RADIATIVE DECAYS OF THE J/ψ AND EVIDENCE FOR A NEW HEAVY RESONANCE

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The three photon final state produced in e^+e^- collisions has been measured at the mass of the J/ψ resonance using the nonmagnetic part of the double arm spectrometer DASP. The decays J/$\psi \to \eta\gamma$, $\eta'\gamma$ and $\pi^0\gamma$ were observed and their branching ratios are given. A four standard deviation signal was observed in the $\gamma\gamma$ mass spectrum at a mass of (2.83 ± 0.03) GeV. An upper limit is given for the direct decay J/$\psi \to 3\gamma$.

This paper presents results on the three photon final state produced in e^+e^- collisions at the mass of the J/ψ resonance. The data were obtained at DORIS using the nonmagnetic detector of the double arm spectrometer DASP. Preliminary results on the three photon final state [1, 2] based on less than half of the present luminosity have been reported earlier.

The nonmagnetic detector is mounted between the two magnetic arms of the DASP detector as shown in fig. 1. It covers geometrically about 70% of 4π and is divided azimuthally in eight sectors. The part of the inner detector facing the magnet aperture consists only of scintillation counters and proportional chambers. A particle emitted towards the remainder of the detector traverses the following elements: one of 22 scintillation counters surrounding the beam pipe, two proportional chambers each with three signal planes (in a part of the azimuthal acceptance), four of the standard units described below and finally a lead-scintillator shower counter 7 radiation lengths thick. The standard unit is a scintillation counter hodoscope, a 5 mm thick lead converter and a proportional tube chamber. Two different types of tube chambers are used. In the units mounted above and below the beam pipe each chamber consists of three signal planes of 10 mm diameter tubes oriented at 0°, −30° and +30° to the beam direction. Three of the four chambers mounted in each side octant have two signal planes with 15 mm diameter tubes oriented at ±30° with respect to the vertical. The fourth chamber has three

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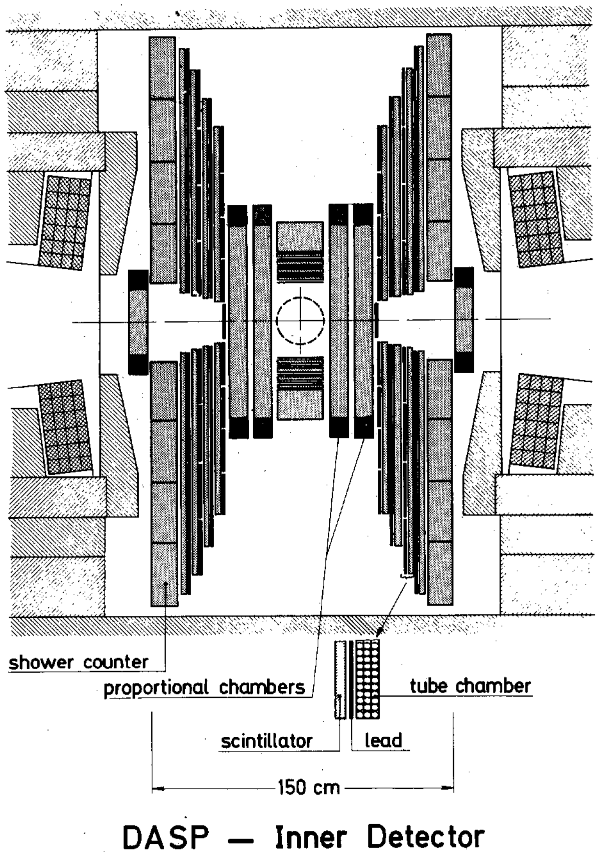

Fig. 1. The nonmagnetic detector viewed along the beam direction.

signal planes with 10 mm diameter tubes oriented at 0° and ±30° with respect to the vertical. With the information from the tube chambers and the location and the size of the interaction point taken from charged final state events the direction of a photon is detemined with a rms error of about 25 mrad.

