# Observation of a New $\eta \pi^{\circ} \pi^{\circ}$ Resonance at $1900 \mathrm{MeV} / \mathrm{c}^{2}$ in Two-photon Scattering 

## The Crystal Ball Collaboration

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Using the Crystal Ball detector at the DORIS II $\epsilon^{+} \epsilon^{-}$storage ring, we measure the $\eta \pi^{0} \pi^{\circ}$ mass spectrum in the reaction $\epsilon^{+} \epsilon^{-} \rightarrow \epsilon^{+} e^{-} \eta \pi^{\circ} \pi^{\circ} \rightarrow e^{+} \epsilon^{-} 6 \gamma$ from the $\eta \pi^{0} \pi^{0}$ threshold to about $2500 \mathrm{MeV} / \mathrm{c}^{2}$. The spectrum is dominated by the $\eta^{\prime}$, for which we determine $\Gamma_{\gamma \gamma}\left(\eta^{\prime}\right) B R\left(\eta^{\prime}-6 \gamma\right)=(0.36 \pm 0.02 \pm 0.03) \mathrm{keV} . \mathrm{In}$ addition, we observe an enhancement in the cross section near $1990 \mathrm{MeV} / \mathrm{c}^{2}$ which we attribute to the two-photon production of a new resonance $X$ (1900). The angular distributions and the invariant mass distribution of the $\eta \pi^{\circ}$ subsystem are consistent with those expected for the hypothetical $\eta_{2}$ meson with $J^{P C}=2^{-+}$. For this $J^{P}$ assignment the resonance parameters are: $\mathrm{M}(\mathrm{X})=(1876 \pm 35 \pm 50) \mathrm{MeV} / \mathrm{c}^{2}$, $\Gamma_{\text {tot }}(X)=(228 \pm 90 \pm 34) \mathrm{MeV} / \mathrm{c}^{2}$ and $\Gamma_{\gamma \gamma}(X) B R(X \rightarrow \eta \pi \pi)=(0.9 \pm 0.2 \pm 0.3) \mathrm{keV}$.

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[^0]We report on an investigation of the reaction $\gamma \boldsymbol{\gamma} \rightarrow \eta \pi^{\circ} \pi^{\circ}$, observed in the six-photon final state [1]. Compared to our previous report on this reaction [2], the present, analysis uses a factor of two more data and a more efficient background rejection. We improve the measurement. of $\Gamma_{\gamma \gamma}\left(\eta^{\prime}\right) B R\left(\eta^{\prime} \rightarrow 6 \gamma\right)$ and report for the first time on an enhancement in the cross section of $\gamma \gamma \rightarrow \eta \pi^{\circ} \pi^{\circ}$ at an invariant mass of about $1900 \mathrm{MeV} / \mathrm{c}^{2}$. We interpret it as the production of a new resonance $\mathrm{X}(1900)$. A similar observation has been made by the CELLO Collaboration [3] in the reaction $\gamma \gamma \rightarrow \eta \pi^{+} \pi^{-}$. The $\mathrm{X}(1900)$ is the first new resonance to be discovered in $\gamma \gamma$ collisions. It may be the $\eta_{2}$, the isospin $I=0$ partner of the $\pi_{2}$, which has recently been studied in $\gamma$, collisions $[4,5]$.

The $\gamma \gamma$ initial state is created by $e^{+} e^{-}$collisions, where each lepton radiates a virtual photon-with Iow $q^{2}$. The leptons are scattered to very small angles. They are not observed in the final state (no-tag experiment). Thus the detected event has nearly balanced transverse momentum with respect to the beam direction. Only states with even charge conjugation $C$ and total spin $J \neq 1$ can be produced in quasi-real yy scattering [6;. The observation of the $\eta \pi^{\circ} \pi^{\circ}$ state limits the isospin to $I=0$ or $I=2$. Angular distributions of the decay particles can yield information on the spin $J$.

This. investigation has been performed with the Crystal Ball detector at the DORIS II $\epsilon^{+} \epsilon^{-}$storage ring at DESY. The integrated luminosity corresponds to $255 p b^{-1}$ and was collected at an average beam energy of 5 GeV between 1982 and 1986.

