**DEUTSCHES ELEKTRONEN – SYNCHROTRON**

DESY 92–083
June 1992

# CRYSTAL BALL Contributions to the 9th International Workshop on Photon-Photon Collisions, La Jolla, 23-26 March 1992

## a) New Crystal Ball Data on Resonance Formation by $\gamma\gamma$–Collisions

## b) Representation of Results on $\gamma\gamma$–Formation of Resonances by Helicity Amplitudes

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ISSN 0418-9833

**NOTKESTRASSE 85 · D-2000 HAMBURG 52**

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ISSN 0418-9833

# NEW CRYSTAL BALL DATA ON RESONANCE FORMATION BY $\gamma\gamma$–COLLISIONS

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### Abstract

The Crystal Ball detector at DORIS-II has observed a hitherto unknown (though expected) resonance at 1870 MeV/c$^2$ in the reaction $\gamma\gamma \to \eta\pi^\circ\pi^\circ$. Decay angular distributions and subsystem invariant masses favor the assignment $\eta_2(1870)$, a $J^{PC} = 2^{-+}$ resonance. An efficient selection of the reaction $\gamma\gamma \to \pi^\circ\pi^\circ$ yielded 7000 events. Angular distributions in narrow mass bins became possible and allowed the decomposition of the cross section into $S-$ and $D-$wave contributions. Thus an $f_0(1250)$ resonance was found under the dominating $f_2(1270)$. The search for the channel $\gamma\gamma \to \eta\eta$ in the same selection yielded only $(16 \pm 6)$ events.

## 1 Introduction

The Crystal Ball collaboration [1] had presented at the last Two-Photon Workshop at Shoresh in 1988 [2] preliminary results on the reaction $\gamma\gamma \to \pi^\circ\pi^\circ$ with emphasis on the measurement of the $\pi^\circ\pi^\circ$ continuum starting at threshold [3] and the reaction $\gamma\gamma \to \pi^\circ\pi^\circ\pi^\circ$ at higher invariant masses $M(\pi^\circ\pi^\circ\pi^\circ)$ which led to the $\gamma\gamma-$formation of the $\pi_2(1670)$ resonance with quantum numbers $J^{PC} = 2^{-+}$ [4]. Both analyses are now published [5, 6]. The work has been continued by analyzing high-mass $\eta\pi^\circ\pi^\circ$ final states and thereby finding the isoscalar partner of the $\pi_2(1670)$, the $\eta_2(1870)$, and by extending the measurement of $\gamma\gamma \to \pi^\circ\pi^\circ$ to higher invariant masses $M(\pi^\circ\pi^\circ)$ with high selection efficiency thus seeing a $f_0(1250)$ resonance under the $f_2(1270)$. The same selection gave only very few $\eta\eta$ events.

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[1] On leave (1991-92) to the Institute of Medium Energy Physics, ETH-Zürich

## 2 The Crystal Ball Detector and its Data Sample

The Crystal Ball detector [7] is a spherical calorimeter for electromagnetically showering particles. So it is well suited to reconstruct $\pi^\circ-$ and $\eta-$mesons. Several of its features make it an excellent instrument for two-photon physics:

1. Its energy resolution for photons (energy E)

   $$\sigma_E/E = 2.7\%/\sqrt[4]{E/\mathrm{GeV}} \quad \text{(corresponding to 5 MeV for E = 100 MeV)},$$

   together with the angular resolution

   $$\sigma_\theta = 1^\circ\ (3^\circ) \quad \text{for high (low) energy photons},$$

   result in mass resolutions for $\pi^\circ$ and $\eta$ of

   $$\sigma_M(\pi^\circ) \approx 10\ \mathrm{MeV}, \ \ \sigma_M(\eta) \approx 20\ \mathrm{MeV}.$$

2. The solid angle coverage is very large,

   $\Omega = 93\% \times 4\pi$ for the main ball,
   $\Omega = 85\% \times 4\pi$ for full shower containment,
   $\Omega = 98\% \times 4\pi$ including the end-caps (used for vetoes).

3. The detector could be operated with low trigger thresholds. The standard $\gamma\gamma-$trigger had a threshold of $E_{th} = 8\% \cdot E_{cm} \approx 800$MeV, while special $\gamma\gamma-$triggers had reached $E_{th} = 0.8\% \cdot E_{cm} \approx 80$ MeV (so that single $\pi^\circ-$formation by $\gamma\gamma-$reactions could be observed [8]).

4. The detector has a low threshold of 10 MeV for photon detection.

Feature 3 is needed because most two-photon reactions have low energies, partly because the two-photon spectrum decreases rather steeply with energy, partly because the meson resonances which we want to observe and measure have low masses. One has to keep in mind that the largest $\gamma\gamma-$cross section is the $f_2(1270)$ formation with $\approx 450$ nb.
Features 2 and 4 are important because two-photon collisions are wide-band beam reactions, their center-of-mass system is not the laboratory system. Consequently the reactions have a Lorentz-boost. A large solid angle and a low photon detection threshold become important.
The Crystal Ball detector had been operated in the years 1982–86 at the DORIS-II $e^+e^-$ storage ring at DESY at about 5 GeV beam energy. An integrated luminosity of 255 pb$^{-1}$ has been collected. Data analysis on $\gamma\gamma-$physics ended in the fall of 1991.

