FIRST OBSERVATION OF PHOTON–PHOTON INTERACTIONS AT DORIS ☆

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With a forward tagging system and the BONANZA detector we observed 24 $e^+e^- \to e^+e^-e^+e^-$ events in agreement with the expected number from QED. We observed no $e^+e^- \to e^+e^-$ + hadrons event, and present an upper limit for the partial width $\Gamma_{\eta' \to \gamma\gamma}$ of 11.5 keV (95% CL) which is evidence against the Han–Nambu quark model.

The investigation of photon–photon interactions (fig. 1) at e^+e^--storage rings was suggested quite early [1]. First experimental observations of these processes were reported from Novosibirsk [2] and, using the tagging technique, from Frascati [3]. We present here results from the measurements of photon–photon interactions at the storage ring DORIS. The experiment was performed using a tagging system to detect the forward going electrons and positrons, and the BONANZA detector for he products of the $\gamma\gamma$-interaction. A general view of the central detector is given in fig. 2. Its innermost part consists of a 5 cylinder proportional chamber system with a two-dimensional readout, followed by 3 rings of scintillators. All counters are equipped with phototubes at both ends, so accurate time and position measurements were possible. The detector was originally designed to detect antineutrons and antiprotons by their annihilation in the second ring, which is therefore 20 cm thick. The deposited energy in these annihilation counters was measured. The bunch crossing times were derived from the DORIS rf. This arrangement of counters, in combination with one radiation length of lead after the third

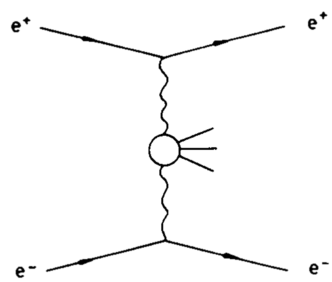

Fig. 1. $\gamma\gamma$-interaction.

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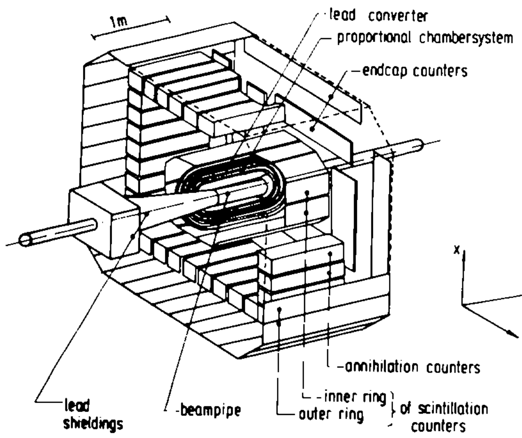

Fig. 2. BONANZA detector.

proportional chamber, is well suited for discriminating electrons and photons from other particles. A more detailed description of the detector is given in ref. [4].

The DORIS tagging system (fig. 3) is based on the fact that because of the vertical crossing angle, the beams pass through the large quadrupoles WQ1 and WQ2 off center. So these quadrupoles, together with

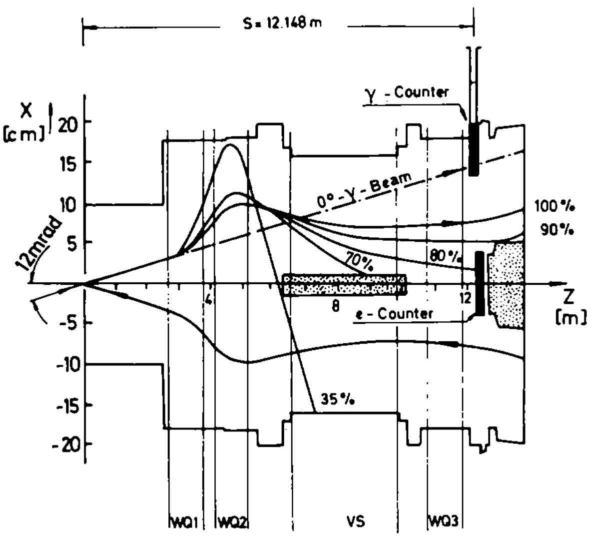

Fig. 3. The tagging system of DORIS. Particle trajectories for different fractions of beam energy are shown. Note the different horizontal and vertical scales.

the homogeneous septum magnet VS, are used as a magnetic spectrometer [10]. The electrons and positrons were each detected by a shower counter (e-counter), mounted in the beam pipe 12 m downstream from the interaction point, about 6×8 cm^2 and 10 radiation lengths thick. The shower counter provided us with energy and time information. A similar counter (γ-counter) was used to veto beam–gas bremsstrahlung events.

