactions in this experiment. A continuum contribution is needed for the fit.

In the channels $\gamma\gamma \to \eta\eta$, $\eta\eta'$, and $\pi^\circ\eta'$ only a few events (18, 1, and 4, resp.) have been seen. Upper limits are derived (see sect. 4).

In the $6\gamma$ final state the channels $\gamma\gamma \to 3\pi^\circ$ (Fig. 2a) [5] and $\gamma\gamma \to \eta\pi^\circ\pi^\circ$ (Fig. 2b) [6] have been observed. The resonances $\eta$ and $\eta'$, resp., show up—and no other resonances.

For $\pi^\circ$ energies above $\sim 600$ MeV the two photons from its decay merge into one energy cluster in the Crystal Ball detector. The second moment of the lateral energy distribution allows to measure the invariant mass, i.e. to identify the $\pi^\circ$'s. Including those merged $\pi^\circ$'s into the analysis one can reach higher invariant masses of the final state. For $\gamma\gamma \to 3\pi^\circ$ the $\pi_2(1680)$ resonance has been seen for the first time (Fig. 2c) [7] in this way. It has $J^P = 2^-$. Table 2 compiles the Crystal Ball results on the partial widths $\Gamma_{\gamma\gamma}$.

Table 2: Crystal Ball results on $\gamma\gamma$ partial widths $\Gamma_{\gamma\gamma}$.

| $0^-$ resonances | $\Gamma_{\gamma\gamma}$/keV | $2^+$ resonances | $\Gamma_{\gamma\gamma}$/keV |
|---|---|---|---|
| $\pi^\circ$ | $(7.7 \pm 0.5 \pm 0.5) \times 10^{-3}$ | $a_2(1320)$ | $1.14 \pm 0.20 \pm 0.26$ |
| $\eta \to 2\gamma$ | $0.51 \pm 0.02 \pm 0.04$ | $f_2(1270)$ | $3.26 \pm 0.16 \pm 0.28$ |
| $\eta \to 3\pi^\circ$ | $0.54 \pm 0.05 \pm 0.10$ | | |
| $\eta' \to \gamma\gamma$ | $4.7 \pm 0.5 \pm 0.5$ | | |
| $\eta' \to \eta\pi^\circ\pi^\circ$ | $4.6 \pm 0.4 \pm 0.6$ | | |

| $0^+$ resonances | $\Gamma_{\gamma\gamma}$/keV | $2^-$ resonances | $\Gamma_{\gamma\gamma}$/keV |
|---|---|---|---|
| $a_0(980)$ | $(0.19 \pm 0.07^{+0.10}_{-0.07})/B_{\pi^\circ\eta}$ | $\pi_2(1680)$ | $1.3 \pm 0.3 \pm 0.2$ |
| $f_0(975)$ | $0.31 \pm 0.14 \pm 0.09$ | | |
| $f_0(1300)$ | $< 0.47/B_{\pi^\circ\pi^\circ}$ | | |

## 4. Interpretation of the Results

The results for $\gamma\gamma$-excitation of resonances are usually given by the partial widths $\Gamma_{\gamma\gamma}(R)$. Those numbers are not easily understood "anschaulich" as they contain kinematic factors. We therefore prefer to present them by their **helicity form factors** [8]. The idea is to expand the hadronic tensor $T_{\mu\nu}$ in the matrix element of $\gamma\gamma$-excitation of resonances into tensors $H_{\mu\nu}$ which give a one-to-one correspondence to helicity matrix elements. The helicity form factors $F$, given by

$$T_{\mu\nu} = \sum_i F_i \times H_{\mu\nu}^{(i)} \tag{2}$$

are characteristic for a resonance. They have to be measured and can then be compared more easily to each other and to predictions of hadron models.