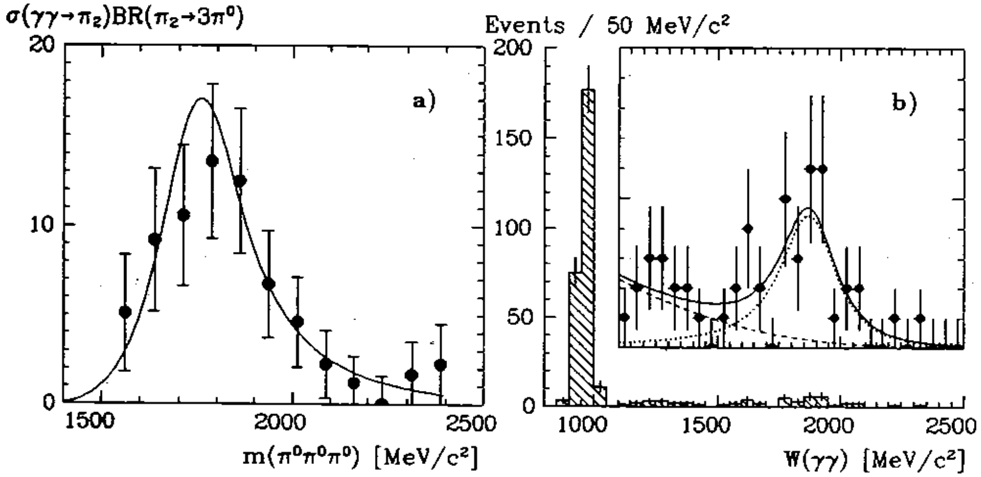

Figure 1: Excitation curves for $\gamma\gamma-$formation: (a) $\pi_2(1670)$ and (b) $\eta_2(1870)$. See text.

## 3 The $J^{PC} = 2^{-+}$ Mesons

Besides the pseudoscalar ($J^{PC} = 0^{-+}$), the scalar ($0^{++}$), and the tensor ($2^{++}$) mesons the $2^{-+}$ mesons are the next lightest mesons which can be produced by $\gamma\gamma-$collisions according to their quantum numbers. They are the ${}^1D_2$ states of the $q\bar{q}-$model of hadrons, i.e. $L = 2$ and $S = 0$ form $J = 2$.

The $\pi_2(1670)$ [9] has been seen in the reaction $\gamma\gamma \to \pi\pi\pi$, for $\pi^+\pi^-\pi^\circ$ by CELLO [10] and for $\pi^\circ\pi^\circ\pi^\circ$ by Crystal Ball [6]. For this rather high-mass resonance also the pions from the decay have higher energies. As a consequence the two photons from the decay of the high energetic $\pi^\circ$ will overlap with high probability. Given the granularity of the Crystal Ball detector this starts between $E_{\pi^\circ} = 600 - 800$ MeV. The study of the transverse energy distribution from $\pi^\circ \to \gamma\gamma$ allows to measure the $\pi^\circ$ mass as well as its energy and direction. Thus we observe five "connected regions" (CR) of energy deposition in the detector: one "merged $\pi^\circ$" and four photons which have to form two $\pi^\circ$'s.

The cross section for the reaction $\gamma\gamma \to \pi^\circ\pi^\circ\pi^\circ$, selected as explained above, shows a resonance at the $\pi_2(1670)$ (see figure 1 a). The measurement of the angular distributions of the $\pi^\circ$'s and the distribution of the invariant mass of the $\pi^\circ\pi^\circ-$subsystem give the assignment $J^{PC} = 2^{-+}$. Thus this resonance is the $\pi_2(1670)$. For details see [6].

The reaction $\gamma\gamma \to \eta\pi^\circ\pi^\circ \to 6\gamma$ had been studied in an early stage of the experiment [11]. It was resumed using the full data sample of 255 pb$^{-1}$ and an improved analysis technique with higher efficiency [12, 13]. The overwhelming feature is the $\eta'(958)$ production (see figure 1 b). But we observe now around 1870 MeV/c² a new resonance dacaying into $\eta\pi^\circ\pi^\circ$. The $p_t^2-$distribution (figure 2) shows that it is a genuine $\gamma\gamma-$reaction. Both mass-bins, $0.8 \leq W \leq 1.1$ GeV ($\eta'(958)$ region) and $1.6 \leq W \leq 2.2$ GeV (our new resonance) show agreement with the Monte Carlo for $\gamma\gamma-$production, while the events in the $1.1 \leq W \leq 1.6$ GeV mass bin are background (containing feed-down from $\gamma\gamma \to \eta\pi^\circ\pi^\circ\pi^\circ \to 8\gamma$ into $6\gamma$). We have only seven events for $W \geq 2.2$ GeV. Unluckily the statistics for the new resonance is small. So the measurements of the angular distributions and of the invariant masses of subsystems do not allow a unique $J^{PC}$ assignment, but $J^{PC} = 2^{-+}$ is favored.

We suppose that this new resonance is the $\eta_2(1870)$ which is the isoscalar partner of the $\pi_2(1670)$, expected in the quark model of hadrons [14], but which had not yet been reported.