The main part of the Crystal Ball detector [2, $\overline{7}]$ consist's of 672 optically isolated $\stackrel{\mathrm{NaI}}{\mathrm{Na}}(\mathrm{Tl})$ crystals which form a hollow sphere of 16 radiation lengths thickness covering $93 \%$ of the total solid angle, wit. 11 two holes for the beam pipe. The solid angle coverage is increased to $98 \%$ by $\mathrm{NaI}(\mathrm{Tl})$ endcap crystals. For electromagnetically showering particles the measured energy resolution is $\sigma_{E} / E=(2.7 \pm 0.2) \% / \sqrt[4]{E / G \epsilon V}$ and the direction (with respect to the beam axis) is determined with an energy-dependent accuracy of $3^{\prime \prime}$ to $1^{\prime \prime}$. The central cavity of the detector is equipped with four double layers of proportional tubes to detect charged particles.

The trigger requires that the total energy deposition be larger than 780 MeV in the calorimeter and that more than 180 MeV be recorded in both the top and the bottom hemisphere. The first layer of crystals surrounding the beam pipe are not included in these energy sums; instead, to reject background events, a veto is set if more than 30 MeV is detected in these crystals. Sharp software thresholds of $800 \mathrm{MeV}, 200 \mathrm{MeV}$ and 25 MeV respectively are applied in the analysis to eliminate effects caused by variations of the trigger thresholds. The efficiency of this trigger is about $78 \%$ in the $\eta^{\prime}$ mass region and falls off slightly to $65 \%$ at $\eta \pi^{\circ} \pi^{\circ}$ invariant masses of $2500 \mathrm{MeV} / \mathrm{c}^{2}$.

Candidate events for the six-photon final state are selected by requiring six energy depositions in the calorimeter. The central crystal in: each energy deposition has to satisfy $|\cos (\theta)|<0.86$. A photon candidate is tagged as charged if one or more hits in the tube
chambers match closely in azimuth the direction of the energy deposit; we ignore the information along the beam axis, since beam-gas event's do not necessarily come from the interaction point. At most one of the six photon candidates is allowed to be tagged as charged by the tube chambers: using only the azimuth information, Including the effect of random hits in the chambers and the conversion probability of the photons in the beam pipe and the tube chambers, this cut has an efficiency of about $75 \%$ for $\eta \pi^{\circ} \pi^{\circ}$ events.

The four-momenta of the photon candidates are determined from the energies and directions measured in the calorimeter and the transverse momentum sum of the six photons is calculated. This transverse momentum sum $\left|\sum \overrightarrow{p_{t}}\right|$ is required to be less than $100 \mathrm{MeV} / \mathrm{c}$. A total of 1200 events pass all these cuts. Events failing only the cut on $\left|\sum \overrightarrow{p_{t}}\right|$ are kept, to study the $\left|\sum \overrightarrow{p_{t}}\right|$-distribution.

The last step of the selection procedure is the $\eta \pi^{\circ} \pi^{\circ}$ event definition. There are 15 possible configurations for grouping six photons into three pairs. The invariant $\gamma \gamma$ mass distribution of all pairs shows a prominent, $\pi^{\circ}$ peak and an $\eta$ signal above a combinatorial background. The positions of the peaks agree within errors with the nominal values [8] and their widths are consistent with those expected from the experimental mass resolution. For each configuration, the energy and angular resolution are used to calculate the $\chi^{2}$ for the $\eta \pi^{\circ} \pi^{\circ}$ and $\pi^{\circ} \pi^{\circ} \pi^{\circ}$ hypotheses. $\eta \pi^{\circ} \pi^{\circ}$ events are selected by requiring that at least one configuration have $\chi^{2}\left(\eta \pi^{0} \pi^{\circ}\right)<9$ and that each configuration have $\chi^{2}\left(\pi^{0} \pi^{\circ} \pi^{0}\right)>9$. If more than one configuration is compatible with the $\eta \pi^{\circ} \pi^{\circ}$ hypothesis, the one with the smallest $\chi^{2}\left(\eta \pi^{\circ} \pi^{\circ}\right)$ is selected. Events which do not fulfill the $\eta \pi^{\circ} \pi^{\circ}$ criterion are kept, to study the $\lambda^{2}$ distribution.