The relation between $\Gamma_{\gamma\gamma}$ and $F$ depends on the spin-parity $J^P$ of the resonance. It is e.g.

$$\begin{array}{ll} J^P = 0^- & \Gamma_{\gamma\gamma} = \frac{1}{64\pi} \cdot M_R^3 \cdot F_{TT0}^2 \\ J^P = 2^+,\ \text{hel.}=2 & \Gamma_{\gamma\gamma} = \frac{1}{80\pi} \cdot \frac{1}{M_R} \cdot F_{TT2}^2 \end{array} \tag{3}$$

where the indices of $F$ indicate production by two transverse photons with total helicity 0 and 2, resp.

Fig. 3 displays the results. For the three pseudoscalar mesons it is $F_{TT0}(\pi^\circ) \approx F_{TT0}(\eta) \approx \frac{1}{2} \cdot F_{TT0}(\eta')$. For unobserved states only the product $\Gamma_{\gamma\gamma}(R) \times BR(R \to \mathit{final\ state})$ can be measured. For upper limits one has to make assumptions on the total width $\Gamma_{tot}(R)$ and the branching ratio $BR(R \to \gamma\gamma$, or $3\pi^\circ$, or $\eta\pi^\circ\pi^\circ)$. The values used seem to be reasonable. Roughly speaking, the upper limits are about a factor of 5 smaller than the helicity form factors of the known resonances. This also holds for the $\pi(1300)$, a candidate for a radial excitation of the $\pi^\circ(135)$.

All three tensor mesons have been observed. The limit on the glueball candidate $f_2(1720)$, unobserved in $\gamma\gamma$-production, is in the range of the helicity form factor of the observed tensor mesons.

The data on scalar resonances are more sparse. Again the upper limit for the glueball candidate $f_0(1590)$ has about the size of $F_{TT0}(f_0(975))$ or $F_{TT0}(a_0(980))$. Upper limits for hypothetical low mass scalar resonances are also displayed.



Table 3: Summary of known mesons measured in $\gamma\gamma$-collisions.

| | $L=0$ $0^{-+}$ pseudoscalar | $L=1$ $0^{++}$ scalar | $2^{++}$ tensor | $L=2$ $2^{-+}$ pseudotensor |
|---|---|---|---|---|
| ground states | $\pi^\circ(135)$ $\eta(549)$ $\eta'(958)$ | $a_0(980)$ $f_0(975)$ $f_0(1300)$ | $a_2(1320)$ $f_2(1270)$ $f_2'(1525)$ | $\pi_2(1680)$ |
| radially excited states | $\pi(1300)$ | | | |
| gluonia | $\eta(1440) = \iota$ | $f_0(1590)$ | $f_2(1720)$ | |

For the observed resonances the octet-singlet mixing angles can be derived. If one uses Crystal Ball results only one gets [9]

$$\begin{array}{ll} \text{for pseudoscalars} & \theta_P = -(21.2 \pm 1.6)^\circ \\ \text{for tensors} & \theta_T = +(30.8 \pm 1.8)^\circ \end{array} \tag{4}$$

i.e. the mixing for pseudoscalars is far from ideal mixing ($\theta_{ideal} = 35.3^\circ$) while it is rather close for tensors (i.e. for them the strange and non-strange states are decoupled). The data for scalars are not yet significant. It should be mentioned that the measured $F_{TT0}$ (scalars) disagree with predictions of $q\bar{q}$-models, but agree with those of 4-quark models.

## 5. Summary

Table 3 shows that the two-photon excitation for all known meson ground states which are accessable because of quantum numbers ($C = +$, $J \neq 1$) has been observed except for the $f_0(1300)$. On the other hand no candidate for radially excited states or for gluonium has been seen. Their couplings to photons seem to be smaller, one has to see whether this is significant for models or not yet.

