Observation of a new $\eta\pi^0\pi^0$ resonance at 1900 MeV/c^2 in two-photon scattering

Crystal Ball Collaboration

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Using the Crystal Ball detector at the DORIS II e^+e^- storage ring, we measure the $\eta\pi^0\pi^0$ mass spectrum in the reaction $e^+e^-\to e^+e^-\eta\pi^0\pi^0\to e^+e^-6\gamma$ from the $\eta\pi^0\pi^0$ threshold to about 2500 MeV/c^2. The spectrum is dominated by the η', for which we determine $\Gamma_{\gamma\gamma}(\eta')\mathrm{BR}(\eta'\to6\gamma)=0.36\pm0.02\pm0.03$ keV. In addition, we observe an enhancement in the cross section near 1900 MeV/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 $\eta\pi^0$ subsystem are consistent with those expected for the hypothetical η_2 meson with $J^{PC}=2^{-+}$. For this J^P assignment the resonance parameters are $M(\mathrm{X})=1876\pm35\pm50$ MeV/c^2, $\Gamma_{\mathrm{tot}}(\mathrm{X})=228\pm90\pm34$ MeV/c^2 and $\Gamma_{\gamma\gamma}(\mathrm{X})\mathrm{BR}(\mathrm{X}\to\eta\pi\pi)=0.9\pm0.2\pm0.3$ keV.

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We report on an investigation of the reaction $\gamma\gamma\to\eta\pi^0\pi^0$, 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 $\Gamma_{\gamma\gamma}(\eta')\mathrm{BR}(\eta'\to6\gamma)$ and report for the first time on an enhancement in the cross section of $\gamma\gamma\to\eta\pi^0\pi^0$ at an invariant mass of about 1900 MeV/c^2. We interpret it as the production of a new resonance X(1900). A similar observation has been made by the CELLO Collaboration [3] in the reaction $\gamma\gamma\ \eta\pi^+\pi^-$. The X(1900) is the first new resonance to be discovered in $\gamma\gamma$ collisions. It may be the η_2, the isospin $I=0$ partner of the π_2, which has recently been studied in $\gamma\gamma$ collisions [4,5].

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[#1] A detailed description of this analysis will be presented in ref. [1].

The $\gamma\gamma$ initial state is created by e^+e^- collisions, where each lepton radiates a virtual photon with low 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 $J\neq1$ can be produced in quasi-real $\gamma\gamma$ scattering [6]. The observation of the $\eta\pi^0\pi^0$ 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 e^+e^- storage ring at DESY. The integrated luminosity corresponds to 255 pb^{-1} and was collected at an average beam energy of 5 GeV between 1982 and 1986.

The main part of the Crystal Ball detector [2,7] consists of 672 optically isolated NaI(Tl) crystals which form a hollow sphere of 16 radiation lengths thickness covering 93% of the total solid angle, with two holes for the beam pipe. The solid angle coverage is increased to 98% by NaI(Tl) endcap crystals. For electromagnetically showering particles the measured energy resolution is $\sigma_E/E=(2.7\pm0.2)\%/\sqrt[4]{E/\mathrm{GeV}}$ and the direction (with respect to the beam axis) is determined with an energy-dependent accuracy of 3° to 1°. 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 MeV, 200 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 η' mass region and falls off slightly to 65% at $\eta\pi^0\pi^0$ invariant masses of 2500 MeV/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 events 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 $\eta\pi^0\pi^0$ 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 $|\Sigma \boldsymbol{p}_t|$ is required to be less than 100 MeV/c. A total of 1220 events pass all these cuts. Events failing only the cut on $|\Sigma \boldsymbol{p}_t|$ are kept to study the $|\Sigma \boldsymbol{p}_t|$ distribution.

The last step of the selection procedure is the $\eta\pi^0\pi^0$ 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 π^0 peak and an η 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 χ^2 (three degrees of freedom) for the $\eta\pi^0\pi^0$ and $\pi^0\pi^0\pi^0$ hypotheses. $\eta\pi^0\pi^0$ events are selected by requiring that at least one configuration has a $\chi^2(\eta\pi^0\pi^0) < 9$ and that the $\pi^0\pi^0\pi^0$ hypothesis is rejected [$\chi^2(\pi^0\pi^0\pi^0) > 9$]. If more than one configuration is compatible with the $\eta\pi^0\pi^0$ hypothesis, the one with the smallest $\chi^2(\eta\pi^0\pi^0)$ is selected. Note that only three events in the $W_{\gamma\gamma}$ range from 1100 MeV/c^2 to 1600 MeV/c^2 and one event above 1600 MeV/c^2 have two configurations with $\chi^2(\eta\pi^0\pi^0) < 9$. No event has more than two $\eta\pi^0\pi^0$ configurations. Events which do not fulfill the $\eta\pi^0\pi^0$ criterion are kept to study the χ^2 distribution.