The final data sample contains 317 events that pass all cuts. Their invariant mass distribution is displayed in Fig. 1. The prominent peak just. below $1000 \mathrm{MeV} / \mathrm{c}^{2}$ contains about 270 events and is due to the $\eta^{\prime}(958)$. In addition, events are found with measured masses larger than the $\eta^{\prime}$. It is these events that are the main subject of this paper.

To calculate the $W_{\gamma}$-dependent yy luminosity and the detection efficiency, and to study the properties of $\epsilon^{+} \epsilon^{-} \rightarrow \epsilon^{+} \epsilon^{-} \eta \pi^{\circ} \pi^{\circ} \rightarrow e^{+} \epsilon^{-} 6 \gamma$ events, we perform a Monte Carlo integration of the two-photon flux given in [9] with a cross section $\sigma\left(\gamma \gamma \rightarrow \eta \pi^{\circ} \pi^{\circ}\right)$ constant in $W_{\gamma \gamma}$. The generated events are passed through a complete detector simulation using the shower development program EGS3 [10] for the simulation of the calorimeter and a detailed simulation of the tube chambers [11]. Beam-related background in the calorimeter and the tube chambers is included by superimposing events which were recorded on every $10^{7}$ th beam crossing with no other trigger requirement. The Monte Carlo events are then analysed in the same way as the data.

In the following. we use the $\Sigma \overrightarrow{p_{t}}$ distribution and the quality of the $\eta \pi^{\circ} \pi^{\circ}$ identification to show that the events in the region $1600 \because W_{\gamma \text { n }}<2200 \mathrm{MeV} / \mathrm{c}^{2}$ are mostly from the reaction $\gamma \gamma \rightarrow \eta \pi^{c} \pi^{\circ}$, while those between 1100 and $1600 \mathrm{MeV} / \mathrm{c}^{2}$ are mostly background
events.
The $\left|\Sigma \overrightarrow{p_{t}}\right|^{2}$ distribution for data events that pass all cuts except the $\left|\Sigma \overrightarrow{p_{t}}\right|$ cut is shown in Fig. 2 b for events with $1600<W_{\gamma \gamma}<2200 \mathrm{MeV} / \mathbf{c}^{2}$. The data peak at low $\left|\sum \overrightarrow{p_{t}}\right|^{2}$ in agreement with the Monte Carlo expectation. The corresponding distribution (Fig. 2a) for 1100 to $1600 \mathrm{MeV} / \mathrm{c}^{2}$ is flat.. indicating that these are not exclusive two-photon events.

The $\chi^{2}\left(\eta \pi^{0} \pi^{\circ}\right)$ dis titor ton for events in the 1600 to $2200 \mathrm{MeV} / \mathrm{c}^{2}$ range peaks at low values. in agreement with the Monte Carlo, while that for the range 1100 to $1600 \mathrm{MeV} / \mathrm{c}^{2}$ is flat, again indicating that the events in this region are not dominated by $\eta \pi^{\circ} \pi^{\circ}$.

To investigate further the presence of $\eta-{ }^{-} \pi^{\circ}$ events, we use an altered selection procedure in which all cuts except the ones on $\chi^{2}\left(\eta \pi^{\circ} \pi^{\circ}\right)$ and $\chi^{2}\left(\pi^{\circ} \pi^{0} \pi^{\circ}\right)$ are applied. Instead we require that four of the six photons can be grouped such that they form two $\pi^{\circ}$, and then plot the invariant mass of the remaining pair of photons. Note that multiple entries for each event are possible. The events in the 1600 to $2200 \mathrm{MeV} / \mathrm{c}^{2}$ region display a prominent $\pi^{0}$ peak as well as a clear $\eta$ signal (Fig. 3b). The $\eta$ signal represents evidence for the observation of $\gamma \eta \rightarrow \eta \pi^{\circ} \pi^{0}$. In the corresponding plot for 1100 to $1600 \mathrm{MeV} / \mathrm{c}^{2}$ (Fig. 3a) a $\pi^{c}$ signal, but no $\eta$ signal, is visible.