## Acknowledgements

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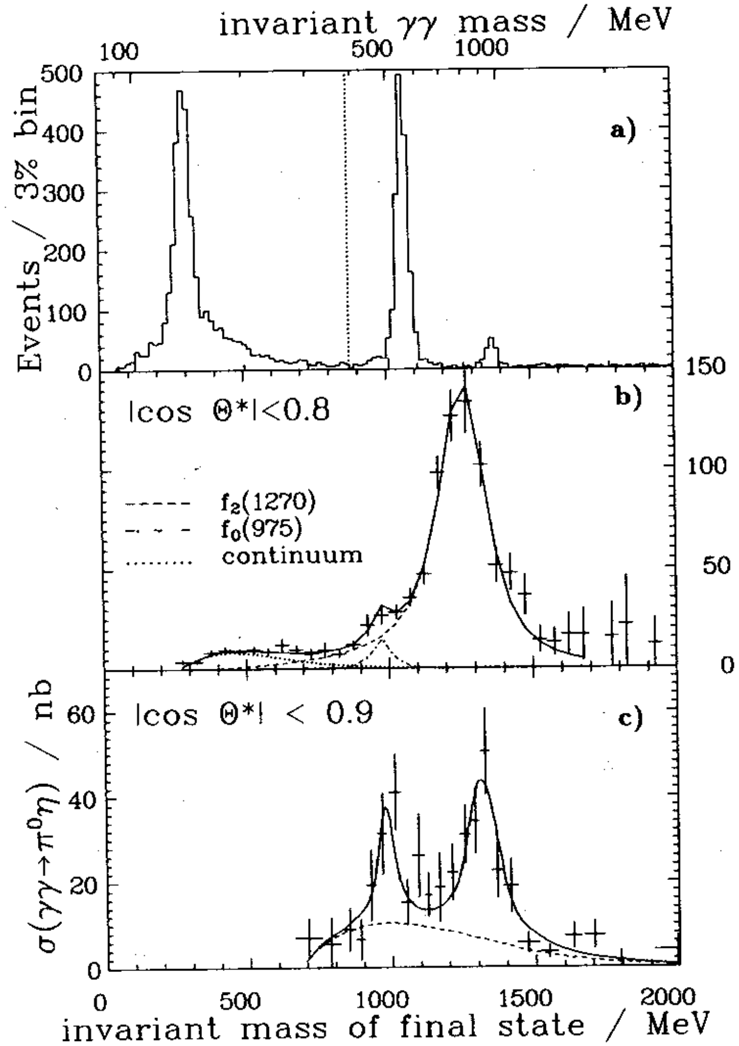


Figure 1: Crystal Ball results on a) $\gamma\gamma \to 2\gamma$ (left side: $\pi^\circ$ trigger, right side: $\pi^\circ$ and $\eta$ triggers), b) $\gamma\gamma \to \pi^\circ\pi^\circ \to 4\gamma$ and c) $\gamma\gamma \to \pi^\circ\eta \to 4\gamma$.

