THE THREE PHOTON FINAL STATE PRODUCED IN e^+e^- COLLISION AT 3.6 GeV AND AT THE ψ'

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The three photon final state produced in e^+e^- collisions at 3.6 GeV and at the mass of the ψ' resonance has been measured using the nonmagnetic part of the double arm spectrometer DASP. A total of 31 events is observed outside the resonance region compared to 35.1 events predicted from QED. At the mass of the ψ' 49 events are observed compared to 37.2 events expected from QED. Limits on radiative decays via intermediate states are given.

In this paper results on the three photon final state produced in e^+e^- collisions for cms energies at the ψ' resonance and in the nonresonant region below the ψ' are reported. The data were collected at the e^+e^- storage ring DORIS using the inner detector of the double arm spectrometer DASP to identify the final state and to measure the directions and the energies of the photons. Data were collected for an integrated luminosity of 256 nb^{-1} at a cms energy of 3.6 GeV and for 460 nb^{-1} in a narrow energy range centered on the ψ' resonance.

The detector and the criteria used to analyse the three photon final state were discussed in detail in a previous publication [1]. Candidates for three photon events were required to have at least 2 GeV deposited in the detector. At most one of the photons was allowed to convert in the beam pipe, and the opening angle between any two photons in the event had to be larger than 30°. A total of 41 events outside the resonance region and a total of 66 events at the ψ' satisfied the criteria.

The χ^2 was computed for the hypothesis that the three photon conversion points and the interaction point lie in a plane. The location and the size of the interaction region were determined from multihadron and Bhabha scattering events. The coplanarity condition will in general not be met by three photon candidates resulting from multihadron or beam gas events with unobserved hadrons. Events with a χ^2 greater than 2.7 were rejected, leaving 31 events at 3.6 GeV and 49 events at the ψ' resonance.

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For the coplanar events the photon energies were computed from the best fit photon directions and the known cms energy. The computed photon energies agree well with the measured values obtained by summing the normalized pulse heights of all the scintillation and shower counters fired along the track. The effective photon pair mass was evaluated using the fitted directions and the computed energies of the photons.

(1) *Nonresonant region.* The events obtained at 3.6 GeV are shown in a Dalitz plot (fig. 1a). The events cluster mainly at high effective mass as expected [2] of two photon annihilation with a photon radiated by one of the incoming electrons. There is no evidence for reactions of the type

$$e^+e^- \to \gamma H \to \gamma\gamma\gamma\,,$$

with $H = \eta, \eta'$ or X(2.83). This is demonstrated more clearly in fig. 1b and fig. 1c, where the events are plotted as a function of the lowest and the highest photon pari-mass observed in the event. The contribution from QED events, shown as the solid lines in figs. 1b, c, was evaluated as follows: three photon events, produced according to the matrix elements listed by Berends and Gastman [2] were used as an input to a Monte Carlo program. The program propagated the photons through the detector evaluating the conversion points and the energy deposited in each layer of the detector. Events satisfying the trigger conditions were analyzed with the standard analysis program. This calculation predicts a total of 35.1 events compared to the 31 events observed. Both the number and the mass distribution of the observed events are compatible with QED production.

