PHYSICAL REVIEW D VOLUME 28, NUMBER 11 1 DECEMBER 1983

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Manuscripts submitted to this section are given priority in handling in the editorial office and in production. A Rapid Communication may be no longer than 3½ printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but, because of the rapid publication schedule, publication is not delayed for receipt of corrections unless requested by the author.

Observation of the production of η mesons in two-photon collisions

A. Weinstein, D. Antreasyan, Y. F. Gu,[a] W. Kollman,[b] M. Richardson, K. Strauch, and K. Wacker[c]
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 01238

C. Edwards, R. Partridge, C. Peck, and F. C. Porter
Physics Department, California Institute of Technology, Pasadena, California 91125

D. Aschman,[d] M. Cavalli-Sforza, D. Coyne, C. Newman-Holmes,[e] and H. F. W. Sadrozinski[f]
Physics Department, Princeton University, Princeton, New Jersey 08544

D. Gelphman, R. Hofstadter, R. Horisberger, I. Kirkbride, H. Kolanoski,[g] K. Königsmann,[h] R. Lee, A. Liberman,[i] J. O'Reilly,[j] A. Osterheld, B. Pollock, and J. Tompkins
Physics Department and High Energy Physics Laboratory, Stanford University, Stanford, California 94305

E. Bloom, F. Bulos, R. Chestnut,[k] J. Gaiser, G. Godfrey, C. Kiesling,[l] W. Lockman, M. Oreglia,[m] and D. L. Scharre[n]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 13 September 1983)

Using 2674 nb^{-1} of data taken at $\sqrt{s}$ from 5.00 to 7.25 GeV with a trigger sensitive to decays of lower-mass particles produced in two-photon collisions, we have observed 56 ± 12 events consistent with the reaction $e^+e^- \rightarrow e^+e^-\eta$, $\eta \rightarrow \gamma\gamma$. Background has been subtracted using separated-beam data. We obtain $\Gamma_{\gamma\gamma}(\eta) = 0.56 \pm 0.16$ keV and the pseudoscalar-nonet mixing angle $\theta_P = -17.6° \pm 3.6°$.

It is well known that e^+e^- colliding-beam machines are also $\gamma\gamma$ colliding-beam machines. Colliding photons can produce positive-*C*-parity mesons; a measurement of the cross section for production of a specific meson in $\gamma\gamma$ collisions determines its decay width to two photons ($\Gamma_{\gamma\gamma}$). Since photons couple to the charge of the quarks in a meson, such a study probes the quark structure of mesons in a given $SU(3)_{flavor}$ nonet.[1] In the case of the pseudoscalar nonet, several experiments[2] have measured $\Gamma_{\gamma\gamma}$ for the η' meson in $\gamma\gamma$ collisions, whereas $\Gamma_{\gamma\gamma}$ for the π^0 and, until now, the η meson have only been measured employing the Primakoff effect.[3] We present here the first observation of η production in two-photon collisions.

The Crystal Ball detector has been described elsewhere,[4] and we briefly mention here those aspects of the detector most relevant to this study. The main component is a spherical, segmented array of NaI(Tl) crystals for high-resolution measurements of the energy and position of electromagnetic showers. The mass resolution for η mesons decaying into two photons is $\sigma \sim 20$–25 MeV, with a weak energy dependence. The solid angle covered by the main array is 93% of 4π sr, and is extended to 98% with additional NaI near the beam pipe. A small-angle Bhabha counter measures the integrated luminosity. The central cavity of the ball contains chambers for identifying charged particles. When the data for this study was being collected, the innermost of our central chambers consisted of a double-layered spark chamber which had an angular coverage equivalent to that of the NaI in the main NaI array, not including end caps. This was followed by a double-layered proportional wire chamber (PWC) which covered 80% of the solid angle and a second double-layered spark chamber covering 72% of the solid angle.

This study is based on 2674 nb^{-1} of data taken at SPEAR at e^+e^- center-of-mass energies ($\sqrt{s}$) from 5.00 to 7.25 GeV, in 250-MeV steps. A "topology" trigger,[4] designed especially to detect two-photon-collision events was used. It required approximate energy balance transverse to the beam axis; no such balance was demanded along the beam axis.