The response of the detector to photons with energies between 50 MeV and 1700 MeV was studied prior to installation using a tagged photon beam. To be detected a photon must fire at least two intersecting tubes and one scintillation counter on the track beyond the conversion point. This criterion gives a detection efficiency of 95% for photons with energies above 300 MeV. For photons with energies below 300 MeV the detection efficiency decreases slowly; a 100 (50) MeV photon is detected with 80 (50)% efficiency. The calibration of the counters were checked frequently using Bhabha scatters and $e^+e^- \to \gamma\gamma$ events as a source of electrons and photons of well defined energies. The energy of a photon is measured by summing the pulse heights of all scintillation counters fired along the track. The rms energy resolution $\Delta E/E$ is $0.14/\sqrt{E(\mathrm{GeV})}$.

The trigger was designed to detect Bhabha and $e^+e^- \to \gamma\gamma$ events as well as final states with three or more particles, of which at least one should be charged. A crude particle counting was facilitated by logically dividing the inner detector into twelve segments subtending roughly equal solid angle. A segment was fired when any tow of the three last planes of scintillation and shower counters in the segment responded in coincidence. The thresholds were set to be sensitive to minimum ionizing particles. The event trigger was an OR of the conditions:

(1) Two or more segments fired in coincidence with at least 500 MeV deposited in their shower counters.

(2) Three or more segments plus at least one of the pipe counters fired.

The three photon final state satisfied the first trigger condition, the second condition allowed for one of the photons to convert in the beam pipe.

Data were collected for a total integrated luminosity of 421 nb^{-1}. The luminosity was determined from a measurement of small angle Bhabha scattering events normalized to large angle Bhabha scattering events for energies outside the resonances. We estimate the systematic error in the normalization of the luminosity measurements to be less than 5%.

The three photon events were selected using the following criteria:

(1) No more than one of the 22 beam pipe counters was allowed to fire. This permits one of the photons to convert in the beam pipe, which was 0.07 of a radiation length thick. Such a track had to develop a shower in the detector.

(2) At least 2.0 GeV had to be deposited in the detector. The event was rejected if less than 10 MeV was deposited in any one hemisphere.

(3) The arrival time of pulses from the various segments had to coincide within 5.5 nsec.

All events satisfying the criteria above were scanned by physicists. Events with three photons were retained, provided that the showers developed outwards from the interaction point and that the minimum opening angle between any pair of photons in the event was greater than 30°. This latter cut, designed to remove $e^+e^- \to \gamma\gamma$ events with widely spreading showers, also removes events from the decay $J/\psi \to \gamma\pi^0$, which required a separate analysis (reported below).

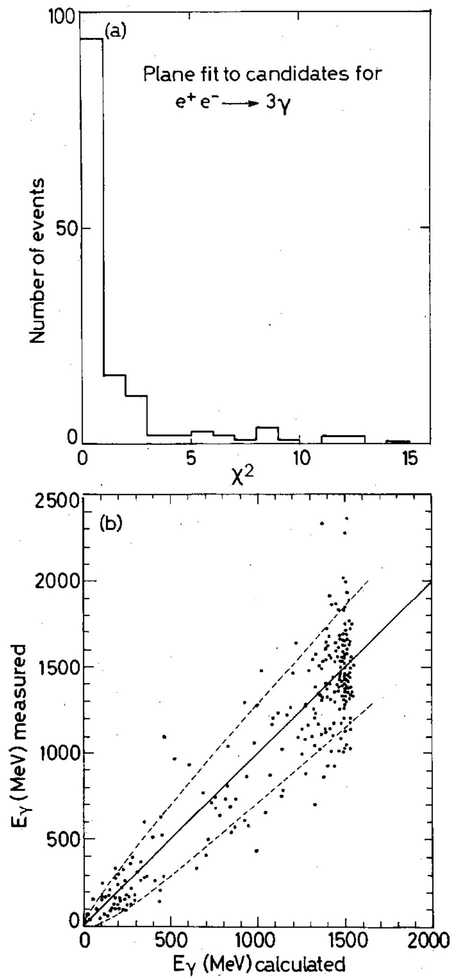

Fig. 2(a) χ^2 distribution for three photon events computed for the hypothesis that the photon conversion points and the interaction point are coplanar. (b) Scatter plot of measured versus computed photon energy for coplanar three photon events. The dotted line indicate the $\pm 2\sigma$ resolution.