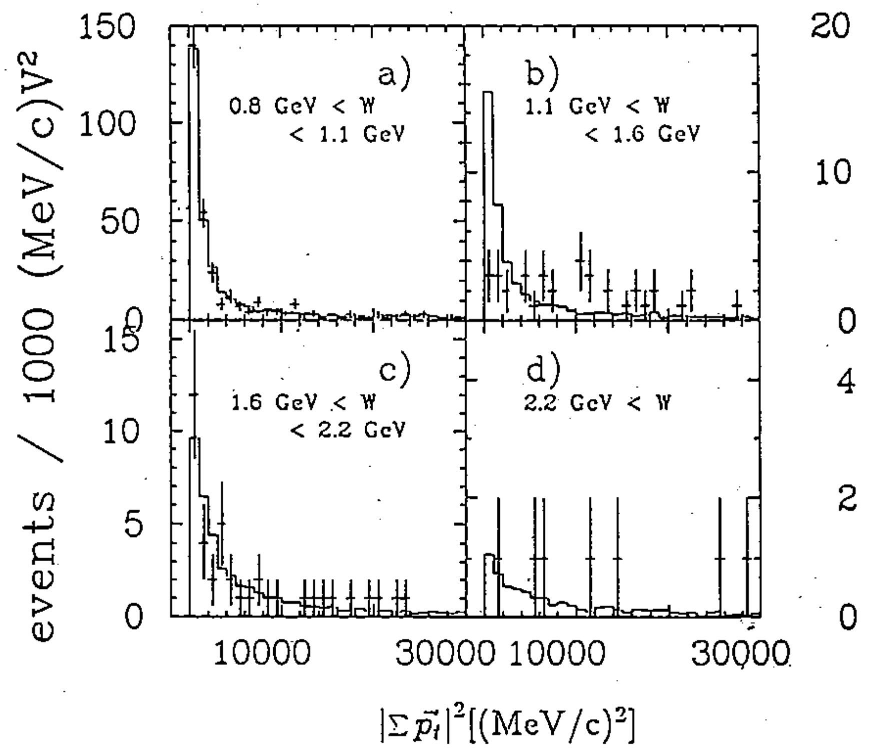

Figure 2: $p_t^2$-distribution of $\eta\pi^\circ\pi^\circ$ events for four mass bins. See text.

Table 1: Resonance parameters of the $J^{PC} = 2^{-+}$ mesons

| | | $\pi_2(1670)$ | $\eta_2(1870)$ |
|---|---|---|---|
| reference | | [6] | [12, 13] |
| mass | MeV/c$^2$ | $1742 \pm 31 \pm 49$ | $1881 \pm 32 \pm 40$ |
| width | MeV | $236 \pm 49 \pm 36$ | $221 \pm 92 \pm 44$ |
| $\Gamma_{\gamma\gamma} \cdot BR$ | eV | $251 \pm 40 \pm 35$ | $950 \pm 270 \pm 200$ |
| $\Gamma_{\gamma\gamma}$ | keV | $1.45 \pm 0.20 ^{+0.35}_{-0.20}$ | $\geq 4.7$ |

Table 1 gives the resonance parameters for the two $J^{PC} = 2^{-+}$ mesons as measured by the Crystal Ball collaboration. For details the reader should refer to the quoted publications.

The $\gamma\gamma$ partial width of the $\pi_2$ has suscited some theoretical discussions [15, 16].

# 4 The Reaction $\gamma\gamma \rightarrow \pi^\circ\pi^\circ$ and the Scalar Mesons

## 4.1 Scalar mesons

It is well known that the $J^{PC} = 0^{++}$ scalar mesons (the $^3P_0$ states in the quark model) pose problems for understanding [17]. They are, in short:

1. More scalar mesons have been observed than are needed for the quark model assignment. Besides the longtime known [9] $a_0(980)$, $f_0(975)$, $f_0(1400)$ these are $f_0'(1525)$ [18], $G/f_0(1590)$ [19], and $f_0(1710)$ [20]. So, six states have been reported instead of one isovector $a_0$ and two isoscalars $f_0$ and $f_0'$.

2. The $0^{++}$ states are difficult to reconcile with the $2^{++}$ ($^3P_2$) and the $1^{++}$ ($^3P_1$) nonets from which they differ just by spin-orbit coupling. This applies for the mass values, for the mass ordering according to preferentially non-strange and strange decays, and especially the $\gamma\gamma$ partial widths, $\Gamma_{\gamma\gamma}$, which are for the the $a_0(980)$ and the $f_0(975)$ much smaller than expected from the results on the $2^{++}$ tensor mesons.

3. This situation has led to models which interpret the $f_0(975)$ and the $a_0(980)$ not as $q\bar{q}$−mesons, but as four-quark states $qq\bar{q}\bar{q}$ [21] or as $K\bar{K}$−molecules [22]. These models can explain the experimental results.

4. If this is true then one major question remains: "Where are the true scalars, i.e. those which belong to the $q\bar{q}$−nonet?" [23].

## 4.2 Crystal Ball contribution to the scalar mesons

The Crystal Ball collaboration presents new data on the reaction $\gamma\gamma \rightarrow \pi^\circ\pi^\circ$. A first publication on this channel [5] had concentrated on the low-mass continuum. Therefore a special trigger had to be installed which was operated during 40% of the integrated luminosity.

The new analysis [24, 25, 26] aimed at high efficiency and higher invariant masses $M(\pi^\circ\pi^\circ)$. Two steps were taken:

1. The full date sample was used. As mentioned above, this implies a trigger threshold of $M(\pi^\circ\pi^\circ) \geq 800$ MeV.

2. A highly efficient selection was developed (applicable only above 800 MeV invariant mass). Figure 3 shows the detection efficiency as a function of $M(\pi^\circ\pi^\circ)$. One can see the trigger threshold. At low energies the four photons from the decay of the two $\pi^\circ$'s are seperated and appear as four "connected regions" (CR) of energy deposition in the calorimeter. At higher energies the two photon-showers from one of the $\pi^\circ$'s start to merge into one CR – the "3 CR" case. At still higher energis both $\pi^\circ$'s produce one CR each ("2 CR" case). The sum of the efficiencies is a smooth increasing curve – increasing because at higher invariant masses the $\gamma\gamma$ center-of-mass system moves slower with respect to the laboratory system and consequently the Lorentz-boost has less influence. It should be mentioned that just at the $f_2(1270)$ mass the efficiencies for selection of 3 CR's and 4 CR's are equal.