A search was made for events from the reaction $e^+e^- \rightarrow e^+e^-\eta$ with the η decaying to two photons, and the scattered electrons moving down the beam pipe undetected. A first selection required (1) the topology trigger and (2) two separate deposits of energy in the ball, neither one of which was caused by a charged particle coming from the e^+e^- interaction point (IP). To ensure efficient identification of such charged particles, we required $|\cos\theta_{\gamma\,beam}| < 0.8$ for both energy deposits (i.e., passage through the PWC). Events from the reaction $e^+e^- \to \gamma\gamma$ were removed by requiring the total energy in the ball to be less than 3 GeV.

This selection yielded about 60 000 events. The vast majority were due to cosmic rays which passed through the ball but not the IP, as indicated by the lack of correlation in time between the event trigger and the beam crossing. The invariant-mass distribution for the selected events peaked at 450–475 MeV, because of the topology-trigger threshold and the large number of minimum-ionizing cosmic rays which traverse the ball nonradially. To remove the large cosmic-ray background, a series of cuts was applied. At each stage, the number of cosmic rays remaining could be determined by examining the trigger timing distribution.

First, events were removed which were consistent with being charged cosmic rays passing through the central chambers but not through the IP. Events were rejected if there were more than two hits in the axial spark chamber and PWC wires were within 5 cm of a line connecting the two energy deposits (in the plane perpendicular to the beam). Because of noise in the chambers, a fraction of the truly neutral events was lost at this stage. In order to estimate the loss, events from the QED processes $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$ were examined and compared with predicted cross sections.[5] The number of $e^+e^- \to \gamma\gamma$ events observed (using the chamber-hit cut described above) divided by the number expected, for each beam energy, was found to be approximately independent of the angle of scattering. That ratio was taken to be the efficiency of the chamber cut for retaining true final-state $\gamma\gamma$ events. The efficiency was $(83 \pm 4)\%$ at $\sqrt{s} = 5.0$–6.5 GeV, but dropped to $(27 \pm 3)\%$ at $\sqrt{s} = 7.25$ GeV due to the larger number of noise hits at higher beam energies. The average efficiency for the entire data set was $(68 \pm 4)\%$.

Cosmic rays which traverse the ball but miss the central chambers completely will survive the cut just described, but will have lateral energy-deposition profiles which differ from those of photons originating from the IP. The former will leave elongated patterns while the latter will leave approximately circular deposition patterns. In addition, these cosmic rays will have high $p_T{}^2$, in contrast to two-photon events which are expected to peak at low $p_T{}^2$ ($p_T{}^2$ is the square of the vector sum of the transverse momenta of the two final-state photon candidates). An energy-pattern cut and a cut $p_T{}^2 < 10\,000$ MeV^2 removed nearly all of the remaining cosmic-ray events: the event-trigger-timing distribution indicated that after out-of-time events were removed, 5 ± 3 cosmic-ray events contaminate the final in-time event sample.

143 events survive all cuts, 112 of which have an invariant mass ($M_{\gamma\gamma}$) between 400 and 700 MeV/c^2. The $M_{\gamma\gamma}$ distribution for these events (not corrected for acceptance) is shown in Fig. 1(a). A clear peak near the η mass can be seen, on top of a background. The $p_T{}^2$ distribution for these events, Fig. 2(a), peaks at zero as expected for two-photon-collision events.

We have verified that the peak is not caused by the energy dependence of the topology trigger. This dependence has been measured from data taken concurrently with a more restrictive trigger which had a lower-energy threshold.[6] The trigger efficiency calculated from that data, as a function of energy deposited in the main NaI array, is presented in Fig. 3. Also shown in that figure is the total deposited energy of