The $\pi^{0}$ signal above $1600 \mathrm{MeV} / \mathrm{c}^{2}$ is evidence for the reaction yy $\rightarrow \pi^{0} \pi^{0} \pi^{0}$, which is dominated by the two-photon production and subsequent. decay of the $\pi_{2}(1670)$ meson [4,5]. A Monte Carlo simulation of this reaction is used to determine its possible contribution to the final $\eta \pi^{0} \pi^{\circ}$ selection. The cut $\chi^{2}\left(\pi^{0} \pi^{\circ} \pi^{\circ}\right)>9$ is very effective; less than one event from . $\pi_{2}$ decays is expected to contribute to the $\eta \pi^{\circ} \pi^{\circ}$ spectrum.

Returning to the events from the complete selection procedure. we conclude that the events in the 1600 to $2200 \mathrm{MeV} / \mathrm{c}^{2}$ region are dominated by $\eta \eta \rightarrow \eta \pi^{\circ} \pi^{\circ}$ events. while those between 1100 and $1600 \mathrm{MeV} / \mathrm{c}^{2}$ are not. The spectrum between 1100 and $2500 \mathrm{MeV} / \mathrm{c}^{2}$ is displayed in the insert, of Fig. 1 with an expanded ordinate. The enhancement of events near $1900 \mathrm{MeV} / \mathrm{c}^{2}$ is broader than the experimental mass resolution of about $35 \mathrm{MeV} / \mathrm{c}^{2}$. It could be due to one or more resonances. Our small number of events is not sufficient to study the possibility of more than one resonance. We assume that the spectrum above the $\eta^{\prime}$ consists of a smoothly decreasing background and one wide resonance. There is predicted to be a $J^{P C}=2^{-+}$state called the $\eta_{2}[12]$ which could explain our data. It is an isoscalar member of the same nonet as the $\pi_{2}$ (1670).

Next we perform an unbinned maximum likelihood fit to the full spectrum. including a Gaussian peak to describe the $\eta^{\prime}$, a $J=2$ Breit-Wigner peak convoluted with the mass resolution, and a quadratic background. Fig. 1 shows the result for $1100<W_{\sim \sim}<2500 \mathrm{MeV} / \mathrm{c}^{2}$. The fit assigns 260 events to the $\eta^{\prime}$ over a background of six. The resulting value [1] of $\Gamma_{\sim \gamma}\left(\eta^{\prime}\right) B R\left(\eta^{\prime} \rightarrow 6 \gamma\right)=(0.36 \pm 0.02=0.03) \mathrm{keV}$ is in good agreement with our previous value [2. The first error is statistical. the second svstematic. The fitted background explains most of the data in the 1100 to $1500 \mathrm{MeV} / \mathrm{c}^{2}$ region. in agreement with our background stud-
ies described above. In the 1500 to $2200 \mathrm{MeV} / \mathrm{c}^{2}$ region the background amounts to five out of a total of 34 events. Extraction of the parameters of this resonance requires information on its decay mode and spin, to which we turn now.

The $\eta_{2}$ is expected [12] to decay to $a_{2} \pi$. Decays to $a_{0} \pi, f_{0} \eta$ and $f_{2} \eta$ are also possible. The invariant mass distribution of the $\pi^{\circ} \pi^{\circ}$ sub-system shows no evidence for the $f_{0}$ or the $f_{2}$. The $M\left(\eta \pi^{0}\right)$ distribution. shown in Fig. 4, has more entries around $1000 \mathrm{MeV} / \mathrm{c}^{2}$ and $1300 \mathrm{MeV} / \mathrm{c}^{2}$ than expected from a 3-body phase space distribution. The $M\left(\eta \pi^{0}\right)$ distribution is compared to the Monte Carlo predictions for a 3-body phase space decay, for a $J^{P}=2^{-}$resonance decaying to $a_{0} \pi^{\circ}$ or $a_{2} \pi^{\circ}$, and for a mixture of the last two possibilities by calculating the likelihood functions for these hypothesis. The data are best described by a mixture of about $(70 \pm \overline{20}) \% a_{2} \pi^{\circ}$ and $(30 \pm 20) \% a_{0} \pi^{\circ}$ in the final state, see the solid curve in Fig. 4.