The selection of the $\gamma\gamma \rightarrow \pi^\circ\pi^\circ$ channel using four, three, and two CR's results in a data sample of $\approx 7000$ events. The $M(\pi^\circ\pi^\circ)$−distribution of the raw data (figure 4) shows the prominent $f_2(1270)$ peak. Also plotted are the background events as obtained from the sideband in the $\pi^\circ\pi^\circ$ selection. They are hardly visible , we have a practically background-free data sample.

With this large data sample one could analyse angular distributions in 100 MeV mass bins. Figure 5 shows some examples. The data are corrected for detection efficiency and $\gamma\gamma$ flux. We want to learn about the $S$−wave and the $D$−wave contributions in the reaction $\gamma\gamma \rightarrow \pi^\circ\pi^\circ$. So the data are fit to the sum$^2$ of $| Y_0 |^2$ and $| Y_2^2 |^2$. In the mass bin 925 – 1025 MeV/c$^2$ (the $f_0(975)$ region) the $S$−wave is dominant. In the mass bin 1225 – 1325 MeV/c$^2$ (the $f_2(1270)$ region) this is true for the $D$−wave. At higher $M(\pi^\circ\pi^\circ)$, 1550 – 1650 MeV/c$^2$, we find pure $D$−wave. But in the mass range around 1250 MeV/c$^2$ (bin 1175 – 1275 MeV/c$^2$ is shown) we find an increase in $S$−wave compared with neighboring mass bins.

After this analysis it was possible to decompose the cross section $\sigma(\gamma\gamma \rightarrow \pi^\circ\pi^\circ)$ into the dominant $D$−wave and an $S$−wave cross section (figure 6). In the $D$−wave we see

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[2] The (spin-2, helicity-0)-contribution has been set to zero because there is no experimental evidence for it [27] in agreement with theoretical expectations [28].

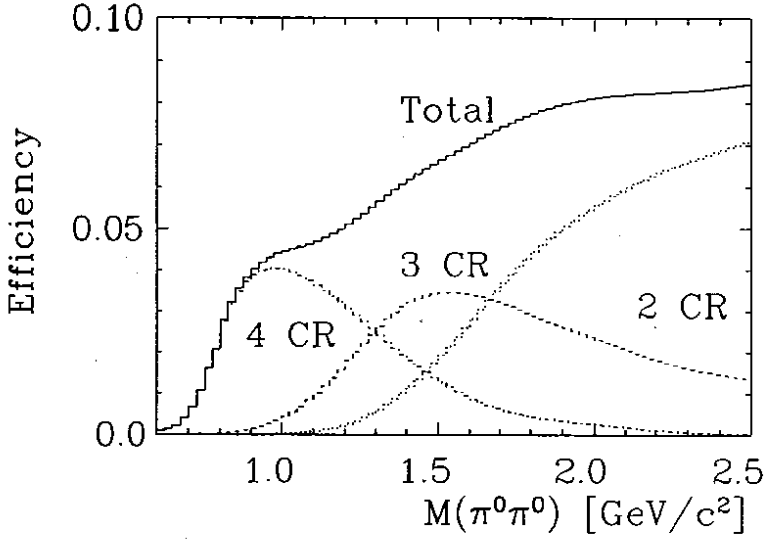

Figure 3: Selection efficieny for $\gamma\gamma \rightarrow \pi^\circ\pi^\circ$ with four (dashed-dotted), three (dashed), and two (dotted) connected regions (CR), full line is sum. See text.

the well-known $f_2(1270)$, also at higher $M(\pi^\circ\pi^\circ)$ it is pure $D-$wave. The $S-$wave cross section shows three features: a tail from the low-mass Born continuum, the $f_0(975)$ which comes out with somewhat less than three standard deviations, and a new broad structure around 1250 MeV/c$^2$ which we call $f_0(1250)$. Table 2 gives the results of a fit to Breit-Wigner resonances. The new broad $S-$wave resonance appears with 5.2 standard deviations while the $f_0(975)$ has $2.8\,\sigma$.

The CELLO [29] and the Mark-II-collaborations [30] have also reported a broad $S-$wave structure under the $f_2(1270)$. But their fits give a different mass value of $\approx$ 1100 MeV. We will compare the systematic effects in the analyses of $\gamma\gamma \rightarrow \pi^+\pi^-$ and $\gamma\gamma \rightarrow \pi^\circ\pi^\circ$. First of all the $\pi^\pm$ have to be identified among the more numerous $e^\pm$ and $\mu^\pm$. Both, CELLO and Mark-II, have made a considerable effort to achieve this. Their results agree. $\pi^\circ$ reconstruction and identification are easier, but one pays with a smaller cross section and a reduced geometrical selection efficiency (because four $\gamma$'s instead of only two charged pions have to appear in the detector). Then, and this will probably explain the different results though it is not yet understood quantitatively, the $\pi^+\pi^-$-resonances sit on a still sizeable low-mass continuum from the Born amplitude. This process cannot produce $\pi^\circ\pi^\circ$ in lowest order, but only via final state interactions and is therefore much smaller (about a factor of ten) for $\pi^\circ\pi^\circ$ than for $\pi^+\pi^-$. It is this argument which makes

