OBSERVATION OF THE TWO PHOTON CASCADE 3.7 → 3.1 + $\gamma\gamma$ VIA AN INTERMEDIATE STATE P_c

DASP-Collaboration

W. BRAUNSCHWEIG, H.-U. MARTYN, H.G. SANDER, D. SCHMITZ, W. STURM and W. WALLRAFF
I. Physikalisches Institut der RWTH Aachen, Germany

K. BERKELMAN*, D. CORDS, R. FELST, E. GADERMANN, G. GRINDHAMMER, H. HULTSCHIG, P. JOOS, W. KOCH, U. KÖTZ, H. KREHBIEL, D. KREINICK, J. LUDWIG, K.-H. MESS, K.C. MOFFEIT, A. PETERSEN, G. POELZ, J. RINGEL, K. SAUERBERG, P. SCHMÜSER, G. VOGEL**, B.H. WIIK and G. WOLF
Deutsches Elektronen-Synchrotron DESY and II. Institut für Experimentalphysik der Universität Hamburg, Hamburg, Germany

G. BUSCHHORN, R. KOTTHAUS, U.E. KRUSE***, H. LIERL, H. OBERLACK, K. PRETZL, and M. SCHLIWA
Max-Planck-Institut für Physik und Astrophysik, München, Germany

S. ORITO, T. SUDA, Y. TOTSUKA and S. YAMADA
High Energy Physics Laboratory and Dept. of Physics, University of Tokyo, Tokyo, Japan

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The two photon cascade decay of the 3.7 GeV resonance into the 3.1 GeV resonance has been observed in two nearly independent experiments. The clustering of the photon energies around 160 MeV and 420 MeV observed in the channel $3.7 \to (3.1 \to \mu^+\mu^-) + \gamma\gamma$ indicates the existence of at least one intermediate state with even charge conjugation at a mass around 3.52 GeV or 3.26 GeV.

In studying the cascade transition of the 3.7 GeV resonance into the 3.1 GeV resonance we have observed the decay channel

$$3.7 \to 3.1 + \gamma\gamma \qquad (1)$$

in two nearly independent experiments. The energies of the two photons cluster around 160 and 420 MeV suggesting the cascade decay to proceed via at least one new resonance with even charge conjugation.

The measurement has been performed at the DESY electron-positron storage rings DORIS using the double arm spectrometer DASP. The DASP detector is shown in fig. 1. It consists of two identical magnetic spectrometers arranged symmetrically with respect to the colliding beams. The details of this part of the spectrometer can be found elsewhere [1]. A large-aperture non magnetic detector is mounted between the two spectrometer arms. It consists of six sectors covering about 75% of 4π. To the top and bottom sectors, described already in previous publications [2], four similar sectors have been added during the course of the experiment. Each sector consists of a scintillation counter hodoscope, a 5 mm thick lead sheet and two or three layers of proportional tubes, all repeated four times and followed by a lead-scintillator shower detector of 7 radiation lengths. In addition the beam pipe is surrounded by a layer of 22 scintillation counters.

The two experiments were carried out as follows:

* On leave from Cornell University, Ithaca, N.Y.
** Now at Hochtemperatur Reaktorbau, Mannheim.
*** On leave from the University of Illinois, Urbana, Illinois.