The counting rates of the tagging counters were – depending on the residual gas pressure and the current in the machine – between 14 and 23 kHz for positrons and between 52 and 123 kHz for electrons (600 MeV threshold). The thresholds for the tagging counters were below the lowest energies (1.53 GeV) accepted by the magnetic spectrometer. In the "off-line" analysis of the data these thresholds were set to 1 GeV.

To determine the acceptance of the tagging system we performed a Monte-Carlo calculation. The angular distribution has a very sharp peak in the forward direction and was calculated in the equivalent photon approximation [6]. The track following through the magnet system was done using a Runge–Kutta method. The important parameters in these calculations are the vertical position of and the beam inclination at the interaction point, together with the field parameters which were always available from the automatic bookkeeping system of DORIS. The interaction point position was determined with the proportional chamber system. The beam inclination was measured with the moveable γ-counters. We found that electrons or positrons with 73%–82% of beam momentum and up to 10 millirad scattering angle were detected [8].

The luminosity was measured in the usual way by small angle Bhabha scattering [9].

The trigger was derived from the BONANZA detector only and required

either: a deposited energy of 84 MeV, i.e. twice the minimum ionization, in one of the annihilation counters, together with either a coincidence in an opposite lying counter, or $\geqslant 2$ central charged tracks in the proportional chambers;

or: $\geqslant 3$ central charged tracks, depositing at least 20 MeV in the annihilation counters.

For the purpose of the experiment reported here this trigger, which had been optimized for another experiment [4], was sensitive mainly to electrons and photons.

If one of the above conditions was fulfilled, the information of both the central detector and the tagging system was recorded on tape.

We took data at beam energies of 2.1, 2.24 and 2.6 GeV and accumulated a total integrated luminosity of 1457 nb^{-1}. We recorded 4.6 million triggers which reduced to 2.2 million after rejection of obvious cosmic ray events. Among them were 54000 single tagged events, i.e. coincides of the central detector with one tagging counter, and 214 double tagged events where both tagging counters had been hit.

The time information from the central and tagging detectors allowed us to determine the interaction time differences, i.e. the time differences between the photon emission of a tagged electron or positron and the bunch crossing immediately before the central detector event. The resolution for this time difference was 0.7 ns FWHM. Fig. 4 shows the distribution for the single tagged event sample. The central peak contains the genuine events, a large number of beam-gas events, and some accidental background. Due to the bunch structure of DORIS, this accidental background has peaks with a separation of 8 ns. The slightly enlarged peak at −8 ns is caused by beam-gas events with very slow reaction products which were therefore assigned to the next bunch crossing.

After rejecting events incorrect by more than 1 ns, 11000 events remain. Most of these events come from electroproduction off the gas molecules in the beam pipe and have consequently the correct timing. Because of this serious background we searched in this sample for events of the type $e^+e^- \to e^+e^-e^+e^-$ only.

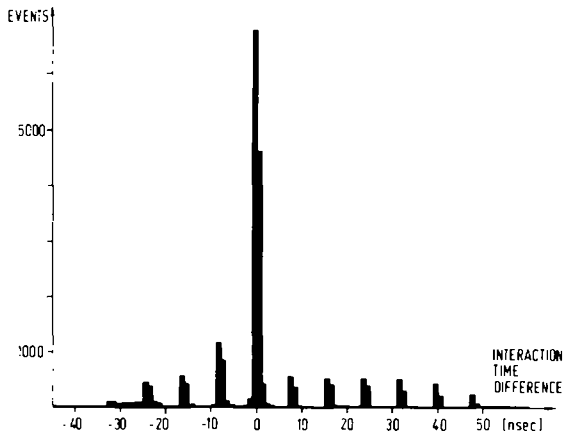

Fig. 4. Interaction time difference distribution for all single tagged events.