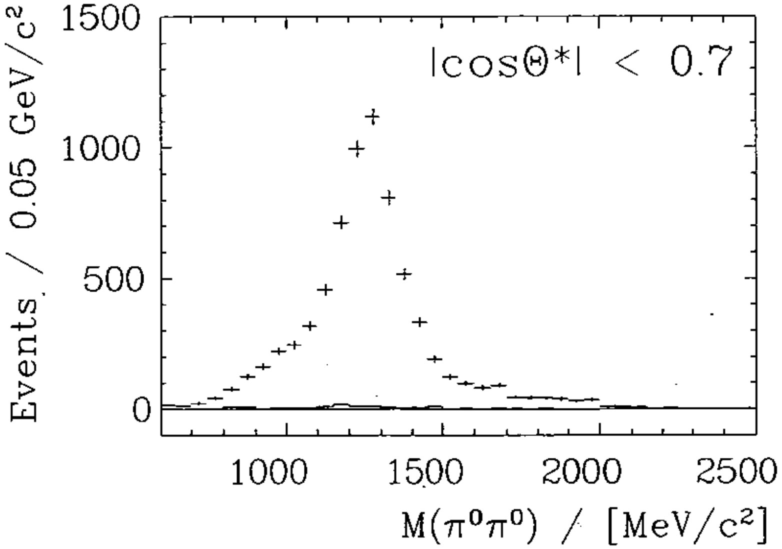

Figure 4: Mass distribution of $\gamma\gamma \rightarrow \pi^\circ\pi^\circ$ events. Raw data (full line) and background (histogram, hardly visible) from sidebands.

Table 2: Results of the fit of $\sigma(\gamma\gamma \rightarrow \pi^\circ\pi^\circ)$ with $S-$ and $D-$wave decomposition. NB! Values without errors have been fixed for the fit. The mass value of the $f_0(1250)$ has been changed to get the best fit. NB! For $\Gamma_{\gamma\gamma}(f_0(1250))$ a branching ratio of $BR(f_0 \rightarrow \pi^\circ\pi^\circ) = 1/3$ has been assumed, i.e. a pure $u-$ and $d-$quark content of the $f_0(1250)$.

| resonance | | $f_2(1270)$ | $f_0(975)$ | $f_0(1250)$ |
|---|---|---|---|---|
| $M$ | MeV/c$^2$ | 1262 ± 8± 3 | 975 | 1250 |
| $\Gamma_{tot}$ | MeV | 190 ± 7 | 33 | 268 ± 70 |
| $\Gamma_{\gamma\gamma} \cdot BR$ | keV | | | 1.29 ± 0.25 ± 0.17 |
| $\Gamma_{\gamma\gamma}$ | keV | 3.21 ± 0.14 ± 0.35 | 0.20 ± 0.07 ± 0.04<br>≤ 0.31 (90%CL) | ≈ 3.9 |

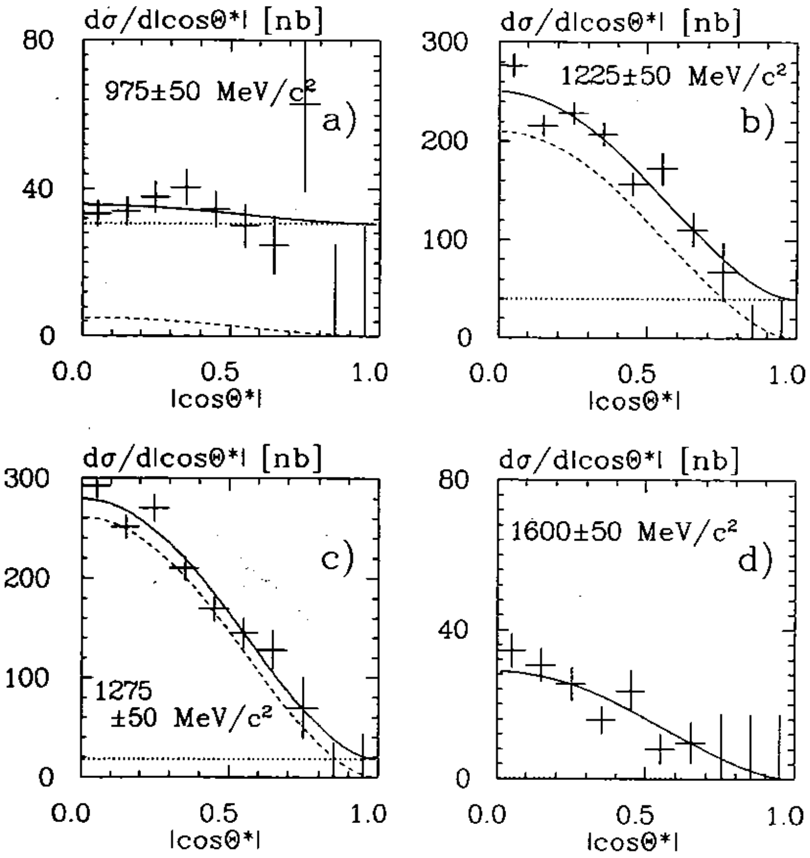

**Figure 5:** Angular distributions of $\gamma\gamma \rightarrow \pi^\circ\pi^\circ$ (four mass bins are shown) with decomposition into $S-$ (dotted) and $D-$wave (dashed) contributions, sum (full line) and data points with error bars.

