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Study of η formation in photon-photon collisions

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The two-photon production of the η meson has been observed, and a value has been determined for the two-photon η-decay width by a measurement of the cross section $\sigma(e^+e^- \rightarrow e^+e^-\eta)$ where $\eta \rightarrow \gamma\gamma$. The measurement was made with the TPC/Two-Gamma facility at the SLAC e^+e^- collider PEP, with an accumulated data sample of 64.5 pb^{-1}. The $\eta \rightarrow \gamma\gamma$ events were both triggered and detected by the pole-tip calorimeter. The measured two-photon η-decay width is $\Gamma_{\eta\rightarrow\gamma\gamma} = 0.64 \pm 0.14$ (statistical) ± 0.13 (systematic) keV, in agreement with earlier similarly determined values.

The measurement of the two-photon decay width of a pseudoscalar meson provides a direct probe of its structure. With the assumption of "nonet symmetry," SU(3) makes explicit predictions[1] for the relative two-photon decay rates of the π^0, η, and η' mesons. The two-photon decay width of the π^0 can be calculated with the Adler-Bell-Jackiw anomaly[2] under the PCAC (partially conserved axial-vector current) hypothesis, giving a value of $\Gamma_{\pi^0\rightarrow\gamma\gamma} = 7.87$ eV. This is in agreement with the experimentally determined value[3] of 7.85 ± 0.54 eV. The two-photon widths of the η

and η' are then related[4] to that of π^0 through a pseudoscalar mixing angle θ:

$$\Gamma_{\eta \to \gamma\gamma} = \Gamma_{\pi^0 \to \gamma\gamma} \left[\frac{m_\eta}{m_{\pi^0}} \right]^3 \tfrac{1}{3}(\cos\theta - \sqrt{8}\sin\theta)^2 \ ,$$
$$\Gamma_{\eta' \to \gamma\gamma} = \Gamma_{\pi^0 \to \gamma\gamma} \left[\frac{m_{\eta'}}{m_{\pi^0}} \right]^3 \tfrac{1}{3}(\sqrt{8}\cos\theta + \sin\theta)^2 \ . \tag{1}$$

Experimental measurements of these two-photon widths are difficult and a spread in the results makes a precise evaluation of the mixing angle difficult.

In this experiment $\Gamma_{\eta \to \gamma\gamma}$ was determined by a measurement of the cross section $\sigma(e^+e^- \to e^+e^-\eta)$, with $\eta \to \gamma\gamma$. The experiment was performed at the TPC/Two-Gamma facility[5] at the SLAC electron-positron collider PEP. The two final-state photons were detected by one of two pole-tip calorimeter (PTC) modules.[6] The PTC is a proportional-mode electromagnetic calorimeter with two modules mounted on the magnet pole tips, just outside the end caps of the time-projection chamber (TPC). It shares an 8.5-atmosphere Ar-CH_4 gas volume with the TPC. The PTC sense-wire orientations provide three stereo views for shower reconstruction. The measured energy resolution is $\simeq 0.22\sqrt{E}$ (E in GeV) and the measured position resolution is $\simeq 0.15°$ for Bhabha events. A forward angular region of $14.9° \leq \theta \leq 38.4°$ is covered, corresponding to 18.3% of the 4π solid angle.

The $\eta \to \gamma\gamma$ events were triggered by a low-energy photon localization trigger. The trigger logic searched for hits corresponding to energy deposits in each of the three views, compared all three-view combinations with valid shower locations, and required that evidence for two localized showers be found along with a total module energy sum ≥ 1.2 GeV.

Our measurement is based on a data sample for an accumulated luminosity of 64.5 pb^{-1} at a center-of-mass energy of 29.0 GeV. A series of cuts was used to select $\eta \to \gamma\gamma$ candidates. Events were required to have exactly two identified photons in a single PTC module within a region of uniform response defined by polar angles $16.2° \leq \theta \leq 32.2°$. Events with identified photons in the other PTC module or in the hexagonal calorimeter which surrounds the TPC were rejected, as were events with identified tracks in the TPC. PTC showers with associated charged tracks too forward to be found by standard TPC tracking techniques were identified with a low-angle tracking algorithm which searched for wire hits within a vertex-independent road from the PTC shower location back through the TPC; the event was rejected as having a charged track if 12 or more wire hits were found. Visual inspection of the TPC wire hit pattern removed additional events with low-angle charged tracks not directed at either of the two identified PTC showers.

