of this work, and to acknowledge the cooperation of the Computer Science Center of the University of Maryland where the calculations were performed.

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†Alfred P. Sloan Foundation Fellow.

[1]A strong correlation of E_T and a_2 was first noted by A. C. Phillips, Nucl. Phys. A107, 209 (1968), and has been extensively corroborated by a multitude of subsequent authors. The form-factor minimum is somewhat ambiguous because of unknown exchange corrections, but a correlation with E_T is suggested by the phase-equivalent calculations of M. I. Haftel, in *Few Particle Problems in the Nuclear Interaction*, edited by I. Šlaus, S. A. Moszkowski, R. P. Haddock, and W. T. H. Van Oers (Elsevier, New York, 1973). Unfortunately, the trend here is opposite to what one would wish.

[2]W. M. Kloet and J. A. Tjon, Nucl. Phys. A210, 380 (1973).

[3]D. D. Brayshaw, Phys. Rev. D 8, 952 (1973); hereafter we shall refer to this as BC1. Although mathematically distinct, this work owes much in spirit to the earlier development of H. P. Noyes, Phys. Rev. D 5, 1547 (1972).

[4]A preliminary investigation of this model for a system of three spinless particles, together with a discussion of appropriate numerical techniques, may be found in D. D. Brayshaw, Phys. Rev. D 8, 2572 (1973).

[5]An alternative choice would have been to fix E_T. However, in the absence of tensor components in this model, taking a_2 as the standard seemed more appropriate. The actual curves for $k \cot\delta$ produced are identical with those obtained in a simple model calculation; see D. D. Brayshaw and B. Buck, Phys. Rev. Lett. 24, 733 (1970).

[6]G. Barton and A. C. Phillips, Phys. Lett. 28B, 378 (1969).

[7]W. M. Kloet and J. A. Tjon, in *Few Particle Problems in the Nuclear Interaction*, edited by I. Šlaus, S. A. Moszkowski, R. P. Haddock, and W. T. H. Van Oers (Elsevier, New York, 1973).

[8]M. Jain, J. G. Rogers, and D. P. Saylor, Phys. Rev. Lett. 31, 838 (1973).

[9]One might also question whether variations in the vicinity of such an interference minimum will not be washed out by small components which one can usually ignore, such as higher partial waves in the two-body force.

[10]In this discussion we have not dealt with the spin observables; however, model calculations do not indicate a sensitivity to off-shell effects. See, for example, I. H. Sloan and J. C. Aarons, Nucl. Phys. A198, 321 (1972). Also, although this analysis has been restricted to energies less than 30 MeV, the continued success of simple separable models at much higher energies would seem to preclude much off-shell sensitivity; see J. M. Wallace, Phys. Rev. C 7, 10 (1973).

[11]D. D. Brayshaw, Phys. Rev. C 7, 1731 (1973).

[12]The Phillips correlation was maintained in this analysis to within a shift of 0.4 MeV in E_T, which is comparable to estimates of relativistic corrections. Underlying this conclusion is the assumption of a detailed fit to the two-nucleon data; one must impose all constraints *simultaneously*. A possible exception is the charge form factor, which *may* be capable of discriminating between such alternatives if exchange corrections are unimportant.

Muon Pair Production by Photon-Photon Interactions in e^+e^- Storage Rings

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The photon-photon interaction has been investigated by e^+ and e^- collisions at about 2.7-GeV total energy. Evidence based on 34 well-identified events has been obtained for the process $e^+e^- \to e^+e^-\mu^+\mu^-$, hitherto unobserved. Such a process is found to occur in agreement with theoretical predictions based on the equivalent-photon approximation. Results on 74 events from the process $e^+e^- \to e^+e^-e^+e^-$ are also reported.

Electron colliding beams provide a means, at present unique, for investigating the photon-photon interaction at high energy, as pointed out by many authors.[1] In the present experiment the outgoing $e^{+,-}$ are detected at very small angles with respect to their incident directions, in coincidence with other particles produced at wide angles (WA particles). This arrangement selects events in which two "quasireal" photons, γ^*, are emitted and annihilate according to the reaction

$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X, \quad (1)$$

where X is a system with $C=+1$. In our experiment X is a pair of WA particles present in the final state as a result of one of the annihilation processes:

$$\gamma\gamma \to \mu^+\mu^-, \quad (2)$$

$$\gamma\gamma \to e^+e^-, \quad (3)$$

$$\gamma\gamma \to \pi^+\pi^-. \quad (4)$$

These particles, emitted at angles θ_1, θ_2, with momenta p_1, p_2, are detected by a system of two WA telescopes as sketched in Fig. 1.

The experiment has been carried out with the Frascati e^+e^- storage ring, at Adone,[2] in runs performed at an average total energy $(E_+ + E_- = 2E = s^{1/2})$ of 2.7 GeV, for an integrated machine luminosity $\int L\,dt = 290\ \text{nb}^{-1}$. The results consist of 34 well-identified events corresponding to process (2), 76 events corresponding to process (3), and 2 candidates for process (4).