A total of 152 events satisfied the selection criteria. For each event a 1C fit was made to the hypothesis that the three conversion points and the interaction point lie in a plane. This coplanarity requirement will in general not be met by events resulting from multihadron events or beam gas interactions. The distribution of χ^2 from the fit (fig. 2a) peaks strongly at low χ^2 showing that the background from these sources is small. Events with a χ^2 of less than 2.7 were retained. The photon energies for the remaining 114 coplanar events were computed from the fitted directions of

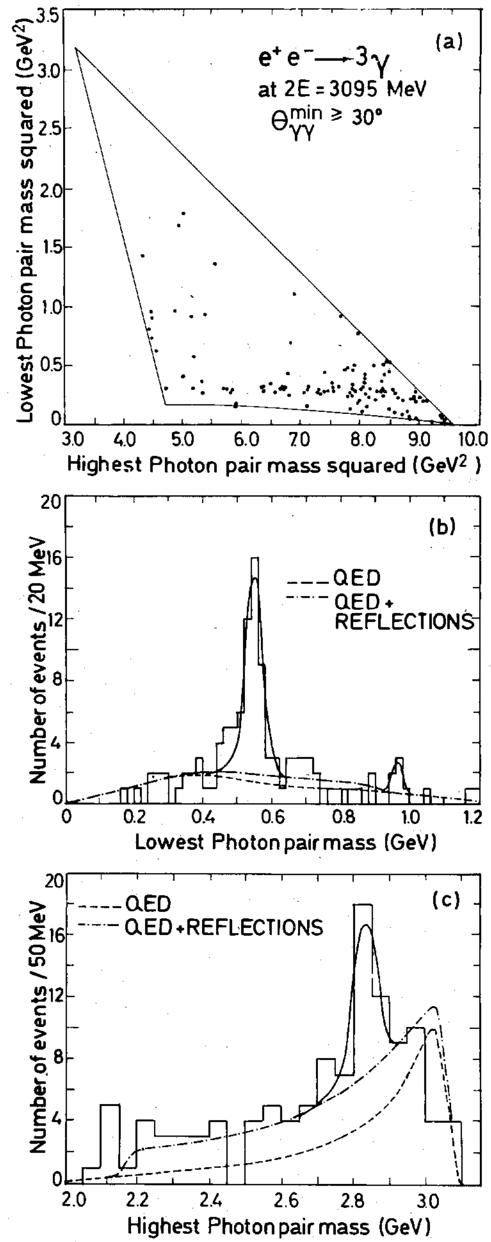

Fig. 3(a) Dalitz plot of coplanar three photon events. (b) The three photon events plotted as a function of the lowest photon pair mass observed in the event. The dashed curve is the QED contribution. The sum of the contributions from QED events and the reflections from the X(2.8) are shown as the dashed-dotted curve. (c) The three photon events plotted as a function of the highest photon pair mass observed in the event. The dashed curve represents the QED contribution. The dashed-dotted curve is the sum of the QED contribution and the reflections from the $\gamma\eta$ and the $\gamma\eta'$ decays.

the three photons and the known cms energy. In fig. 2b the events are shown in a scatter plot of the photon energy measured in the scintillation and shower counters versus the computed photon energy. These energies agree within the experimental resolution as expected for genuine three photon events with no missing energy. The effective mass of any photon pair is evaluated from the fitted directions of the photons and the computed energies. The two photon mass resolution (rms) predicted by a Monte Carlo calculation is about 20 MeV nearly independent of mass.

A three photon final state might arise from the following sources.

(1) The radiative decay [3] of the J/ψ into a state with even charge conjugation and spin different from one which subsequently decays into two photons.

(2) The radiative decay of the J/ψ directly [4] into three photons.

(3) Hard photon correction [5] to the e^+e^- annihilation into two photons.

The events are shown in Dalitz plot in fig. 3a. A cluster of events at the mass of the η, a few events consistent with η' and some events with a mass between 2.8 GeV and 2.9 GeV are visible. There are also events outside these mass bands, clustering mainly at high effective mass as expected both from QED and the direct decay of the J/ψ.

(A) $J/\psi \to \gamma\eta$ and $\gamma\eta'$. The events are plotted in fig. 3b as a function of the lowest photon pair mass observed in the event. A clear signal at the mass of the η and a few events at the mass of the η' are superimposed on a smoothly varying background.