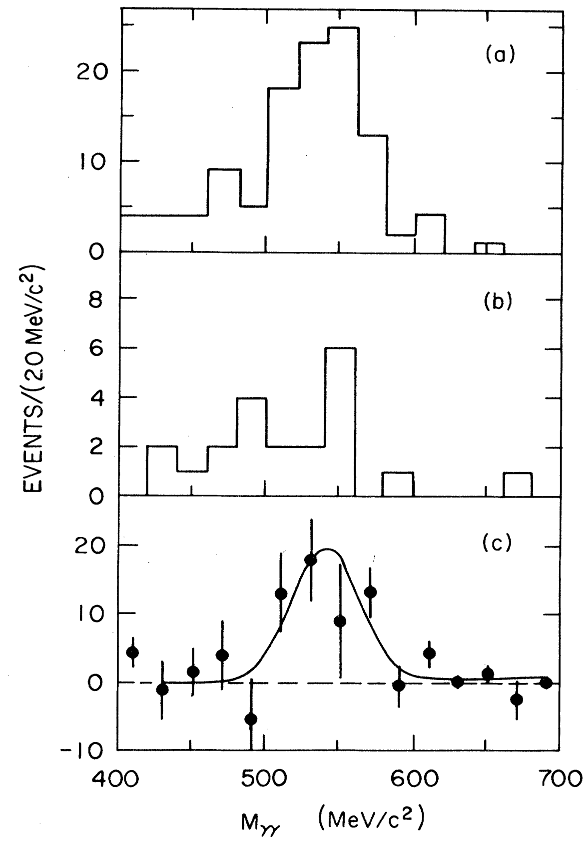

FIG. 1. Distribution of $M_{\gamma\gamma}$ for all events passing the cuts described in the text. (a) Colliding-beam data. Five events have invariant masses below 400 MeV, and 26 events have masses above 700 MeV. (b) Separated-beam data [the scale of the ordinate is adjusted to make the figure directly comparable to Fig. 1(a)]. One event has an invariant mass below 400 MeV, and no events have masses above 700 MeV. (c) Data points represent the background-subtracted data, while the curve represents a fit to the data employing a simple Gaussian and a small amount of residual background.

(1) the events shown in Fig. 1(a) (histogram) and (2) those events with $500 < M_{\gamma\gamma} < 600$ MeV/c^2. We conclude that the peak is not produced by the topology-trigger threshold.

There still remains a background due to beam-gas collisions. In order to estimate this background, the same cuts as described above were applied to data taken in the same period as the colliding-beam data and under the same conditions, but with beams separated so that no e^+e^- collisions occurred. The colliding-beam data contained 2.7 ± 0.3 times as many beam-gas collisions as the separated-beam data. This ratio was obtained by two different methods with good agreement in the results: (1) kinematically isolating beam-gas events in both samples, and (2) comparing the quantity *PIT*, defined as the time-integrated (vacuum pressure) $\times$(beam currents), for the two data sets, which should be proportional to the number of beam-gas-collision events in each data set. Figure 1(b) shows the 21 events which satisfy all cuts in the separated-beam data. The $p_T{}^2$ distribution for these events, Fig. 2(b), is flat. A bin-by-bin subtraction was performed to obtain the data points of Figs. 1(c) and 2(c).