Resonances produced in two-photon collisions have characteristically low transverse momentum, so the $\gamma\gamma$ final states were required to have total $\mathbf{p}_T^2 \leq 0.16$ $(\mathrm{GeV}/c)^2$ and the two photons had to be $\geq 135°$ apart in the azimuthal angle ϕ. Figure 1 shows the distributions in the square of the transverse momentum and in the azimuthal separation between the two photons. The contributions of the η' and f are discussed below. The entire selection process resulted in 145 clean PTC $\gamma\gamma$ events.

The PTC was modeled in realistic detail by Monte Carlo studies in which showers were simulated with the electron-gamma shower[7] (EGS) program. The two η-decay photons were followed through an accurate replication of the beam pipe and surrounding material. To simulate the track cuts applied to the data, Monte Carlo events were rejected if either photon converted in the material. The Monte Carlo simulation of the PTC response and the treatment of the beam-pipe material is in good agreement with PTC studies[8] of $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$.

Nearly half of the $\eta \to \gamma\gamma$ events within the PTC geometry were expected to have total $\gamma\gamma$ energies below trigger threshold so that an accurate trigger Monte Carlo

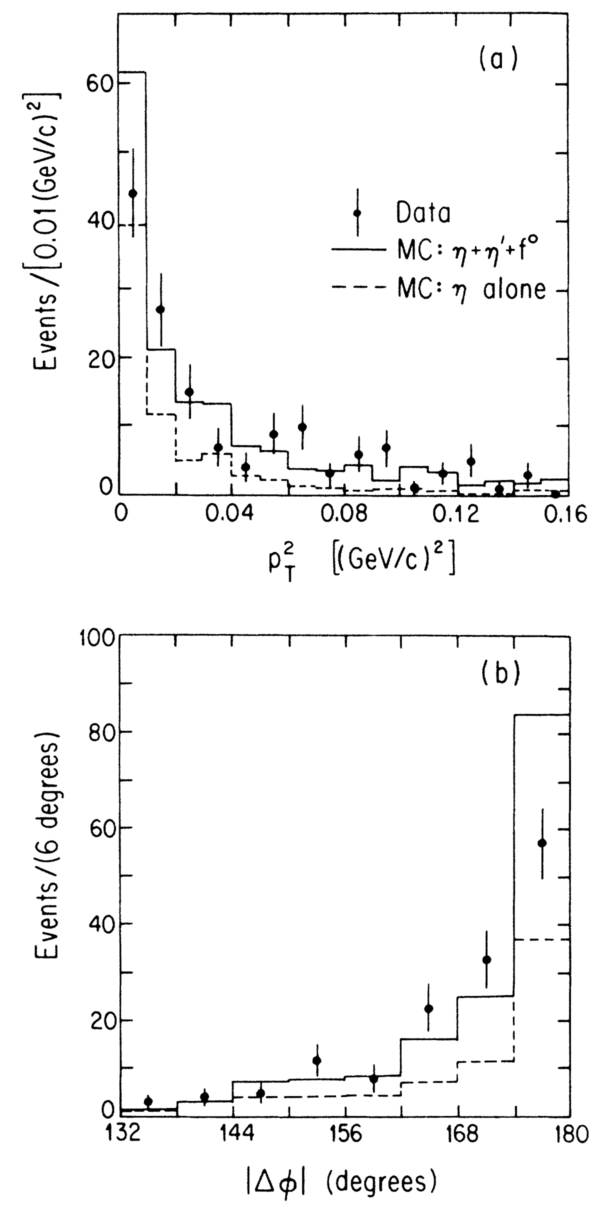

FIG. 1. Distribution in (a) the square of the transverse momentum, $\mathbf{p}_T^2$, and (b) azimuthal opening angle $|\Delta\phi|$ between the two photons for η-decay candidates. The solid points are data corresponding to the 145 events in the final selection. The error flags represent the statistical uncertainty. The solid histogram is the Monte Carlo result for η and background together; the η contribution is indicated by the dashed histogram.

simulation was essential in determining the overall η detection efficiency. The trigger threshold efficiency was measured as a function of energy for the total energy sum as well as for the photon localization logic by using the PTC trigger record for events which satisfied an independent charged-particle trigger. The PTC EGS output was then processed on an event-by-event basis through a complete trigger simulation based on the measured threshold response distributions.