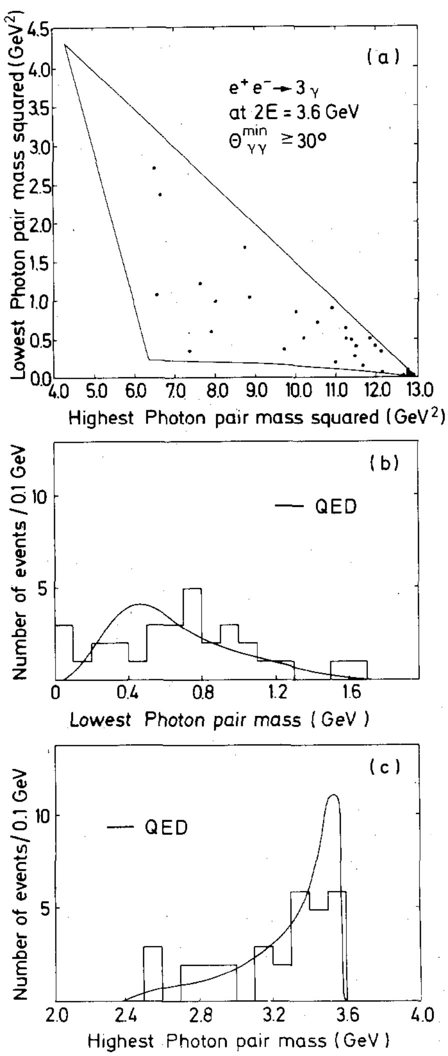

Fig. 1. (a) Dalitz plot of coplanar three photon events at $\sqrt{s} = 3.6$ GeV. (b) The three photon events plotted as a function of the lowest photon pair mass observed in the event. The solid curve is the QED contribution. (c) The three photon events plotted as a function of the highest photon pair mass observed in the event. The solid curve is the QED contribution.

Upper limits on resonance production were determined by fitting to the observed data the sum of the computed QED contribution and resonance production represented by a Gaussian. The Gaussian was centered at the mass of the assumed resonance with a mass resolution taken from a Monte Carlo calculation. This ansatz fits the data at the J/ψ resonance. The following 90% upper confidence limits on resonance production were obtained

$$\sigma(e^+e^- \to \gamma\eta) < 0.21 \text{ nb} \quad \text{and}$$

$$\sigma(e^+e^- \to \gamma X) \cdot BR(X \to \gamma\gamma) < 0.11 \text{ nb}.$$

In this energy region a total cross section for hadron production of roughly 20 nb is observed [3].

(2) *ψ'-region.* At the ψ' resonance the three photon final state can come from

(a) the QED process,

(b) radiative decays via intermediate states with even charge conjugation and spin different from one, and

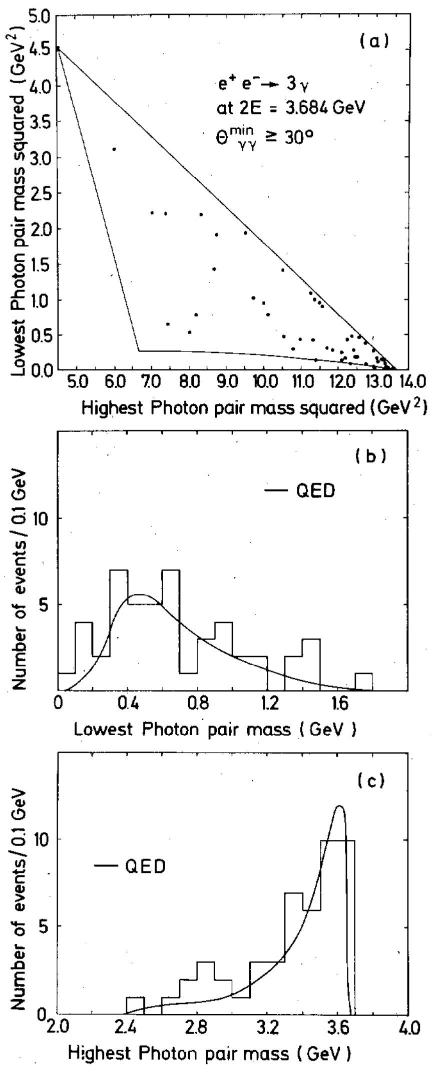

Fig. 2. (a) Dalitz plot of coplanar three photon events at the ψ' resonance. (b) The three photon events plotted as a function of the lowest photon pair mass observed in the event. The solid curve is the QED contribution. (c) The three photon events plotted as a function of the highest photon pair mass observed in the event. The solid curve is the QED contribution.

(c) direct decay into three photons.

A Dalitz plot of the three photon events obtained at the ψ' resonance is shown in fig. 2a. The events tend to cluster at high mass with no striking evidence for the radiative decay via intermediate states. The events are histogrammed in figs. 2b and 2c as a function of the lowest and the highest photon pair mass observed in the event. The QED contribution is shown as solid lines.