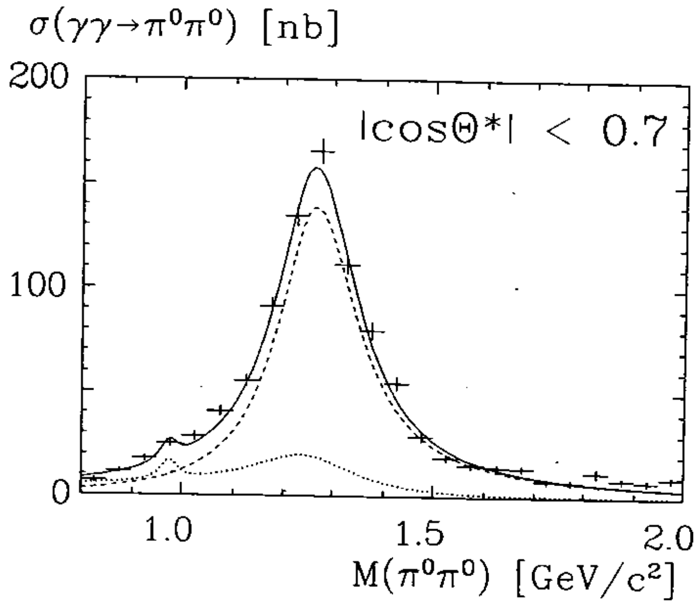

Figure 6: The cross section $\sigma(\gamma\gamma \rightarrow \pi^\circ\pi^\circ)$ and its partial wave decomposition as a function of the invariant mass. Points with error bars: data, full line: Breit-Wigner fit, dashed line: $D-$wave, dotted line: $S-$wave.

us believe that the interpretation of the data for $\gamma\gamma \rightarrow \pi^\circ\pi^\circ$ is easier and may be more reliable.

One last remark. The reader may wonder that the $f_2\,(1270)$ and the $f_0\,(1250)$ have about the same partial width $\Gamma_{\gamma\gamma}$ while the cross section for the $f_2\,(1250)$ is much larger. It is the spin factor in the Breit-Wigner cross section which favors the formation of spin-2 mesons - and makes the observation of spin-0 states very difficult.

### 4.3 Present situation for scalar mesons

The present situation for the $0^{++}$ scalar mesons can be summarized as follows:

Three states which fit into the scheme for $q\bar{q}-$mesons have been reported: $a_0\,(1320)$ [19], $f_0\,(1250)$ [24, 25, 26], and $f_0'\,(1525)$ [18]. Masses and widths of these states agree with expectation if one relates the $^3P_0$ nonet with the $^3P_1$ and the $^3P_2$ nonets. This is also true for the ratio $\Gamma_{\gamma\gamma}(f_0\,(1250))/\Gamma_{\gamma\gamma}(f_2\,(1270)) = 1.26 \pm 0.33$ (experimental result). Theoretically one expects in the non-relativistic quark model a ratio of 3.8, while a relativistic calculation [28] gives $\approx 2$. So the situation seems at the moment satisfactory. This, by the way, supports indirectly the models which assume four quarks or a $K\bar{K}-$molecule as the constituents of the $f_0\,(975)$ and the $a_0\,(980)$.

But one has to keep in mind:

- The data need confirmation because they have been reported by only one experiment each and have been achieved only by partial wave analysis.
- $\Gamma_{\gamma\gamma}(a_0(1320))$ and $\Gamma_{\gamma\gamma}(f_0'(1520))$ should be measured.

We can now determine the quark-flavor mixing angle for the scalar mesons. We assume that the $a_0(1320)$, $f_0(1250)$, and $f_0'(1525)$ are the neutral members of the nonet. With the quadratic mass formula

$$\tan^2\theta(0^{++}) = -\frac{3M^2(f_0') - 4M^2(K_0^*) + M^2(a_0)}{3M^2(f_0) - 4M^2(K_0^*) + M^2(a_0)}$$

one gets

$$\theta(0^{++}) = (35 \pm 10)^\circ,$$

i.e. the states in this nonet are ideally mixed within the (large) error - no wonder as all states are degenerate with $2^{++}$ tensor mesons which are known to be ideally mixed.

### 4.4 $\pi^\circ\pi^\circ$ production at invariant masses above 1.5 GeV/c$^2$

Figure 7 shows the cross section $\sigma(\gamma\gamma \to \pi^\circ\pi^\circ)$ for $M(\pi^\circ\pi^\circ) \geq 1.5\,\mathrm{GeV}/c^2$. The data are compared to two QCD-inspired models [31, 32]. Both predictions are more than a factor 10 below the data. But when we extrapolate the tail of the $f_2(1270)$ Breit-Wigner resonance shape to these masses (assuming that this is allowed) the data are described very well by this ansatz. So we cannot draw any conclusion about the validity of the QCD models. It is worth mentioning that an enhancement between 1.7 and 2.0 GeV/c$^2$ is at the position where the $f_2(1810)$ has been seen. But our data don't allow a firm conclusion.

## 5 The $\eta\eta$ Channel and Glueballs

It is the most important task of hadron spectroscopy to identify glueballs. How can $\gamma\gamma$-physics contribute? Glueballs, having no charged constituents, will not couple to $\gamma\gamma$ in lowest order, but can do so via quark loops. So we expect for glueballs the two-photon width $\Gamma_{\gamma\gamma}$ to be suppressed compared to $q\bar{q}$−resonances. Therefore we can decide on glue-glue- vs. $q\bar{q}$-constituents of a resonance $R$ by comparing $R \to gg$ (measured by $J/\psi \to \gamma gg \to \gamma R$) with $\Gamma_{\gamma\gamma}$. This is quantified by the "stickiness S" [33]

$$\frac{R \to gg}{R \to \gamma\gamma} \sim S = \frac{\Gamma(J/\psi \to \gamma R)/\text{phase space}}{\Gamma_{\gamma\gamma}(R)/\text{phase space}}$$