The final data sample contains 317 events that pass all cuts and are identified as $\eta\pi^0\pi^0$ events. Of the remaining 1220–317 events 137 fit the $\pi^0\pi^0\pi^0$ hypothesis. The invariant mass distribution of the 317 $\eta\pi^0\pi^0$ events is displayed in fig. 1. The prominent peak just below 1000 MeV/c^2 contains about 270 events and

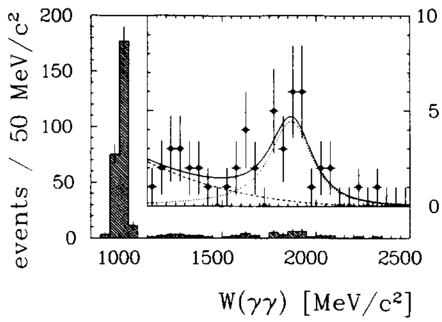

Fig. 1. Invariant mass distribution of the selected $\eta\pi^0\pi^0$ events (shaded histogram). The insert shows the distribution of events with 1100 MeV/c^2 < $W_{\gamma\gamma}$ < 2500 MeV/c^2. The full line is the fit to the data, the dotted line is the Breit–Wigner and the dashed line is the background.

is due to the $\eta'(958)$. In addition, events are found with measured masses larger than the η'. It is these events that are the main subject of this paper.

To calculate the $W_{\gamma\gamma}$-dependent $\gamma\gamma$ luminosity and the detection efficiency, and to study the properties of $e^+e^- \to e^+e^-\eta\pi^0\pi^0 \to e^+e^-6\gamma$ events, we perform a Monte Carlo integration of the two-photon flux given in ref. [9] with a cross section $\sigma(\gamma\gamma\to\eta\pi^0\pi^0)$ 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 10^7th beam crossing with no other trigger requirement. The Monte Carlo events are then analyses in the same way as the data.

In the following, we use the $|\Sigma \boldsymbol{p}_t|$ distribution and the quality of the $\eta\pi^0\pi^0$ identification to show that the events in the region $1600 < W_{\gamma\gamma} < 2200$ MeV/c^2 are mostly from the reaction $\gamma\gamma\to\eta\pi^0\pi^0$, while those between 1100 and 1600 MeV/c^2 are mostly background events.

The $|\Sigma \boldsymbol{p}_t|^2$ distribution for data events that pass all cuts except the $|\Sigma \boldsymbol{p}_t|$ cut is shown in fig. 2b for events with $1600 < W_{\gamma\gamma} < 2200$ MeV/c^2. The data peak at low $|\Sigma \boldsymbol{p}_t|^2$ is in agreement with the Monte Carlo expectation. The corresponding distribution (fig. 2a) for 1100 to 1600 MeV/c^2 is flat, indicating

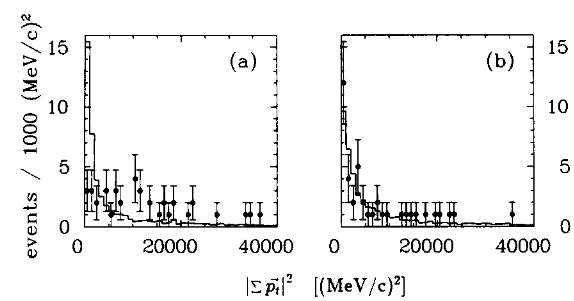

Fig. 2. Distribution of the square of the transverse momentum sum $|\Sigma \boldsymbol{p}_t|^2$ of data (dots with error bars) and MC events (histogram) for (a) 1100 MeV/$c^2 < W_{\gamma\gamma} <$ 1600 MeV/c^2, and (b) 1600 MeV/$c^2 < W_{\gamma\gamma} <$ 2200 MeV/c^2.

that these are not exclusive tow-photon events.

The $\chi^2(\eta\pi^0\pi^0)$ distribution for events in the 1600–2200 MeV/c^2 range peaks at low values, in agreement with the Monte Carlo, while that for the range 1100–1600 MeV/c^2 is flat, again indicating that the events in this region are not dominated by $\eta\pi^0\pi^0$.

To investigate further the purity of the $\eta\pi^0\pi^0$ events, we use an altered selection procedure in which all cuts except the ones on $\chi^2(\eta\pi^0\pi^0)$ and $\chi^2(\pi^0\pi^0\pi^0)$ are applied. Instead we require that four of the six photons can be grouped such that they form two π^0, 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 η' mass region (850–1100 MeV/c^2) display a very prominent η peak (fig. 3a). The η signal represents evidence for the observation of $\gamma\gamma\to\eta\pi^0\pi^0$. In the corresponding plot for the 1100–1600 MeV/c^2 region, in fig. 3b, a π^0 signal, but no η signal, is visible. The events in the 1600–2200 MeV/c^2 region display a prominent π^0 peak as well as a clear η signal on a rather small combinatorial background (fig. 3c).