Several background processes which might produce a final state with just two observed PTC photons and no other observed particle have been investigated. The QED reaction $e^+e^- \rightarrow e^+e^-\gamma\gamma$ contributes less than one event from both the two-photon production continuum[9] and double bremsstrahlung.[10] The background from the electroproduction of η's in beam-gas collisions has been estimated[11] from photoproduction cross sections and PEP pressure records to be 1.4 ± 1.4 events. This calculated estimate has been verified by studying electroproduction η's which were produced in beam-gas collisions outside the e^+e^- interaction region and which were identified by the observation of tracks in the TPC associated with the conversion of one or both η-decay photons. Four such candidates were found coming from the regions between 50 and 100 cm away from the e^+e^- interaction region while two events were expected.

A non-negligible background contribution comes from two-photon produced n' and f^0 events, where $n' \rightarrow \gamma\gamma$, and $f^0 \rightarrow \pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma$, with two of the four photons undetected. Most of these f^0 and η' events have $\gamma\gamma$ invariant masses well above the η mass region. While the Monte Carlo calculation of this background is consistent with observation, evaluation of the efficiencies is uncertain. Therefore, the contribution of these two processes was fitted simultaneously with $\eta \rightarrow \gamma\gamma$ in order to determine the background under the η mass peak.

A χ^2 function was formed by comparing the data and Monte Carlo $\gamma\gamma$ mass distributions in seven mass intervals from 0.36 to 1.20 GeV/c^2. The χ^2 was minimized by varying the η, η', and f^0 contributions, as well as a gain factor that sets the Monte Carlo pulse-height scale. The latter was determined to within 4% by the fit and is in good agreement with the value found for Bhabha events as well as for low-energy PTC photons obtained in a fit to two-photon produced $\eta' \rightarrow \rho^0\gamma$ events. The fit of the Monte Carlo mass distributions to data gave $\chi^2 = 3.1$ for 3 degrees of freedom. The effective-mass distribution for the two photons is shown in Fig. 2(a). The background-subtracted data peaks at 556.4 ± 2.7 MeV/c^2 compared to 555.0 ± 0.5 MeV/c^2 predicted for events which satisfy the trigger selection. When corrected for the total energy trigger threshold effect, the background-subtracted data peaks at 549.4 MeV/c^2.

The distribution in total energy of the two photons is shown in Fig. 2(b), with the effect of the trigger energy threshold at 1.2 GeV clearly evident. A comparison between data and Monte Carlo energy distributions which uses the mass-fit parameters gives, for seven bins from 0.9 to 3.0 GeV, $\chi^2 = 3.7$ for 3 degrees of freedom. The transverse momentum and azimuthal separation distributions for Monte Carlo η and background events are included in Figs. 1(a) and 1(b).

The measured η-production cross section is given by

$$\sigma(e^+e^- \rightarrow e^+e^-\eta) = (N_\eta/\epsilon)/(B\mathscr{L}) \ , \quad (2)$$

where $N_\eta/\epsilon = (4.0 \pm 0.9) \times 10^4$ from the fit ($N_\eta = 70$ is the