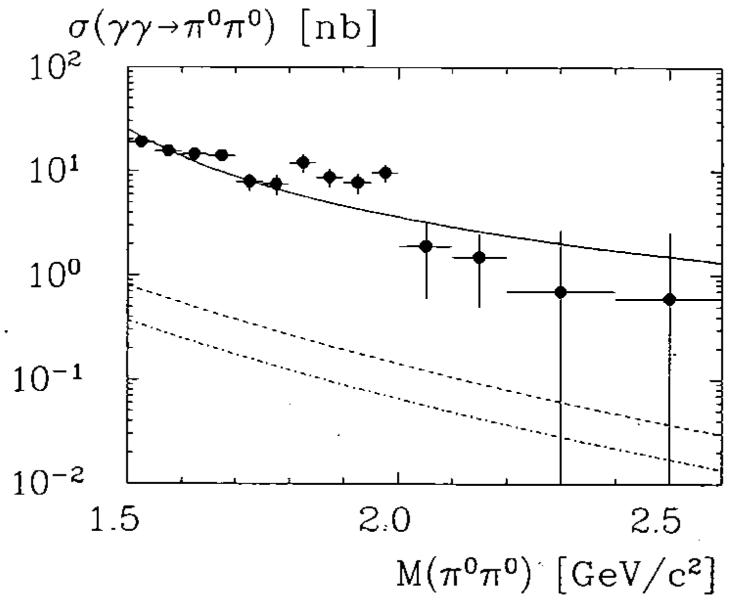

Figure 7: The cross section $\sigma(\gamma\gamma \to \pi^\circ\pi^\circ)$ for $W_{\gamma\gamma} > 1.5$ GeV. Shown are the Crystal Ball data and the theoretical predictions of [31] (dashed) and [32] (dashed-dotted).

In this game which seems to be the most promising for identifying glueballs as such the $\gamma\gamma$-physics has to play the unthankful rôle: not seeing the resonance which is a glueball candidate.

Glueballs are flavor-neutral. So we expect equal branching ratios (after phasespace correction) for $G \to \pi\pi$, $\to K\bar{K}$ and $\to \eta\eta$. It is the latter decay channel which the Crystal Ball detector can observe.

Crystal Ball presents a new analysis of the reaction $\gamma\gamma \to \eta\eta$. The selection was performed together with the $\pi^\circ\pi^\circ$-channel. Figure 8 a) shows the scatter plot $M(\gamma_1\gamma_2)$ – $M(\gamma_3\gamma_4)$ (three entries per event). The $\pi^\circ\pi^\circ$ events are already removed (which removes also a lot of combinatoric background). One can see the $\pi^\circ\eta$ events and already the $\eta\eta$ agglomeration. In figure 8 b) also the $\pi^\circ\eta$ events have been removed (together with their combinatoric background). Now the $\eta\eta$ events are clearly visible.

We find altogether 22 events $\gamma\gamma \to \eta\eta$. The sideband in the scatter plot gives 6 events which have to be subtracted from the 22 events. This number of $(16 \pm 6)$ $\eta\eta$−events has to be compared with 7000 $\pi^\circ\pi^\circ$ events. So our main result is that $\eta\eta$ production by $\gamma\gamma$ is considerably suppressed.

Figure 9 shows the distribution of the invariant mass $M(\eta\eta)$ for those events. The results are:

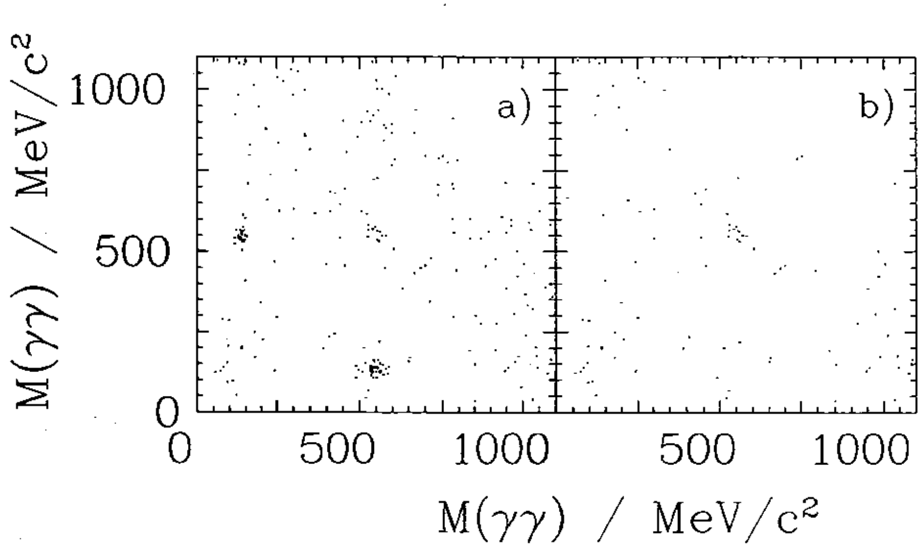

Figure 8: Selection of $\eta\eta$ events: Scatter plot $M(\gamma_1\gamma_2) - M(\gamma_3\gamma_4)$, three entries/event. a) Only $\pi^\circ\pi^\circ$ events removed, b) also $\eta\pi^\circ$ events removed.

1. In the $f_2(1270)$ region we find 11 $\eta\eta$ events and 5 background events. This rate agrees with the expectation from the known branching ratio $f_2 \rightarrow \eta\eta$. We consider this as a check of our selection.