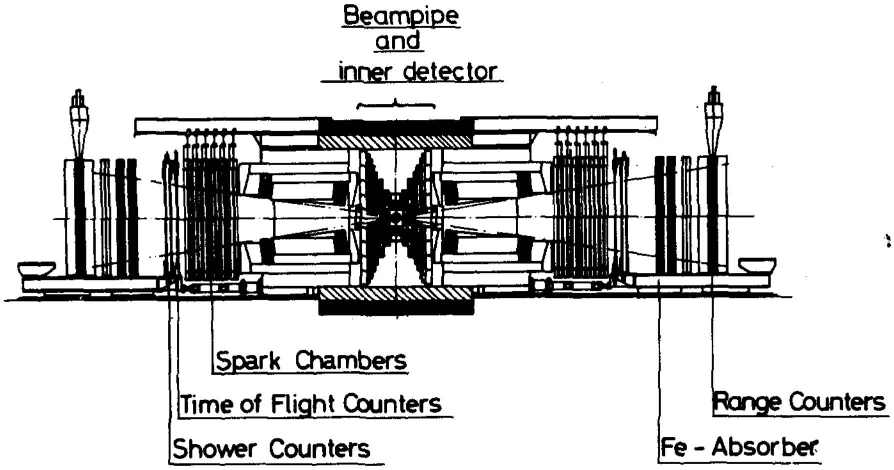

Fig. 1a. A schematic view of DASP showing the two magnetic spectrometer arms and the non magnetic detector (inner detector) mounted in the free space between the two spectrometer arms.

In the first experiment, the decay $3.7 \to 3.1 + \gamma\gamma$ was identified by measuring the two electrons from the decay of the 3.1 GeV resonance together with the two photons from the cascade, using the non magnetic detector only. The event was then completely reconstructed from the measurement of the emission angles of the four particles. In a second experiment, done concurrently with the first one, the reaction was identified by observing the decay of the 3.1 GeV resonance into a pair of muons with the magnetic spectrometers and selecting events with just two photons identified in the inner detector. The two experiments will be discussed separately.

A. $3.7 \to (3.1 \to e^+e^-) + \gamma\gamma$

Using the scanning criteria listed below events with just two electrons and two photons in the inner detector were selected.

For an electron we required:

(a) the appropriate beam pipe scintillation counter is fired.

(b) an electromagnetic shower is produced with energy greater than 700 MeV, as determined from the pulse height observed in the combined scintillator shower counter system (the loss of events due to this cut is at most a few percent).

Electron pairs in the top or bottom of the inner detector or in the horizontal part of the solid angle covered by the proportional chambers P1 and P2 were accepted. The angles of the electrons were determined to $\pm 1^\circ$.

For a photon we required:

(a) a nonzero pulse height in the shower counter (with the threshold set at 0.3 of the pulse height for a minimum ionizing particle) or at least one proportional tube and one scintillation counter fired,

(b) the appropriate beam pipe counters and front counters in the inner detector module did not fire.

Photon showers which were within 15° of the axis of the electron shower were not accepted. The angular resolution for photons is $\pm 2^\circ$ if they convert before a proportional tube chamber, and $\pm 8^\circ$ in Φ and $\pm 20^\circ$ in θ if they are detected by means of the counter hodoscope only.

Restricting the non-collinearity angle of the electrons to less than 45° we found 71 events with just two electrons and two photons as defined above. From the measured directions of the four particles and the known initial energy, a OC calculation was made yielding the momenta of the four particles. From the momenta so determined the effective mass distribution of the electron pairs was computed and is plotted in fig. 2a. The plot shows a clear peak centered at 3.1 GeV less than 200 MeV wide. This is consistent with the position and width expected for the decay:

$$3.7 \to (3.1 \to e^+e^-) + \gamma\gamma \,. \qquad (2)$$

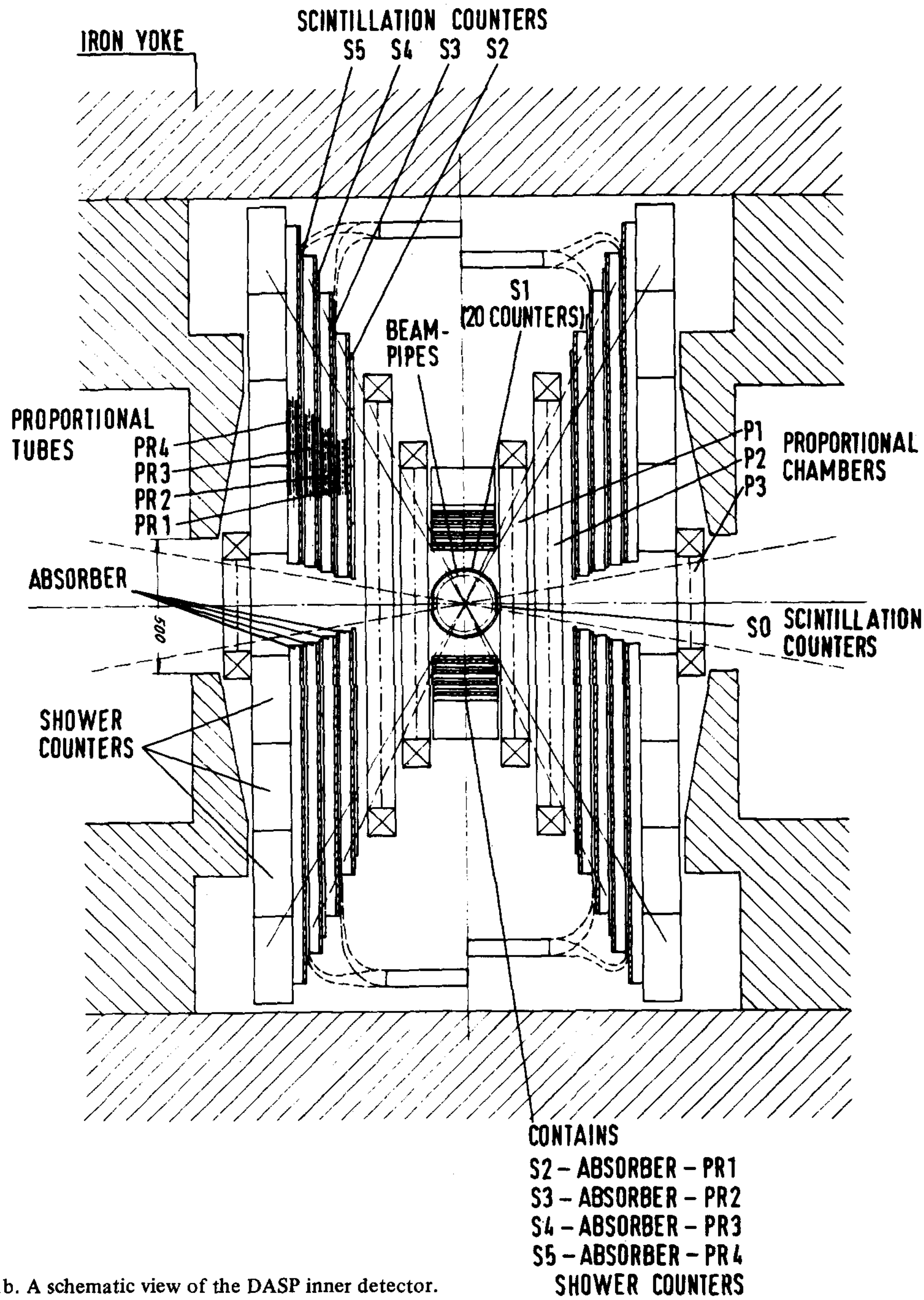

Fig. 1b. A schematic view of the DASP inner detector.

Here a Monte Carlo computation, including the measurement errors, predicts a peak at 3.1 GeV in the effective mass distribution of the e^+e^- pairs with a width of 130 MeV (FWHM).