The background expected from QED events is shown as the dashed line in fig. 3b. This contribution was evaluated using the matrix elements given by Berends and Gastman [5] as input to a Monte Carlo calculation. A similar calculation reproduces both the absolute number and the mass distribution of three photon events observed [6] at energies outside of the J/ψ and the ψ' resonances. The sum of the QED contribution and the reflections from a state with a mass around 2.8 GeV is represented by the dash dotted line in fig. 3b.

A fit was made to the mass distribution taking the background and its normalization from this calculation plus a Gaussian peak of variable mass and width. The fitted peak is shown as the solid curve. The fitted mass was 545 ± 5 MeV in good agreement with the η mass 548.8 MeV. The fitted width of 22 ± 4 MeV (rms) agrees well with the expected mass resolution of 20 MeV.

Table 1
Branching ratios for the radiative decays of J/ψ

Mode	Candidates (events)	Background (events)	Branching ratio ($\times 10^{-3}$)	Width (eV)
$J/\psi \to \gamma\pi^0$	18	9	0.073 ± 0.047	5.0 ± 3.2
$\gamma\eta$	48	8	0.80 ± 0.18	55 ± 12
$\gamma\eta'$	6	2.5	2.2 ± 1.7	152 ± 117
γX	30	14.6	0.12 ± 0.05	8.3 ± 3.5
$\gamma\gamma\gamma$	5	5.7	<0.078	<5.4

The number of events, the estimated background from QED and reflections and the integrated cross section are listed in table 1. The branching ratios, also listed in table 1, were obtained by normalizing the integrated cross section to the total integrated cross section for J/ψ production [7].

The width $\Gamma(J/\psi \to \gamma\eta) = 55 \pm 12$ eV is consistent with but lower than the value reported earlier [1]. The width $\Gamma(J/\psi \to \gamma\eta') = 152 \pm 117$ eV is in agreement with the value found [8] by identifying the η' via its $\rho\gamma$ decay mode.

The decays to η and η' proceed with rates of the same order of magnitude as the rate for the strong decay $J/\psi \to \rho^0\pi^0$ [8, 9]. The large $\gamma\eta$ and $\gamma\eta'$ decay widths might be explained by interactions violating the OZI rule [10] and introducing [3, 11] a small $c\bar{c}$ component in the physical η and η' mesons. The J/ψ and the ψ' are mainly SU(3) singlets whereas the η is mainly SU(3) octet. The similarity of the $\gamma\eta$ and $\gamma\eta'$ decay rates indicates that in this case SU(3) must be strongly broken by the $c\bar{c}$ mixing interaction.

(B) $J/\psi \to \gamma X(2.8)$. The events are plotted in fig. 3c as a function of the highest photon pair mass observed in the event. A narrow peak superimposed on a smooth background is observed between 2.8 GeV and 2.9 GeV. The background expected from QED events is shown as the dashed line. The absolute number of events expected from QED and reflections from J/ψ decay into $\gamma\eta$ and $\gamma\eta'$ is shown as the dashed-dotted line in fig. 3c. The events outside the peak region can be accounted for by these sources only.

Using the computed QED contribution and interpolating the $\gamma\eta$ and the $\gamma\eta'$ contributions between 2.8 GeV and 2.9 GeV 14 events are expected in this

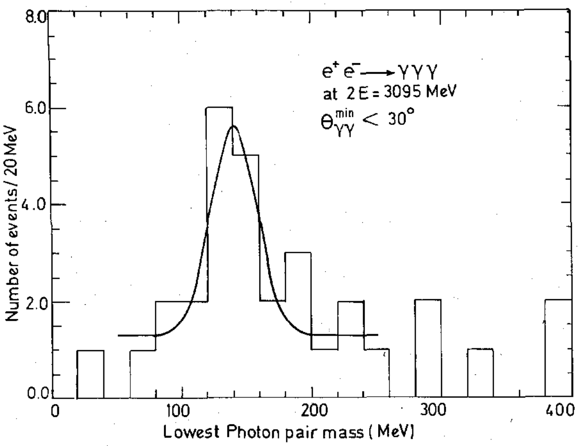

Fig. 4. Coplanar three photon events with a smallest opening angle of less than 30° plotted as function of the lowest photon pair mass.

mass region compared to the 30 events observed. This corresponds to a 4 standard deviation signal for the existence of a resonance X. A fit was made to the mass distribution taking the background and its normalization from this calculation plus a Gaussian peak of variable mass and width for the resonance. The fitted mass and width were 2.83 ± 0.03 GeV and 29 ± 14 MeV. The fitted width agrees with the expected mass resolution of 20 MeV for a narrow resonance and is inconsistent with a resonance width greater than 50 MeV (90% C.L.). From the fit we find $BR(J/\psi \to \gamma X) \times BR(X \to \gamma\gamma) = (1.2 \pm 0.5) \times 10^{-4}$. Both the mass and the product of the branching ratios are consistent with results [1] reported earlier.