2. No clustering in mass of the remaining 11 $\eta\eta$ events (-1 background event) has been observed.

## 6 Summary

The Crystal Ball results for $\gamma\gamma$-physics can be summarized as follows:

1. Crystal Ball has first-observed $\pi_2(1670) \rightarrow \pi^\circ\pi^\circ\pi^\circ$ in $\gamma\gamma$ formation and has discovered a new resonance, possibly the $\eta_2(1870)$ (more statistics is needed for an unambiguous assignment of its quantum numbers). These are the first members of the $J^{PC} = 2^{-+}$ nonet for which the $\Gamma_{\gamma\gamma}$ has been measured and the $\eta_2(1870)$ has been observed for the first time.

2. Crystal Ball has observed an $S-$wave resonance under the $f_2(1270)$. We call this new resonance the $f_0(1250)$.

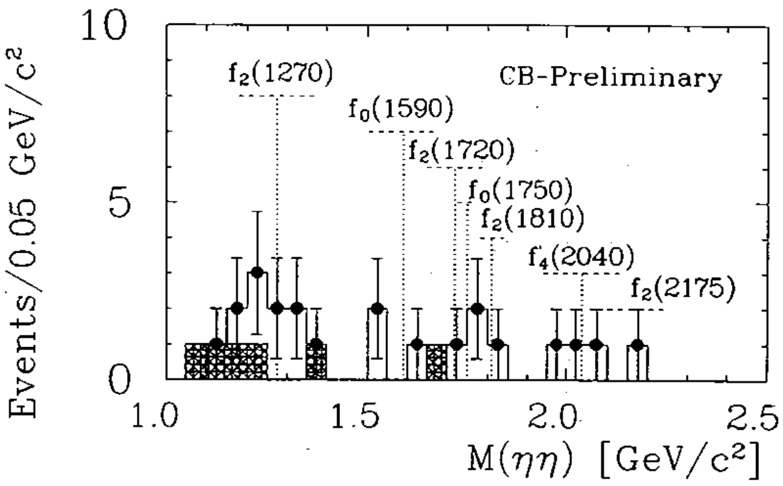

Figure 9: The invariant mass $M(\eta\eta)$. Points with error bars: experimental data, hatched: background (from sideband). Also given are the positions and widths of resonances with known dacays into $\eta\eta$. $\sigma(\gamma\gamma \rightarrow \pi^\circ\pi^\circ)$ for $W_{\gamma\gamma} > 1.5$ GeV. Shown are the Crystal Ball data and the theoretical predictions of [31] (dashed) and [32] (dashed-dotted).

3. Only very few $\eta\eta$ events have been seen compared to the many $\pi^\circ\pi^\circ$ events. This supports the hypothesis that the resonances with a strong decay into $\eta\eta$ may have constituent gluons.

4. A complete set of data for two-photon formation of meson resonances has been obtained. Table 3 summarizes the observations.

From these measurements the quark-flavor (singlet-octet) mixing angles for $0^{-+}-$ and $2^{++}-$mesons have been determined [36]. For $2^{-+}-$mesons limits can be given [37]. Limits have been presented for $\gamma\gamma$-formation of states at other masses in the observed channels, esp. for candidates for radially excited states and for glueballs.
I want to mention two experiences which we had during our work:

1. Nearly all resonances have a decay channel into only neutrals $(\pi^\circ, \eta)$. So the Crystal Ball detector, though it is a specialized detector, could make contributions in a wide field.

2. It turned out to be an advantage to measure only all-neutral final states. Clearly, one gets less events. But one also escapes serious problems for analysis and interpretation. One example, the Born term contribution to low-mass $\pi\pi$ production,

Table 3: Listing of resonances seen by CB in $\gamma\gamma-$ formation

| reaction | channel | resonances observed | references |
|---|---|---|---|
| $\gamma\gamma \to 2\gamma$: | | $\pi^\circ$, $\eta$, $\eta'(958)$ | [8] |
| $\gamma\gamma \to 4\gamma$: | $\pi^\circ\pi^\circ$ | $f_2(1270)$, $f_0(975)$, continuum | [5] |
| | | $f_0(1250)$, $f_0(975)$ | [24, 25, 26] |
| | $\eta\pi^\circ$ | $a_0(980)$, $a_2(1320)$, continuum | [35] |
| | $\eta\eta$ | | this report |
| $\gamma\gamma \to 6\gamma$: | $\pi^\circ\pi^\circ\pi^\circ$ | $\eta$ | [34] |
| | | $\pi_2(1670)$ | [6] |
| | $\eta\pi^\circ\pi^\circ$ | $\eta'(958)$ | [11, 13] |
| | | $\eta_2(1870)$ | [12, 13] |
| $\gamma\gamma \to 8\gamma$: | | $a_0(980)$, $a_2(1320)$ | [24] |
| $\gamma\gamma \to 10\gamma$: | | $\eta'(958)$ | [24] |
| $\gamma\gamma \to 12\gamma$: | no $\gamma\gamma-$events found | | |

has been mentioned. Another is the observation of the $\pi_2(1670) \to \pi\pi\pi$. In the channel $\pi^\circ\pi^\circ\pi^\circ$ the $\pi_2$ appears as a peak. The only observed intermediate state in its decay is the $f_2(1270)\pi^\circ$. But the channel $\pi^+\pi^-\pi^\circ$ has also the isobar $\rho^\circ\pi^\circ$. The same intermediate state appears in the decay of the $a_2(1320)$. And both mix. The analysis becomes more complicated. The advantage when working with $\pi^\circ$: $\rho^\circ$ is not possible. One has less events, but they are easier to interpret.

# Acknowledgement

I would like to thank all the collaborators over the years for getting data with the Crystal Ball detector and analyzing them. Among those who specialized on two-photon physics I want to mention especially K. Wacker, H. Marsiske, B. Muryn, and K.-H. Karch.

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