The data show no significant peaks from the decay via intermediate states. However, a total of only 37.2 events is expected from QED compared to 49 events observed. The 90% confidence upper limits on $\psi' \to \gamma\eta$ and $\psi' \to \gamma\eta'$ obtained as above are

$$\Gamma(\psi' \to \gamma\eta) < 87 \text{ eV},$$

$$\Gamma(\psi' \to \gamma\eta') < 1.4 \text{ keV}.$$

These limits are larger than the widths (55 ± 12) eV and (152 ± 117) eV measured for the decay $J/\psi \to \gamma\eta$ and $J/\psi \to \gamma\eta'$.

The decay $\psi' \to \gamma X(2.83)$ would appear as a peak in the high mass spectrum (fig. 2c) centered at 2.83 GeV. A total of 3 events is observed within the mass range (2.83 ± 0.05) GeV corresponding to a mass interval of about twice the expected FWHM resolution. A total of 0.8 events is expected from QED. From these data a 90% confidence upper limit on $BR(\psi' \to \gamma X) \times BR(X \to \gamma\gamma$ of 3×10^{-4} can be extracted. This limit, combined with the value [1] for $J/\psi \to \gamma X(2.83)$, leads to

$$\frac{\Gamma(\psi' \to \gamma X(2.83))}{\Gamma(J/\psi \to \gamma X(2.83))} < 10 .$$

The significance of this number is partially hidden by the large difference in phase space available for the two reactions. If the X(2.83) is identified with the lowest $^1S_0$ state in the charmonium model the width should be proportional to $k^3 |\langle n_f | n_i \rangle|^2$ since these are M1 transitions. Here k is the photon energy and $\langle n_f | n_i \rangle$ the overlap integral of the wave functions. With these assumptions we find

$$\frac{|\langle X | \psi' \rangle|^2}{|\langle X | J/\psi \rangle|^2} < 0.23 .$$

In the charmonium model a small ratio is expected.

The $C = +1$ states observed [4] between the ψ' and the J/ψ are compatible with being the ^3P states in the charmonium model. In particular, the states at 3.41 GeV and 3.56 GeV are usually identified [5] with the $^3P_0$ and $^3P_2$ states with quantum numbers $J^{PC} = 0^{++}$ and 2^{++}. Both states can in principle decay into two photons. No evidence for these decays is seen. The 90% confidence upper limits on the product of the branching ratios are listed in table 1. The upper limits

Table 1
Upper limits on $\psi' \to \gamma H \to \gamma\gamma\gamma$.

Decay	$BR(\psi' \to \gamma H) \times BR(H \to \gamma\gamma)$	$BR(H \to \gamma\gamma)$
$\psi' \to \gamma\eta \to \gamma\gamma\gamma$	$< 1.6 \times 10^{-4}$	–
$\to \gamma\eta' \to \gamma\gamma\gamma$	$< 1.2 \times 10^{-4}$	–
$\to \gamma X(2.83) \to \gamma\gamma\gamma$	$< 3.4 \times 10^{-4}$	
$\to \gamma\chi(3.41) \to \gamma\gamma\gamma$	$< 4.0 \times 10^{-4}$	$< 5.7 \times 10^{-3}$
$\to \gamma\chi(3.45) \to \gamma\gamma\gamma$	$< 3.1 \times 10^{-4}$	–
$\to \gamma P_c(3.51) \to \gamma\gamma\gamma$	$< 2.6 \times 10^{-4}$	$< 3.0 \times 10^{-3}$
$\to \gamma\chi(3.55) \to \gamma\gamma\gamma$	$< 2.0 \times 10^{-4}$	$< 2.5 \times 10^{-3}$

on branching ratio for the decay of the resonances into two photons can be obtained from these data using the measured [6, 7] values for $BR(\psi' \to \gamma P_c/\chi)$.

The limits found are on the order of a few times 10^{-3}, compatible with the values predicted [8] for these decays in the charmonium model using the short range picture.

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