The most serious background comes from the decay

$$3.7 \to (3.1 \to e^+e^-) + (\pi^\circ\pi^\circ)\,, \tag{3}$$

with only two of the four photons detected. The con-

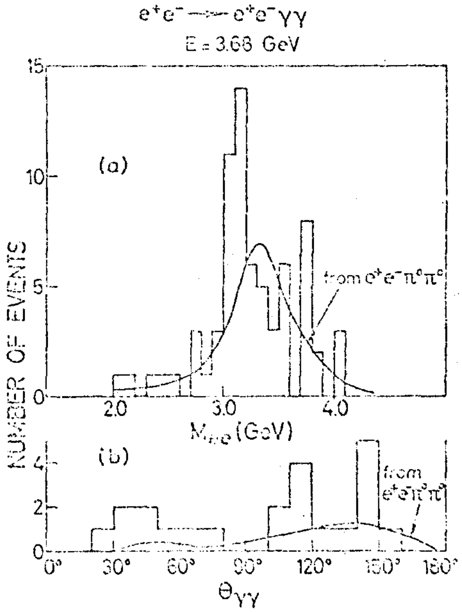

Fig. 2. Candidates for the reaction $e^+e^- \to e^+e^-\gamma\gamma$.
a) e^+e^- effective mass distribution
b) Distribution of the two-photon opening angle for events with $3.0 < M_{ee} < 3.2$ GeV.
The curves show the background from $e^+e^- \to (3.1 \to e^+e^-)\ \pi^\circ\pi^\circ$ as predicted by the Monte Carlo calculation.

tribution from this decay mode was calculated by a Monte Carlo calculation.

As an input to the Monte Carlo calculation the shape of the $\pi^\circ\pi^\circ$ mass distribution was taken to be identical to the mass distribution observed for the $\pi^+\pi^-$ pairs from the decay $3.7 \to (3.1 \to \mu^+\mu^-) + \pi^+\pi^-$ (see below). For the absolute prediction the branching ratio $\pi^\circ\pi^\circ/\pi^+\pi^-$ was assumed to be 0.5, as expected for a $\Delta I = 0$ transition. In the calculations the geometric acceptance and the measured photon detection efficiency were used. Also the measurement errors listed above were included in the computation. The shape and the magnitude of the effective e^+e^--mass distribution predicted by this calculation is plotted as the solid curve in fig. 2a. The predicted mass distribution of the e^+e^- pairs peaks at an effective mass of 3.3 GeV and is 600 MeV wide (FWHM) in disagreement with the narrow peak observed at 3.1 GeV. Neglecting the measurement errors changes neither the predicted width nor the position of the peak. We therefore conclude that the narrow peak observed at 3.1 GeV, cannot be explained by the background from the $\pi^o\pi^o$ decay mode (3). The events outside the peak, however, are all consistent with being from $\pi^o\pi^o$ decay.

The decay

$$3.7 \to (3.1 \to e^+e^-) + (\eta \to \gamma\gamma, 3\pi^o) \qquad (4)$$

with two photons detected will also contribute to the background. A Monte Carlo calculation of $3.7 \to (3.1 \to e^+e^-) + (\eta \to \pi^o\pi^o\pi^o)$ leads to a wide mass distribution of the corresponding e^+e^- pairs. Since its absolute magnitude is very small compared to the background from (3) it is neglected. The contribution from $3.7 \to (3.1 \to e^+e^-) + (\eta \to \gamma\gamma)$ corresponds to electron pairs with a well defined mass centered at 3.1 GeV. However since the η is produced nearly at rest, the angle $\theta_{\gamma\gamma}$ between the two photons from its decay will be larger than 140°. The $\theta_{\gamma\gamma}$ distribution for events in the peak between 3.0 and 3.2 GeV is shown in fig. 2b together with the Monte Carlo prediction for the background from $e^+e^-\pi^o\pi^o$. It follows from fig. 2b that only 4 events in the narrow peak at 3.1 GeV can be due to $\eta \to \gamma\gamma$. To exclude these events and also reduce the background from the $\pi^o\pi^o$ decay mode only $\gamma\gamma$ events which fulfill the conditions $3.0\ \mathrm{GeV} < M_{ee} < 3.2$ GeV, and $\theta_{\gamma\gamma} < 120°$ were considered. There remains 14 events which satisfy these criteria. The Monte Carlo computation gives a $\pi^o\pi^o$ background of 3.7 events in this sample. From the data presented above we conclude that we have observed the cascade decay $3.7 \to (3.1 \to e^+e^-) + \gamma\gamma$.

B. $3.7 \to (3.1 \to \mu^+\mu^-) + \gamma\gamma$

The decay

$$3.7 \to (3.1 \to \mu^+\mu^-) + X \qquad (5)$$

was investigated by detecting the two muons with the two magnetic spectrometers of DASP and separating the various channels X using the information from the inner detector.