The experimental results on processes (2) and (3) agree with the theoretical predictions based on the equivalent-photon approximation (EPA).[1]

The forward-emitted electron and/or positron are recorded by "tagging counters," as also shown in Fig. 1. The tagging technique adopted[3] utilizes the machine bending magnet as a momentum analyzer. The momentum of the e^+ and/or e^- is determined with a typical accuracy of ± 5% by measuring the propagation time of the scintillation light. The tagging counter system accepts $e^{+,-}$ scattered with energy from $0.2E$ to $0.85E$. The (geometric) detecting efficiency ϵ, as calculated assuming EPA, increases from ~0.35 at $0.2E$ to ~0.6 at $0.65E$. Its average value in this interval is $\bar{\epsilon} = \sim 0.5$.

In the WA apparatus[4] two thin-foil spark chambers placed near the machine vacuum chamber are used for kinematical reconstruction of the events. All other track detectors (thick-plate chambers) are used to observe particle stops, or nuclear interactions, or the development of electromagnetic showers.

The basic requirements for the selection of the events are (i) presence of two single tracks, one in each of the two kinematical chambers, converging in the e^+e^- interaction region; (ii) time coincidence, within about ± 10 nsec, with the instant of beam-beam collision; (iii) coincident pulse in at least one of the two tagging counters; (iv) penetration of the WA particles in the WA telescopes as specified in Table I.

The selected events are subdivided into two categories: (1) singly tagged (ST) events, and (2) doubly tagged (DT) events. The $\gamma\gamma \to \mu^+\mu^-$ events (below called μ events for briefness) are searched for among those events which show no shower or nuclear interaction in the thick plate chambers. The $\gamma\gamma \to e^+e^-$ events (e events) are searched for among those which do exhibit an electromagnetic shower in at least one of the two WA telescopes.

We have recorded fourteen DT-μ candidates, of which ten had at least one track stopping in the WA telescopes. Identification of these ten events as μ events is based primarily on the distribution of the quantity

$$\Delta K = K_{\text{rec}} - K_{\text{meas}},$$

where K_{meas} is the photon momentum as derived

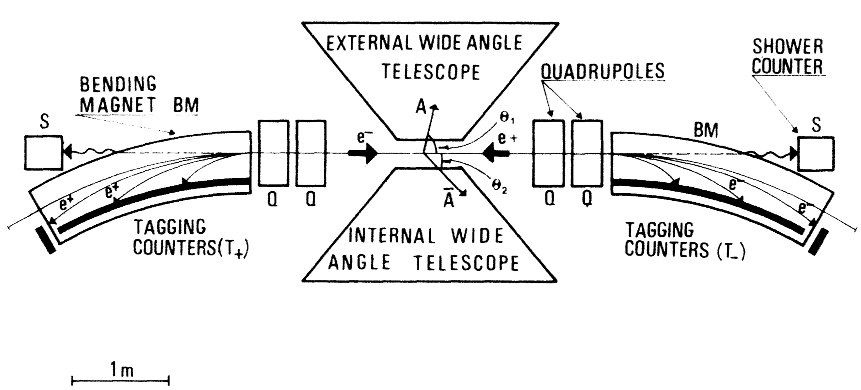

FIG. 1. Schematic view of the general setup. The "shower counters," S, were used to veto events involving photons from real bremsstrahlung. A and $\bar{A}$ are WA particles.

TABLE I. Minimum particle penetration required in the WA telescopes (expressed in g/cm^2 of iron equivalent) for various types of events.

Event type	Penetration in one telescope	Penetration in other telescope
DT-μ	40	10
ST-μ	40	40
DT-e	40	10
ST-e	40	22

from the tagging-counter information and K_{rec} is the value of the same quantity obtained from a kinematical reconstruction. The latter is based on angle and range measurements of the WA particles, *assumed to be muons*. The ΔK distribution reported in Fig. 2(a) indeed shows a peak about $\Delta K = 0$ as expected if the events were correctly identified. Process (4) can give at most a contamination of 0.7 events to the fourteen DT-μ events, as estimated starting from the two observed $\gamma\gamma \to \pi^+\pi^-$ candidates.

Further evidence of the correct identification comes from the ΔK distribution of the ST-μ candidates reported in Fig. 2(b). For these events we require that both WA tracks stop in the WA telescopes, so that we have one-constraint events. It is seen from Fig. 2(b) that twenty out of the 56 recorded candidates cover essentially the same region as the DT-μ event distribution. They are interpreted as "good" μ events ($\gamma\gamma \to \mu^+\mu^-$). The remaining 36 events, on the other hand, exhibit a rather flat distribution in ΔK, clearly separated from the former one. These 36 events are interpreted as "background" events which originated in beam-gas collisions. This interpretation is supported by the results of the background runs, carried out with separated e^+ and e^- beams, in which seven events were recorded. These last events have indeed the ΔK distribution shown in Fig. 2(c) and their number (seven) is consistent with the previous 36 background events, if allowance is made for a normalization factor of ~4.5.