The π^0 signal above 1600 MeV/c^2 is evidence for the reaction $\gamma\gamma\to\pi^0\pi^0\pi^0$, 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 $\eta\pi^0\pi^0$ selection. The cut $\chi^2(\pi^0\pi^0\pi^0) > 9$ is very effective; less than one event from π_2 decays is expected to contribute to the $\eta\pi^0\pi^0$ spectrum.

Returning to the events from the complete selection procedure, we conclude that the events in the 1600–2200 MeV/c^2 region are dominated by $\gamma\gamma\to\eta\pi^0\pi^0$ events, while those between 1100 and 1600 MeV/c^2 are not. The spectrum between 1100 and 2500 MeV/c^2 is displayed in the insert of fig. 1 with an expanded ordinate. The enhancement of events near 1900 MeV/c^2 is broader than the experimental mass resolution of about 35 MeV/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 η' consists of a smoothly decreasing background and one wide resonance. There is predicted to be a $J^{PC} = 2^{-+}$ state called the η_2 [12] which could explain our data. It is an isoscalar member of the same nonet as the $\pi_2(1670)$. In the following we will test whether our data are consistent with the two-photon production and decay of an η_2 meson.

Next we perform an unbinned maximum likelihood fit to the full spectrum, including a gaussian peak

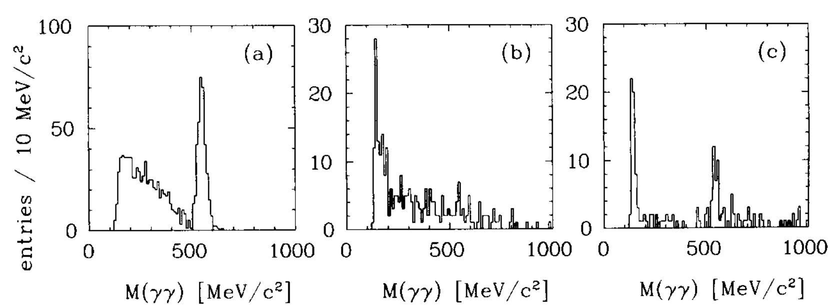

Fig. 3. Distribution of the invariant mass of the remaining pair of photons for events in which four photons can be grouped to two π^0 for (a) 850 MeV/$c^2 < W_{\gamma\gamma} <$ 1100 MeV/c^2, (b) 1100 MeV/$c^2 < W_{\gamma\gamma} <$ 1600 MeV/c^2, and (c) 1600 MeV/$c^2 < W_{\gamma\gamma} <$ 2200 MeV/c^2. Note that multiple entries per event are possible.

to describe the η', a $J=2$ Breit–Wigner peak convoluted with the mass resolution, and a quadratic background. Fig. 1 shows the result for $1100 < W_{\gamma\gamma} < 2500$ MeV/c^2. The fit assigns 260 events to the η' over a background of six. The resulting value [1] of $\Gamma_{\gamma\gamma}(\eta')\mathrm{BR}(\eta' \to 6\gamma) = 0.36 \pm 0.02 \pm 0.03$ keV is in good agreement with our previous value [2]. The first error is statistical, the second systematic. The fitted background explains most of the data in the 1100–1600 MeV/c^2 region, in agreement with our background studies described above. In the 1600–2200 MeV/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 η_2 is expected [12] to decay dominantly 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 $\pi^0\pi^0$ sub-system shows no evidence for the f_0 or the f_2. The $M(\eta\pi^0)$ distribution, shown in fig. 4, has more entries around 1000 MeV/c^2 and 1300 MeV/c^2 than expected from a three-body phase space distribution. The $M(\eta\pi^0)$ distribution is compared to the Monte Carlo predictions for a three-body phase space decay, for a $J^P=2^-$ resonance decaying to $a_0\pi^0$ or $a_2\pi^0$, 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 $(70 \pm 20)\%$ $a_2\pi^0$ and $(30 \pm 20)\%$ $a_0\pi^0$ 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 $|\cos(\theta^*_\eta)|$, where θ^*_η is the angle in the $\eta\pi^0\pi^0$ rest frame between the η momentum vector and the beam direction, is shown in fig. 5a for events in the $W_{\gamma\gamma}$ range 1600–2200 MeV/c^2. For the same events, the distribution of $|\cos(\theta^*_{\mathrm{dec}})|$, with θ^*_{dec} the angle in the $\eta\pi^0\pi^0$ 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 three-body phase space decay (as appropriate for $J^P=0^-$) and for a $J^P=2^-$ resonance decaying via $a_2\pi^0$ 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 $\gamma\gamma$ collisions only in the helicity 0 state. A test of these two J^P assignments based on the two angular distributions favors 2^- over 0^-. Assuming $J^P=0^-$ and three-body phase space decay results in $\chi^2=13.8$ for eight degrees of freedom. For the $J^P=2^-$ case, the decay via $a_0\pi^0$ gives $\chi^2=12.6$; the $a_2\pi^0$ decay mode has $\chi^2=6.1$; and the mixture of 70% $a_2\pi^0$ and 30% $a_0\pi^0$ [our best fit to the $M(\eta\pi^0)$ mass plot] gives $\chi^2=5.8$ 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 η_2. We use that assignment to extract the resonance parameters. The efficiency appropriate to $J^{PC}=2^{-+}$ and decay via $a_2\pi^0$ is used. A factor of 3 is