Muons were positively identified by requiring one or both of the oppositely charged particles, accepted by the magnet, to penetrate 70 cm of iron. The effective mass distribution of these pairs, plotted in fig. 3, shows a peak at 3.7 GeV from the direct decay of the 3.7 GeV resonance and the contribution from QED. A second peak, centered at a mass of 3.09 GeV, results from the cascade decay via the 3.1 GeV resonance. Accepting muon-pairs with an effective mass between

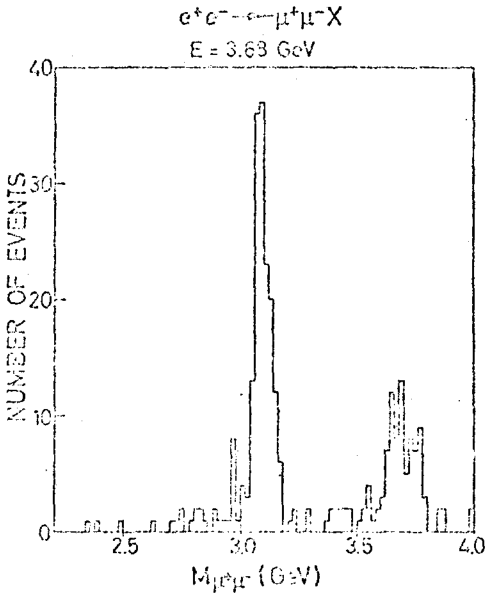

Fig. 3. Effective $\mu^+\mu^-$-mass distribution for the reaction $e^+e^- \to \mu^+\mu^- X$.

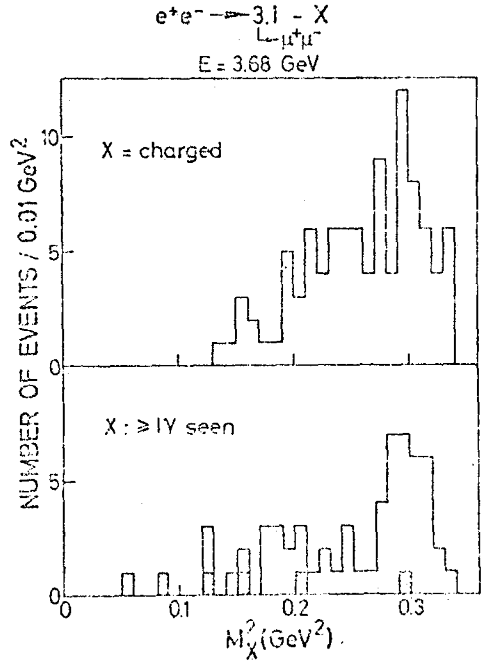

Fig. 4. The M_X^2-distribution for events of the type $e^+e^- \to \mu^+\mu^- X$ with 2.9 GeV < $M_{\mu^+\mu^-}$ < 3.2 GeV for
a) only charged particles observed in the inner detector
b) at least one photon detected in the inner detector. The shaded histogram shows the events of the reaction 3.7 → (3.1 → $\mu^+\mu^-$)$\gamma\gamma$.

2.9 GeV and 3.2 GeV yields 164 events.

Using the information from the inner detector these events are split into two groups: The one group contains only charged particles, in the second group at least one photon must be observed. The distribution of the events as a function of their mass squared recoiling against the 3.1 GeV state was computed from the known muon momenta and is plotted for the two classes of events in fig. 4a and 4b. In this calculation the effective mass of the muon pair was constrained to be 3.09 GeV.