The 2γ decay mode shows that the state has even charge conjugation and spin different from one. It is tempting to associate this state with the lowest pseudoscalar $c\bar{c}$ state in the charmonium spectrum [12]. However, it should be noted that this assignment is not proven by the available data.

Two candidates for the decay $J/\psi \to \gamma X \to \gamma p\bar{p}$ were reported earlier [1]. Increasing the luminosity by a factor of two failed to produce any new candidates. The 90% confidence upper limit on the product of the branching ratios $BR(J/\psi \to \gamma X) \cdot BR(X \to p\bar{p})$ is 2×10^{-4}. The observed events might result from the direct radiative decay of the $J/\psi \to \gamma p\bar{p}$.

(C) $J/\psi \to \gamma\gamma\gamma$. To search for the direct decay $J/\psi \to 3\gamma$ only events with a minimum photon pair mass larger than 1.0 GeV were considered. This cut excludes the radiative decays via the η, η' and the X(2.83). A total of 5 events is observed compared to 5.7 events predicted from QED. This leads to a 90% confidence upper limit of 3.7 events for the decay. The detection efficiency was estimated using the differential cross section evaluated by Berends and Komen [4] and the known response of the detector. A 90% confidence upper limit on the width $\Gamma(J/\psi \to 3\gamma)$ of 5.1 eV results. This limit is about a factor of two above the rate predicted [4] using the charmonium model of a found $c\bar{c}$ pair and the short range picture of the decay. In this model the rate for $J/\psi \to 3\gamma$ is proportional to the sixth power of the charge of the quark. The upper limit found is therefore well below the value predicted [4] for a quark with unit charge.

(D) $J/\psi \to \gamma\pi^0$. To search for the decay $J/\psi \to \gamma\pi^0$ a separate analysis was made relaxing the requirement that there be at least 30° between any pair of photons. This is necessary since the photons from the π^0 decay have typical opening angles between 10° and 13°. That the detector is capable of resolving nearby photons was ascertained by a measurement of the known decay $J/\psi \to \rho^0\pi^0$ which leads to photons with only slightly larger opening angles. A minimum acolinearity angle greater than 2° was required to discriminate against events of the type $e^+e^- \to \gamma\gamma$, where the spray from one of the photons fakes a third low energy photon.

The three photon events obtained in this analysis are plotted in fig. 4 as a function of the lowest mass occurring in the event. At the mass of the π^0 there is a peak with a width consistent with the experimental resolution as shown by the solid curve in fig. 4. The integrated cross section and the branching ratio are listed in table 1. The radiative width $\Gamma(J/\psi \to \gamma\pi^0) = 5.6$ eV is much smaller than the radiative decay width to η and η'. This is understandable in the $c\bar{c}$ mixing model [11] since a $c\bar{c}$ component in the π^0 is forbidden by isospin. The width $\Gamma(J/\psi \to \gamma\pi^0)$ agrees roughly with the value predicted [3] from the vector dominance model, coupling a photon to ρ^0 in the $J/\psi \to \rho^0\pi^0$.

It has been assumed in the discussion that the observed final states are direct decays of the J/ψ resonance. In principle, they might be second order radiative decays with the J/ψ transforming into a virtual timelike photon which in turn decays into the observed final state. Such decays [7], which lead to the same final states as those produced in e^+e^- collisions at nearby energies, account for 17% of the total J/ψ decay width. However, second order radiative decays are expected to yield larger cross sections for $\gamma\pi^0$ than for $\gamma\eta$ and $\gamma\eta'$, contrary to the experimental findings. Estimates of the absolute rate [13] via this mechanism yield cross sections much smaller than observed. It therefore seems likely that the observed radiative decays are indeed direct decays as assumed. However note that this is not yet proven experimentally [6].

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