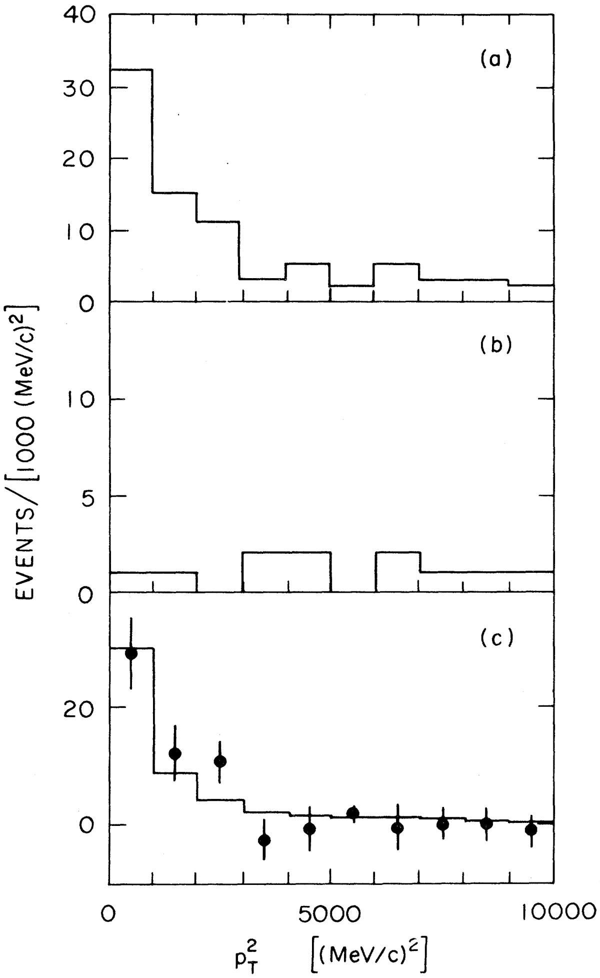

FIG. 2. Distribution of p_T^2 for events passing all cuts, with $500 < M_{\gamma\gamma} < 600$ MeV. (a) Colliding-beam data. (b) Separated-beam data [the scale of the ordinate is adjusted to make the figure directly comparable to Fig. 2(a)]. (c) Data points represent the background-subtracted data, while the histogram represents the prediction of Ref. 6 for the Crystal Ball, normalized to the number of events in the data.

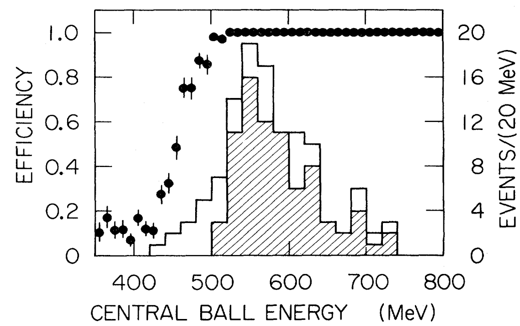

FIG. 3. Data points show the efficiency for the topology trigger as a function of total energy deposited in the crystals. The histogram (refer to the scale on the right) is the distribution of total energy deposited in the crystals by the η candidates. The shaded part of the histogram indicates those events with $500 < M_{\gamma\gamma} < 600$ MeV/c^2.

The final invariant-mass distribution, Fig. 1(c), was fit with a simple Gaussian and a linear background. The mass (542 ± 6 MeV) and width ($\sigma_m = 21 \pm 3$ MeV) of the peak are consistent with previous Crystal Ball studies of the η meson in other production channels. The p_T^2 distribution for these events shows a clear peak at zero; it compares well with the predicted shape[7] [shown as the histogram of Fig. 2(c), normalized to the number of events in the data]. We therefore associate the 56 ± 12 events in the peak with the two-photon production of η mesons.

Possible sources of single η-meson decays other than from the reaction $\gamma\gamma \to \eta$ include events from the reactions $\gamma\gamma \to \eta' \to \eta\pi\pi$ and $\gamma\gamma \to A_2 \to \eta\pi$ where the extra pion(s) go down the beam pipe undetected. We estimate that less than one event from these channels appears in our final sample. Events from the reaction $e^+e^- \to \gamma\gamma(\gamma)$, where a radiated photon carrying much of the total energy goes down the beam pipe, contaminates our final sample at invariant masses above 1500 MeV; less than one event is estimated[5] to remain with $M_{\gamma\gamma}$ below that value. The background from $\gamma\gamma \to \gamma\gamma$ (continuum)[8] and double bremsstrahlung[9] is estimated to be negligible, as are other sources from one- and two-photon channels. Electroproduction of η mesons by beam $e^{\pm}$ colliding with the residual gas in the beam pipe is estimated (using *PIT*) to be the same order of magnitude as the background in Fig. 1(a). This process contributes to the separated-beam data as well, and is therefore accounted for in the background subtraction.