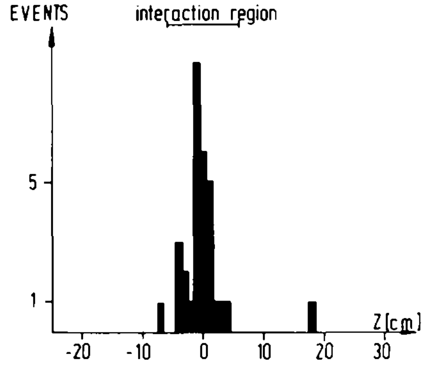

Fig. 5. z-distribution for the single tagged events showing at least one showering track.

We therefore looked for events which had two nearly collinear tracks in the x, y projection (see fig. 2), at least one of them satisfying shower conditions in the annihilation counters. From the 11000 events above, 31 satisfy this requirement. The distribution of these events along the beam is shown in fig. 5. The peak in the interaction region contains 29 events above a small background of 0.4 ± 0.2 events. The application of the same conditions to the neighbouring bunches from fig. 4 showed that these 29 events contain an additional background of 4.8 ± 1 events from accidental coincidences. These are all large angle e^+e^--pairs from Bhabha scattering and their number is in good agreement with the calculated accidental coincidence rate. So 24 genuine $e^+e^- \to e^+e^-e^+e^-$ events with one tagged electron or positron were measured with an error of ±5.8 events.

The electron and positron interaction time differences of the 214 double tagged events are plotted against each other in fig. 6. A double periodic structure with 8 ns period (i.e. bunch separation) can be seen. The "cross" consists mainly of electroproduction events on the residual gas with an accidential coincidence in the other tagging counter. All genuine $\gamma\gamma$-events should have both interaction time differences smaller than 1 ns. Only 10 events satisfy this condition. The background due to electroproduction estimated from the plot in fig. 6 is 4.5 events. Indeed, from the 10 events lying in the ±1 ns window we find 3 electro-

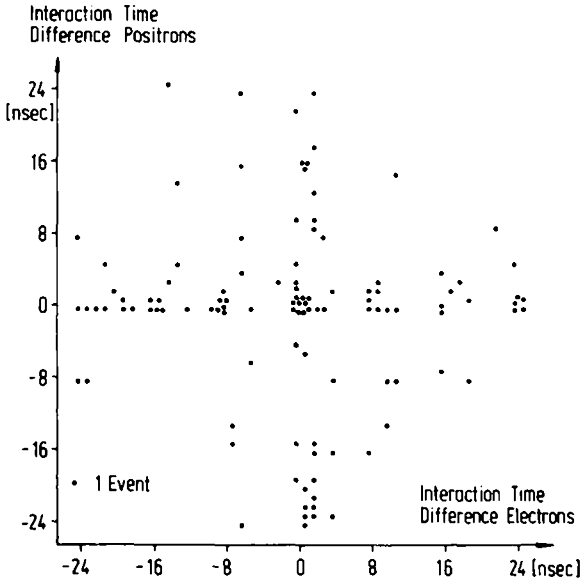

Fig. 6. Two-dimensional interaction time difference distribution for the double tagged events.

production events not coming from the interaction region. This agrees with the background estimation. The background from other sources is negligible.

Thus, in the case of double tagged events, only the time coincidence condition is required to yield a fairly clean sample of $\gamma\gamma$-events.

The 7 events coming from the interaction region are all two-prongs which are nearly collinear in the x, y projection and show a shower in at least one track. So we conclude that all 7 double tagged events we observed, are due to the fourth order QED reaction $e^+e^- \to e^+e^-e^+e^-$.

The detection probability for large angle e^+e^--pairs in the BONANZA detector was calculated, using a comprehensive Monte-Carlo shower program [4,5,8]. This program was tested by measuring and calculating large angle Bhabha and $e^+e^- \to \gamma\gamma$ events at energies of about 3.1 and 4.2 GeV. Good agreement within 10% was found. The QED cross section was computed in the Weizsäcker–Williams approximation [6]. A summary of the luminosities, acceptances and measured and calculated QED event rates, is given in table 1. The QED results are in good agreement with our measurements for both single and double tagged events.