Candidates for the reaction

$$3.7 \to (3.1 \to \mu^+\mu^-) + \gamma\gamma \qquad (6)$$

were selected from the 164 events by requiring just two photons in the inner detector. Twelve such candidates were found. The energies of the two photons were calculated from the energy $E_{3.1}$ and momentum $\boldsymbol{P}_{3.1}$ of the 3.1 GeV resonance and the measured direction of the two photons, where

$$\boldsymbol{P}_{3.1} = \boldsymbol{P}_{\mu_1} + \boldsymbol{P}_{\mu_2} \quad \text{and} \quad E_{3.1} = \sqrt{(3.09)^2 + P_{3.1}^2}\ .$$

For genuine events of reaction (6) the missing energy

$$\Delta E = E_{3.7} - E_{3.1} - E_{\gamma_1} - E_{\gamma_2}$$

and the angle $\Delta\theta$ between the momentum vector of the 3.1 GeV resonance and the plane spanned by the directions of the two photons should be zero, within experimental uncertainties. For the twelve candidates the errors in $\Delta\theta$ and ΔE were computed event by event. Five events were within 2σ of $\Delta\theta = \Delta E = 0$ and were taken to be genuine $\gamma\gamma$ events. The $\gamma\gamma$ effective mass spectrum for the five events is shown as the black squares in fig. 4b. One of the five events has a mass M_X = (0.543 ± 0.010) GeV and is therefore likely to be due to the decay:

$$3.7 \to (3.1 \to \mu^+\mu^-) + (\eta \to \gamma\gamma)\ .$$

In the remainder we have demanded $M_X < 0.450$ GeV in order to eliminate a possible η contribution.

The background resulting from the $\pi^0\pi^0$ decay mode was evaluated by a similar Monte Carlo calculation as described above, with the e^+e^- detection efficiency replaced by the $\mu^+\mu^-$ detection efficiency. It was checked by comparing the predicted yield of the

$\pi^0\pi^0$ decay mode for 0, 1, 2, 3 or 4 of the photons detected in the inner detector with the experimental data. The results are listed in table 1.

Table 1

Number of photons detected:	0	1	2	3	4
Monte Carlo	: 8.8	12.7	8.2	2.2	0.2
Observed	: 5	19	8	4	0

The Monte Carlo calculation predicts a background distributed rather uniformly in $\Delta\theta$ and ΔE with a density consistent with that observed for the rejected events. The calculated background of 0.2 events is to be compared with the 4 events found within the same cuts on ΔE, $\Delta\theta$ and M_X. A 2C fit was made to the remaining four events in order to improve on the determination of the photon energies. The resulting photon energies and the effective masses of the photon pairs are listed in table 2. We observe that the events cluster in a narrow band of photon energies around 160 MeV and 420 MeV.

Table 2

Event#	E_{γ_1}(MeV)	E_{γ_2}(MeV)	$M_{\gamma\gamma}$(MeV)
1	179 ± 53	408 ± 53	291
2	167 ± 16	404 ± 16	449
3	156 ± 23	406 ± 21	354
4	96 ± 22	463 ± 31	396

From the rate observed in $3.7 \to (3.1 \to e^+e^-) + \gamma\gamma$ we would expect to find 3 such events.

Conclusions: We have observed the decay $3.7 \to 3.1 + \gamma\gamma$ in two experiments. The observed tendency for the photon energies to cluster around 160 and 420 MeV strongly suggests that the $\gamma\gamma$ decay takes place in two stages via an intermediate particle, for which we suggest the name P_c:

$$3.7 \to P_c + \gamma$$

$$P_c \to 3.1 + \gamma\,.$$

The simultaneous emission of the two photons in a direct decay would produce photon pairs with a spectrum of energies, and would be expected to be very weak (of order α^2) relative to the strong mode $3.7 \to 3.1\ \pi^+\pi^-$. Since we have not determined whether the 160 or the 420 MeV photon is emitted first, the mass of the P_c is ambiguous:

$$m_{P_c} = 3.52 \pm 0.05 \text{ GeV}$$

or

$$m_{P_c} = 3.26 \pm 0.05 \text{ GeV}\,.$$

A very preliminary evaluation leads to a branching ratio $(3.7 \to P_c\gamma \to 3.1\ \gamma\gamma)/(3.7 \to \text{all})$ between 2% and 12%. Comparing the result of this experiment with the experimental limits on a monochromatic photon line [3], suggests the radiative decay mode $P_c \to 3.1 + \gamma$ to be a major decay mode of the new resonance.

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