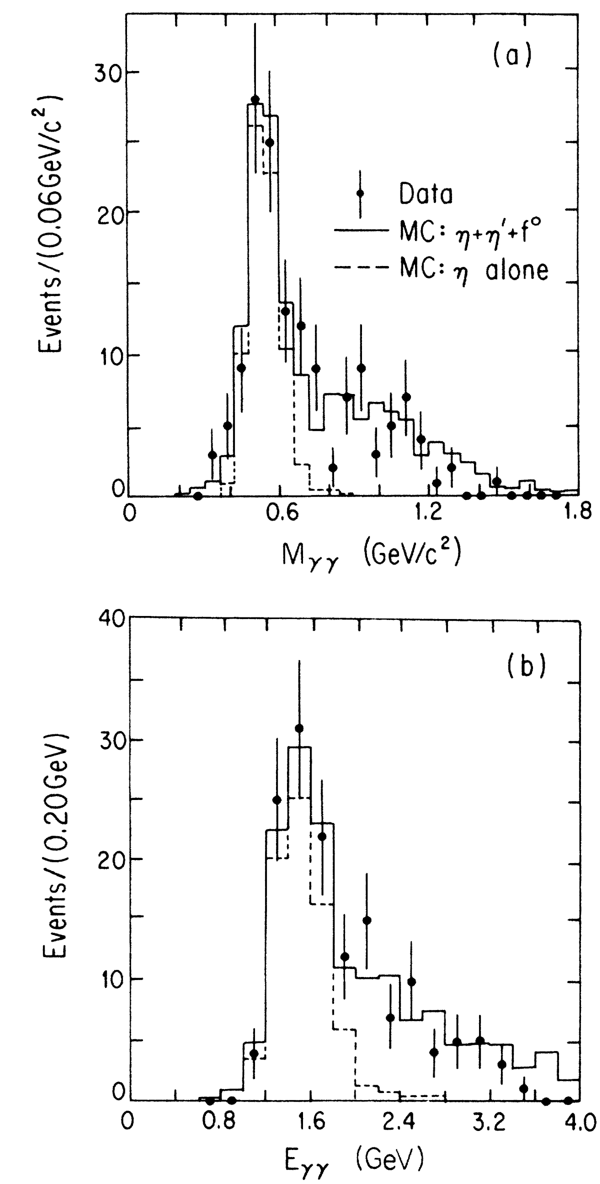

FIG. 2. Distribution in (a) effective mass and (b) total energy of the two-photon system. Data and Monte Carlo simulation are indicated as in Fig. 1.

number of η events), $B = 0.390 \pm 0.008$ is the $\eta \rightarrow \gamma\gamma$ branching ratio,[3] and the integrated luminosity $\mathscr{L} = 64.5 \pm 4.5$ pb^{-1}. The PTC detection, event selection, and analysis efficiencies are combined to give the overall efficiency $\epsilon = 0.0017$. It includes a geometric efficiency of 1.40%, a photon-shower reconstruction efficiency of 81%, an efficiency of 75% for event-selection cuts, a total trigger efficiency measured to be 39%, and an efficiency of 50% for both final-state photons to pass through the beam-pipe material without converting.

The measured cross section is $\sigma(e^+e^- \rightarrow e^+e^-\eta) = 1.62 \pm 0.35 \pm 0.32$ nb. A calculation which uses exact photon-flux factors[12] leads to the two-photon width of the η:

$$\Gamma_{\eta \rightarrow \gamma\gamma} = 0.64 \pm 0.14 \pm 0.13 \text{ keV} \ ,$$

where the quoted errors are statistical and systematic, respectively. The statistical error is derived from a 20% error on the ratio of the number of fit η events to the Monte Carlo efficiency, along with a 10% statistical error on the aforementioned cuts and efficiencies. The 20% systematic error is estimated from approximately equal contributions from uncertainties in trigger efficiency, trigger threshold, photon conversion, photon detection efficiency, background subtraction, and luminosity. The result of 0.64 keV is insensitive to the $\mathbf{p}_T^2$ and $\Delta\phi$ cuts in the regions of 0.16 $(\mathrm{GeV}/c)^2$ and 135°, respectively.

Previously published values of the $\eta \rightarrow \gamma\gamma$ width are 0.324 ±0.046 (Ref. 13) and 1.00 ±0.22 keV (Ref. 14) from experiments using the Primakoff effect and 0.56 ±0.12 ±0.10 from the Crystal Ball[15] and 0.53 ±0.04 ±0.04 keV from JADE[16] at e^+e^- colliders. The two methods of determining $\Gamma_{\eta\rightarrow\gamma\gamma}$ have very different experimental difficulties. The Primakoff measurements are high-statistics experiments but require separation of the Primakoff η-production amplitude from the amplitude for photoproduction in the hadronic field of the nucleus and from that contributed by interference between the Primakoff and nuclear amplitudes. The measurements at e^+e^- colliders, like the measurement reported here, are limited by the low event rate. The present measurement of high-rapidity two-photon η production leads to average detected photon energies of 800 MeV. This results in good photon detection by the pole-tip calorimeter. Our result is in poor agreement with either Primakoff measurement but in good agreement with the other two e^+e^- results.

TABLE I. Pseudoscalar mixing angle from measured two-photon widths.

	π^0 (Ref. 3)	η (This paper)
π^0 (Ref. 3)	...	−20.0° ±7.0°
η' (Ref. 17)	−24.2° ±3.6°	−21.8° ±4.5°

Our $\eta \rightarrow \gamma\gamma$ width and the measured π^0 and η' two-photon widths[3,17] can be taken in pairs to calculate the mixing angle θ. The three values so determined are shown in Table I and are seen to be consistent results.

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