In the case of double tagged events we know that

Table 1
The lower acceptance of the single tag events is caused by more restrictive conditions for the selection of these events. The quoted errors for the expected numbers of events reflect the accuracies of the tagged momentum window.

beam energy [GeV]		2.1	2.24	2.6
tagged $\gamma\gamma$-CMS energy [GeV]		0.76 -1.13	0.81 -1.21	0.94–1.40
integrated luminosity $\int L dt$ [nb^{-1}]		242	499	716
acceptance for events satisfying the geometrical constraints of the central and tagging detector	$e^+e^- \to e^+e^-e^+e^-$ double tag	73%	80%	81%
	$e^+e^- \to e^+e^-e^+e^-$ single tag	41%	47%	49%
QED cross sections in the geometrical acceptance of the central and tagging detector	$e^+e^- \to e^+e^-e^+e^-$ double tag	5.2 pb	4.7 pb	3.8 pb
	$e^+e^- \to e^+e^-e^+e^-$ single tag	34.0 pb	30.1 pb	24.4 pb
expected number of events	$e^+e^- \to e^+e^-e^+e^-$ double tag		5.0 ± 0.5	
	$e^+e^- \to e^+e^-e^+e^-$ single tag		18.9 ± 0.6	
observed number of events	$e^+e^- \to e^+e^-e^+e^-$ double tag		7 ± 2.7	
	$e^+e^- \to e^+e^-e^+e^-$ single tag		24 ± 5.8	

we have not recorded any $\gamma\gamma$-event with hadrons in the final state. Our trigger was sensitive to hadronic final states containing many charged particles or at least one photon. The η' decays mainly to such final states and its mass is well covered by our $\gamma\gamma$-CMS energy window at beam energies of 2.1 and 2.24 GeV. Therefore it should be seen in our apparatus. The trigger probability for the η' in the central detector has been calculated with our Monte-Carlo program [5] and was found to be 14.2 ± 1% and only slightly dependent on the beam energy. The crucial parts of this computation were also performed with the EGS-program ‡1 and led to the same results. The fact that we observe no η' event in the double tagged event sample leads to a new upper limit for its $\gamma\gamma$-decay width: $\Gamma_{\eta'\to\gamma\gamma} < 11.5$ keV with 95% confidence level [15] ‡2.

As pointed out in ref. [7], the $\gamma\gamma$-width of the η' meson is particularly sensitive to the quark charge assignment. For the fractionally charged (Gell-Mann) and the integer charged (Han–Nambu) quarks this width is

$$\Gamma_{\eta'\to\gamma\gamma}^{\text{Han-Nambu}} = 25.6 \text{ keV}, \quad \Gamma_{\eta'\to\gamma\gamma}^{\text{Gell-Mann}} = 6 \text{ keV}.$$

The big difference between them is mainly caused by the properties of the SU(3) singlet amplitude which dominates η'. The SU(3) octet amplitude leads to no differences between both models as in the π^0-case. Since the new analyses of pseudoscalar meson decays [11–13] confirm the SU(3) singlet dominance of $\eta'(958)$ we conclude that our upper limit is evidence against the Han–Nambu quark model.

We acknowledge the help of many colleagues. We especially thank the DORIS crew for their cooperation and Professor W. Paul for his continued support. We also thank Professor P. Waloschek for drawing our attention to the tagging system of DORIS.

‡1 EGS: The HEPL–SLAC–Monte Carlo Electron Gamma Shower Program, see ref. [14].

‡2 We note that our upper limit combined with the measured branching ratio $\Gamma_{\gamma\gamma}/\Gamma_{tot}$ [16] gives an independent but somewhat larger upper limit for the total η' width [17]. Due to the experimental errors of $\Gamma_{\gamma\gamma}/\Gamma_{tot}$ and uncertainties of Γ_{tot} it is not possible from their measurements to give an upper limit for $\Gamma_{\eta'\to\gamma\gamma}$ which excludes the Han–Nambu model.

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