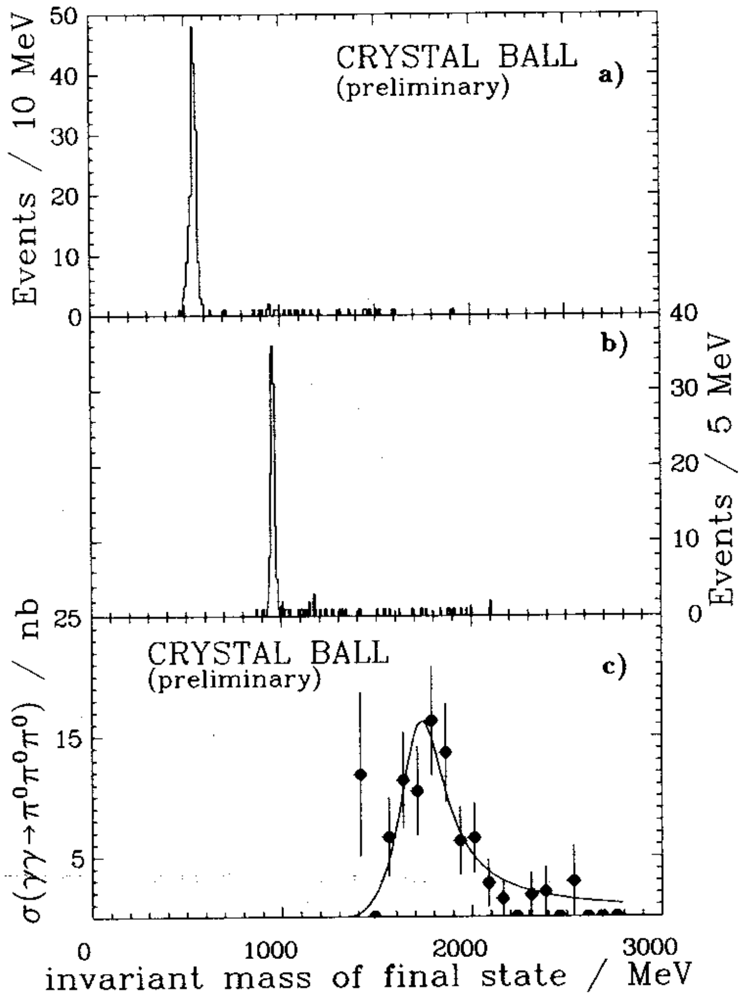


Figure 2: Crystal Ball results on a) $\gamma\gamma \rightarrow \pi^\circ\pi^\circ\pi^\circ \rightarrow 6\gamma$, b) $\gamma\gamma \rightarrow \eta\pi^\circ\pi^\circ \rightarrow 6\gamma$, and c) $\gamma\gamma \rightarrow \pi^\circ_{merged}\pi^\circ\pi^\circ \rightarrow 5$ *energy clusters.*



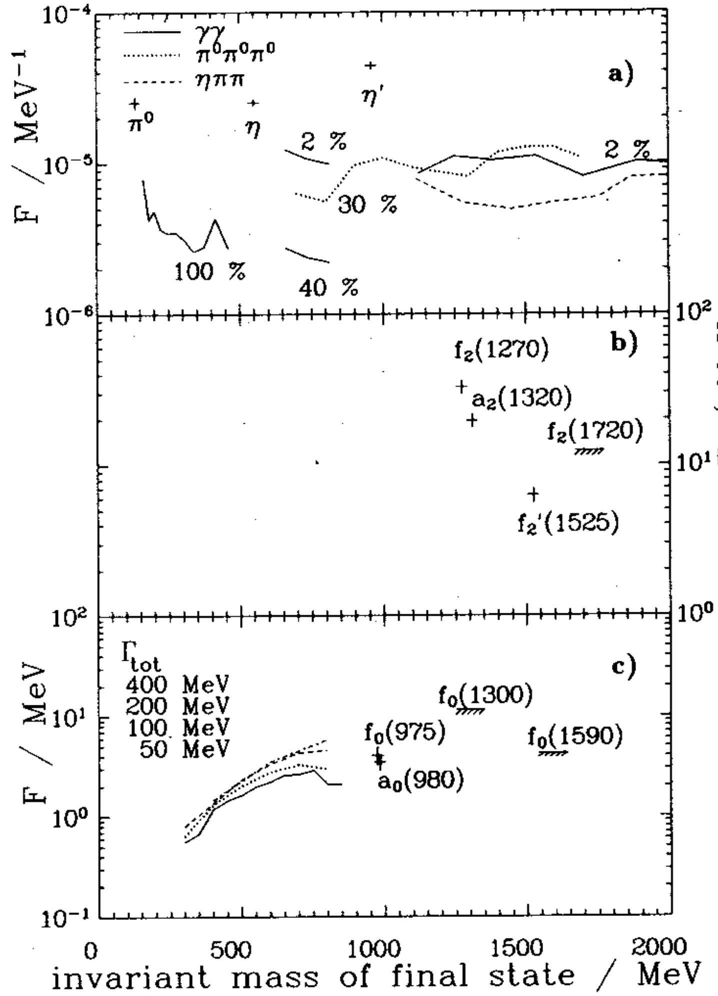


Figure 3: The helicity form factors for a) pseudoscalar, b) tensor, and c) scalar resonances. The values for observed states are given with their errors. Upper limits for unobserved states are displayed, the assumptions on their decay branching ratio and total width are indicated.