We calculate $\Gamma_{\gamma\gamma}(\eta)$ using the formula

$$\Gamma_{\gamma\gamma}(\eta) = \frac{N}{L\sigma' B \epsilon_r \epsilon_n} ,$$

where N is the number of observed events (56 ± 12), L is the total integrated luminosity, σ' is the cross section for the reaction $e^+e^- \to e^+e^-\eta$ per unit $\gamma\gamma$ decay width of the η meson (calculated[7] to be 0.94 ± 0.04 nb/keV at an average $\sqrt{s}$ of 6.1 GeV), B is the decay branching ratio of the η meson to $\gamma\gamma$ (0.391 ± 0.008),[10] ϵ_r is the overall efficiency for reconstructing events from the reaction $e^+e^- \to e^+e^-\eta$ (determined by Monte Carlo calculations to be 15%),[11] and ϵ_n is the efficiency for retaining truly neutral events (determined as described above). We thus obtain $\Gamma_{\gamma\gamma}(\eta) = 0.56 \pm 0.12 \pm 0.10$ keV, where the first error is statistical and the second systematic. The systematic error includes the effects of changing the cuts, as well as changing the background-subtraction normalization constant.

This result can be compared to previous measurements of this quantity by experiments which employed the Primakoff effect: photoproduction of η mesons in the Coulombic field of a nuclear target. A pioneering DESY experiment[12] yielded $\Gamma_{\gamma\gamma}(\eta) = 1.0 \pm 0.2$ keV, while a more recent Cornell experiment[13] gave $\Gamma_{\gamma\gamma}(\eta) = 0.324 \pm 0.046$ keV. These experiments had high statistics, and their errors were dominated by systematic uncertainties in separating the component of η production in the Coulombic nuclear field from that in the hadronic nuclear field. In addition, the $\gamma\gamma$ decay width had to be extracted from the Coulombic cross section by estimating the nuclear electromagnetic form factor (the uncertainty in this calculation dominates the error in the Cornell result). This measurement of $\Gamma_{\gamma\gamma}$ using η production in $\gamma\gamma$ collisions at e^+e^- storage rings is, in principle, free from such theoretical uncertainties, but is limited by low statistics.

The $\gamma\gamma$ decay widths of neutral members of SU(3) nonets are related[1,14] by the nonet mixing angle (θ_P in the case of the pseudoscalar nonet). We take as input (1) our result $\Gamma_{\gamma\gamma}(\eta) = 0.56 \pm 0.16$ keV (errors added in quadrature), (2) $\Gamma_{\gamma\gamma}(\eta') = 5.3 \pm 0.6$ keV (world average from two photon experiments),[15] and (3) the Particle Data Group[10] value $\Gamma_{\gamma\gamma}(\pi^0) = 7.83 \pm 0.56$ eV. We obtain by χ^2 minimization $\theta_P = -17.6° \pm 3.6°$, with a $\chi^2 = 0.01$ for one degree of freedom. Taking, instead, the Cornell value[13] for $\Gamma_{\gamma\gamma}(\eta)$, as well as the above values of $\Gamma_{\gamma\gamma}(\pi^0)$ and $\Gamma_{\gamma\gamma}(\eta')$, yields $\theta_P = -9.5° \pm 2.0°$, with a $\chi^2 = 2.4$ for one degree of freedom.

We gratefully acknowledge the efforts of A. Baumgarten and J. Broeder (SLAC) and B. Beron, E. B. Hughes, and R. Parks [High Energy Physics Laboratory (HEPL), Stanford University], as well as those of the linac and SPEAR staff at the Stanford Linear Accelerator Center. We thank S. Cooper for many useful discussions. This work was supported in part by the U.S. Department of Energy under Contracts Nos. DE-AC03-76SF-00515 (SLAC), DE-AC02-76ER03064 (Harvard), DE-AC03-81ER40050 (Caltech), and DE-AC02-76ER03072 (Princeton); and by the National Science Foundation under Contracts Nos. PHY81-07396 (HEPL), PHY79-16461 (Princeton), and PHY75-22980 (Caltech). One of us (H.K.) acknowledges receipt of a NATO Fellowship, and one of us (F.C.P.) acknowledges receipt of a Chaim Weizmann Fellowship.

---

[a]Present address: Institute of High Energy Physics, Academia Sinica, Beijing, People's Republic of China.

[b]Present address: Hermann Diestel Strasse 28, D-2050 Hamburg 80, Federal Republic of Germany.

[c]Present address: Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305.

[d]Present address: University of Capetown, Capetown, South Africa.

[e]Present address: Fermi National Accelerator Laboratory, Batavia, IL 60510.