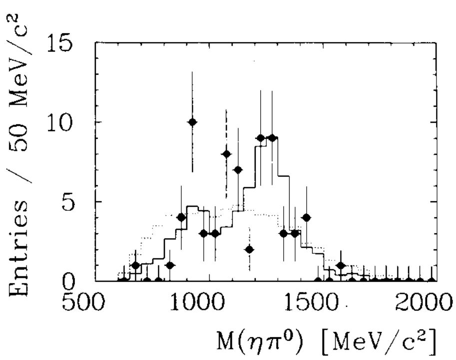

Fig. 4. Invariant mass distribution of the $\eta\pi^0$ subsystems of selected events with 1600 MeV/$c^2 < W_{\gamma\gamma} < 2200$ MeV/c^2 (two entries per event). Dots with error bars are data; the full histogram is the best fit; the dotted histogram is the expected distribution for three-body phase space decay.

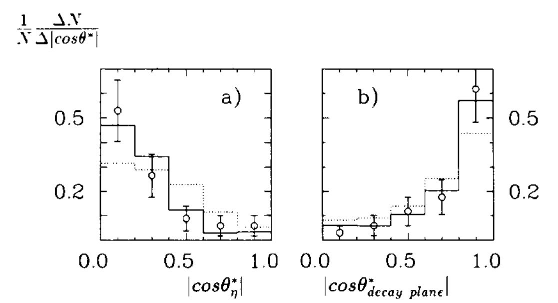

Fig. 5. Angular distributions in the $\eta\pi^0\pi^0$ rest frame, for events with 1600 MeV/$c^2 < W_{\gamma\gamma} < 2200$ MeV/c^2, normalized to unit area. (a) Absolute value of the cosine of the angle between the η momentum and the beam direction. (b) Absolute value of the cosine of the angle between 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 $a_2\pi^0$ while the dotted line is the expectation for $J^P=0^-$ and a three-body phase space decay.

included to account for the branching ratio of an isoscalar to the $\eta\pi\pi$ final state ($\eta\pi^0\pi^0$ as well as $\eta\pi^+\pi^-$). The following values are obtained:

$$\Gamma_{\gamma\gamma}(\mathrm{X})\mathrm{BR}(\mathrm{X}\to\eta\pi\pi)=0.9\pm0.2\pm0.3\ \mathrm{keV},$$

$$M(\mathrm{X})=1876\pm35\pm50\ \mathrm{MeV}/c^2,$$

$$\Gamma_{\mathrm{tot}}(\mathrm{X})=228\pm90\pm34\ \mathrm{MeV}/c^2.$$

The systematic error on $\Gamma_{\gamma\gamma}$BR covers the variation obtained by using an isotropic or an $a_0\pi^0$ decay instead of $a_2\pi^0$. Because of the factor $2J+1$ in the total cross section [13], the corresponding 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 Γ_{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 $\gamma\gamma\to\eta\pi^0\pi^0\to6\gamma$. The invariant mass spectrum displays two structures, the well known $\eta'(958)$ and an enhancement around 1900 MeV/c^2. The partial width of the η' to two photons times its branching ratio to the six-photon final state is $\Gamma_{\gamma\gamma}(\eta')\times\mathrm{BR}(\eta'\to6\gamma)=0.36\pm0.02\pm0.03$ keV.

The enhancement of events near 1900 MeV/c^2 has several features that are consistent with those expected for the two-photon production of the η_2 meson, the previously missing isoscalar member of the $J^{PC}=2^{-+}$ nonet. The invariant mass distribution of the $\eta\pi^0$ subsystem favors a decay via $a_2\pi$ and $a_0\pi$ over a decay according to three-body phase space. The angular distributions of the decay plane and of the η 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 $I^G(J^{PC})=0^+(2^{-+})$. 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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