The angular distributions reveal information about. the spin and parity of the resonance. The distribution of $\left|\cos \theta_{\eta}^{*}\right|$, where $\theta_{\eta}^{*}$ is the angle in the $\eta \pi^{\circ} \pi^{\circ}$ rest frame between the $\eta$ momentum vector and the beam direction, is shown in Fig. 5a for events in the $W_{\gamma}$ range from 1600 to $2200 \mathrm{MeV} / \mathrm{c}^{2}$. For the same events, the distribution of $\left|\cos \theta_{\text {dec }}^{*}\right|$, with $\theta_{\text {dec }}^{*}$ the angle in the $\eta \pi^{\circ} \pi^{\circ}$ frame between the normal to the decay plane and the beam direction, is shown in Fig. 5b. These distributions are not corrected for acceptance. The Monte Carlo predictions for 3-body phase space decay (as appropriate for $J^{P}=0^{-}$) and for a $J^{P}=2^{-}$ resonance decaying via $a_{2} \pi^{\circ}$ are also plotted. For the Monte Carlo with assignment $J^{P}=2^{-}$, we used the fact[13] that a $2^{-}$resonance is produced in quasi-real yy collisions only in the helicity 0 state. A test of these two $J^{P}$ assignments based on the two angular distribution favors $2^{-}$over $0^{-}$. Assuming $J^{P}=0^{-}$and S-body phase space decay results in $\chi^{2}=13.8$ for eight. degrees of freedom. For the $J^{P}=2^{-}$case, the decay via $a_{0} \pi^{\circ}$ gives $\chi^{2}=12.6$; the $a_{2} \pi^{0}$ decay mode has $\chi^{2}=6.1$; and the mixture of $70 \% a_{2} \pi^{\circ}$ and $30 \% a_{0} \pi^{\circ}$ (our best fit to the $M\left(\eta \pi^{0}\right)$ mass plot) gives $\lambda^{2}=5.8$ for eight degrees of freedom. The assignment $J^{P}=2^{+}$as well as the effect of isobars on a $0^{-}$decay are under investigation [1].

Although we cannot yet exclude other possibilities. we have shown that the resonance is consistent with the $\eta_{2}$. We use that assignment. to extract the resonance parameters. The efficiency appropriate to $J^{P C}=2^{-+}$and decay via $a_{2} \pi^{\circ}$ is used. A factor of 3 is included to account. for the branching ratio of an isoscalar to the $\eta \pi \pi$ final state ( $\eta \pi^{\circ} \pi^{\circ}$ as well as $\eta \pi^{+} \pi^{-}$). The following values are obtained:

$$
\begin{aligned}
\Gamma_{\gamma \gamma}(X) B R(X \rightarrow \eta \pi \pi) & =(0.9 \pm 0.2 \pm 0.3) \mathrm{keV} \\
M(X) & =(1876 \pm 35 \pm 50) \mathrm{MeV} / \mathrm{c}^{2} \\
\mathrm{I}^{\prime},,,(X) & =(228 \pm 90 \pm 34) \mathrm{MeV} / \mathrm{c}^{2}
\end{aligned}
$$

The systematic error on $\Gamma_{\gamma \gamma} B R$ covers the variation obtained by using an isotropic or an $a_{0} \pi^{c}$ decay instead of $a_{2} \pi^{*}$. Because of the factor $2 J-1$ in the total cross section 13 , the corre sponding product would be five times greater, i.e. 4.5 keV . if the state were a pseudoscalar
(note that. this number is smaller than our previous upper limit. [2] in this mass range). The main contribution to the systematic error on $\Gamma_{\text {tot }}$ is from the variation of the background shape? while that on the mass is dominated by the uncertainty in our absolute energy scale.