[f]Present address: Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, CA 95064.

[g]Present address: University of Bonn, Bonn, Federal Republic of Germany.

[h]Present address: University of Würzburg, Würzburg, Federal Republic of Germany.

[i]Present address: Schlumberger-Doll Research Center, Ridgefield CT 06877.

[j]Present address: Network Design Associates, 766 La Prenda, Los Altos, CA 94022.

[k]Present address: 830 Tulane Drive, Mountain View, CA 94040.

[l]Present address: Max Planck Institute for Physics and Astrophysics, D-8000 Munich (40), Federal Republic of Germany.

[m]Present address: Enrico Fermi Institute, University of Chicago, Chicago, IL 60637.

[n]Present address: Space Applications Corporation, Sunnyvale CA 94086.

[1]See, for example, F. Gilman, in *Proceedings of the 1979 International Conference on Two-Photon Interactions, Lake Tahoe, California*, edited by J. F. Gunion (Physics Department, University of California, Davis, California, 1980), p. 215.

[2]G. Abrams *et al.*, Phys. Rev. Lett. 43, 477 (1979); W. Bartel *et al.*, Phys. Lett. 113B, 190 (1982); H. J. Behrend *et al.*, *ibid.* 114B, 378 (1982); preliminary results from the TASSO group, in *Proceedings of the Fifth International Workshop on Photon-Photon Collisions, Aachen, 1983,* edited by Ch. Berger (Heidelberg, Springer, in press).

[3]H. Primakoff, Phys. Rev. 81, 899 (1951).

[4]M. Oreglia *et al.*, Phys. Rev. D 25, 2259 (1982); A. Weinstein, Ph.D. thesis, Harvard University, 1983. The last reference contains a description of the topology trigger.

[5]R. Kleiss, thesis, Leiden University, Leiden Report No. RX-988, 1982; F. A. Berends and R. Kleiss, Nucl. Phys. B186, 22 (1981).

[6]This more restrictive trigger required two back-to-back energy depositions, of 35 MeV each, collinear to within $<15°$, and minimum total energy of 150 MeV. Events accepted by this trigger, and which also satisfied the geometrical requirements of the topology trigger, were used to determine the topology-trigger efficiency.

[7]The calculation of cross sections and the generation of predictions for kinematical distributions used a Monte Carlo program described in J. A. M. Vermaseren, Report No. NIKHEF-H/82-15, 1982 (unpublished); J. A. M. Vermaseren, J. Smith, and G. Grammer, Phys. Rev. D 19, 137 (1979).

[8]H. Cheng, E. Tsai, and X. Zhu, Nuovo Cimento Lett. 34, 427 (1982); Phys. Rev. D 26, 922 (1982).

[9]V. N. Bayer and V. M. Galitsky, Zh. Eksp. Teor. Fiz. Pis'ma Red. 2, 259 (1965) [JETP Lett. 2, 165 (1965)]; P. DiVecchia and M. Greco, Nuovo Cimento 50, 319 (1967).

[10]Particle Data Group, Phys. Lett. 111B (1982).

[11]The efficiency is constant for $M_{\gamma\gamma} > 475$ MeV/c^2, but drops to 5% for an η mass of 400 MeV/c^2 due to the energy dependence of the topology-trigger efficiency near threshold.

[12]C. Bemporad *et al.*, Phys. Lett. 25B, 380 (1967). The quoted measurement of 1.21 ± 0.26 has been corrected for a revised η two-photon branching ratio of 0.391.

[13]A. Browman *et al.*, Phys. Rev. Lett. 32, 1067 (1974); A. Browman *et al.*, Cornell Reports Nos. CLNS 224 and 242, 1973 (unpublished).

[14]We use the formulas given in Ref. 1 for the extraction of θ_P from the $\gamma\gamma$ decay widths of the η, η', and π^0 mesons. As was done there, we make the simplifying assumption that the spatial wave functions for all states of a given J^P nonet are the same ("nonet symmetry").

[15]J. Olsson, in *Proceedings of the Fifth International Workshop on Photon-Photon Collisions, Aachen, 1983* (Ref. 2).