In conclusion, we have measured the reaction yy $\rightarrow \eta \pi^{0} \pi^{0} \rightarrow 6 \gamma$. The invariant mass spectrum displays two structures, the well known $\eta^{\prime}$ (958) and an enhancement around $1900 \mathrm{MeV} / \mathrm{c}^{2}$. The partial width of the $\eta^{\prime}$ to two photons times its branching ratio to the six-photon final state is $\Gamma_{\gamma \gamma}\left(\eta^{\prime}\right) B R\left(\eta^{\prime} \rightarrow 6 \gamma\right)=(0.36 \pm 0.02 \pm 0.03) \mathrm{keV}$.

The enhancement of events near $1900 \mathrm{MeV} / \mathrm{c}^{2}$ has several features that are consistent with those expected for the two-photon production of the $\eta_{2}$ meson, the previously missing isoscalar member of the $J^{P C}=2^{-+}$nonet. The invariant. mass distribution of the $\eta \pi^{\mathrm{c}}$ subsystem favors a decay via $a_{2} \pi$ and $a_{0} \pi$ over a decay according to 3 -body phase space. The angular distributions of the decay plane and of the $\eta$ meson are better described by the decay of a pseudotensor state than by that of a pseudoscalar. We obtain the resonance parameters under the assumption that the enhancement is only one wide resonance $X(1900)$ with quantum numbers $I^{G}\left(J^{P C}\right)=0^{+}\left(2^{-+}\right)$. Higher statistics are necessary to unambiguously resolve the mass spectrum, the decay mechanism, the spin-parity and the two-photon coupling of states decaying to $\eta \pi^{0} \pi^{0}$ in this mass range.

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## Figure Captions

1. Invariant mass distribution of the selected $\eta \pi^{\circ} \pi^{\circ}$ events (shaded histogram). The insert shows the distribution of events with $1100 \mathrm{MeV} / \mathrm{c}^{2}<W_{n}<2500 \mathrm{MeV} / \mathrm{c}^{2}$. The full line is the fit to the data, the dotted line is the Breit-Wigner and the dashed line is the background.
2. Distribution of the square of the transverse momentum sum $\left|\sum \vec{p}_{t}\right|^{2}$ of data (dots with errorbars) and MC events (histogram) for a) $1100 \mathrm{MeV} / \mathrm{c}^{2}<W_{\gamma \gamma}<1600 \mathrm{MeV} / \mathrm{c}^{2}$, and b) $1600 \mathrm{MeV} / \mathrm{c}^{2}<W_{\gamma \gamma}<2200 \mathrm{MeV} / \mathrm{c}^{2}$.
3. Distribution of the invariant mass of the remaining pair of photons for events in which four photons can be grouped to two $\pi^{\circ}$ for a) $1100 \mathrm{MeV} / \mathrm{c}^{2}<W_{\gamma \gamma}<1600 \mathrm{MeV} / \mathrm{c}^{2}$, and b) $1600 \mathrm{MeV} / \mathrm{c}^{2}<W_{\gamma}<2200 \mathrm{MeV} / \mathrm{c}^{2}$. Note that multiple entries per event are possible.
4. Invariant mass distribution of the $\eta \pi^{0}$ subsystems of selected events with $1600 \mathrm{MeV} / \mathrm{c}^{2}<$ $W_{\gamma,}<2200 \mathrm{MeV} / \mathrm{c}^{2}$ (two entries per event). Dots with error bars are data; the full histogram is the best fit; the dotted histogram is the expected distribution for S -body phase space decay.
5. angular distributions in the $\eta \pi^{\circ} \pi^{\circ}$ rest frame: for events with $1600 \mathrm{MeV} / \mathrm{c}^{2}<W_{m}<$. $2200 \mathrm{MeV} / \mathrm{c}^{2}$, normalized to unit, area. a) Absolute value of the cosine of the angle between the $\eta$ momentum and the beam direction. b) Absolute value of the cosine of the angle between the normal to the decay plane and the beam direction. Circles with error bars are the data, the full line corresponds to $J^{P}=2^{-}$and decay via $a_{2} \pi^{\circ}$ while the dotted line is the expectation for $J^{P}=0^{-}$and a 3 -body phase space decay.


Figure 1:


Figure 2 :



Figure 3 :


Figure 4:


Figure 5:


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