The momentum distribution of the quasireal photons relative to the DT-μ events is shown in Fig. 3(a) (full line).

Simultaneously with the μ events we have collected also the e events, as first observed at Novosibirsk.[5] No event of the e type was observed during the background runs. Within the energy error $\pm\delta K_{(+,-)}$ the twelve DT-e events are

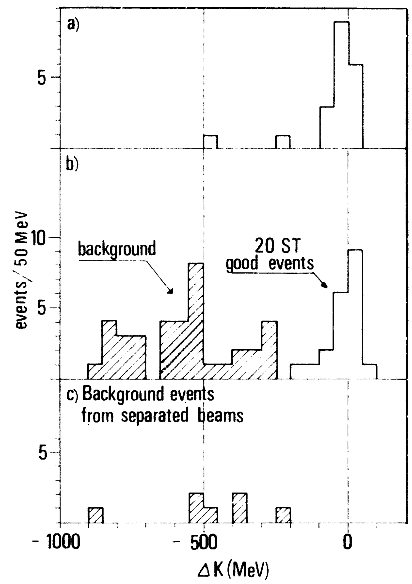

FIG. 2. $\Delta K = K_{rec} - K_{meas}$ distribution (a) for ten DT-μ events; (b) for 56 ST-μ events; (c) for seven ST background μ events obtained with separated e^+ and e^- beams. 36 of the 56 ST events in (b) can be interpreted as background events. Of course each doubly tagged event contributed two points to the ΔK distribution.

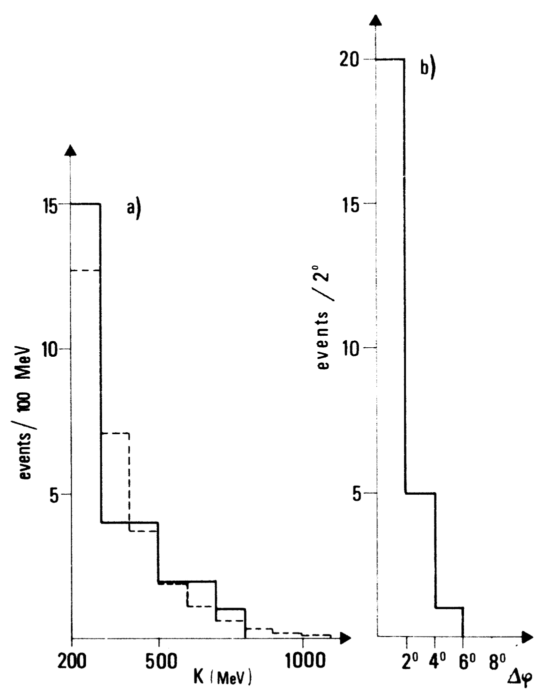

FIG. 3. (a) Photon momentum distribution relative to the DT-μ events. The dashed line is derived from a Monte Carlo calculation based on the equivalent-photon approximation. (b) Acoplanarity angle distribution for all recorded DT events. For the distribution (a) each doubly tagged event is plotted twice (as in Fig. 2).

TABLE II. Comparison between numbers of observed and expected events. The numbers in brackets indicate systematic errors.

Type of event	Expected number	Observed number
DT-μ	10.9 ± 1	14 ± 4
ST-μ	27.9 ± 2.6	20 ± 5
(ST + DT)-μ	38.8 ± 3	34 ± 6
DT-e	8.0 ± 1	12 ± 4
ST-e	41 ± 5	$49 \pm (6) \pm 7$
(ST + DT)-e	49 ± 5	$61 \pm (6) \pm 8$
(ST-e)[a]	18 ± 9	$15 \pm (6) \pm 4$

[a]e events involving a deeply virtual photon (Refs. 6 and 7).

found to fulfill the relationship

$$\beta = \frac{K_- - K_+}{K_- + K_+} = \frac{\sin(\theta_1 + \theta_2)}{\sin\theta_1 + \sin\theta_2}, \tag{5}$$

where β is the c.m. velocity and $K_{(+,-)}$ the energy of the photon emitted by the $e^{+,-}$ scattered into the tagging counter.

Equation (5) holds for any event involving WA particles of rest energy much smaller than their kinetic energy. For the ST-e events we use then Eq. (5) to derive the energy K_x of the photon associated with the undetected electron, with an uncertainty of $\pm\,\delta K_x$. For 43 out of the 64 ST-e events we found that, as expected, $0 \leq K_x \pm \delta K_x \leq E$. These 43 events are interpreted as $\gamma\gamma \to e^+e^-$ events with two "quasireal" photons. Another nine events do not fulfull the above inequalities, yielding $K \pm \delta K > E$. They are interpreted as due to bremsstrahlung of one of the primary electrons, $e^{+,-}$, followed by conversion into a pair, a member of which undergoes an elastic scattering with the other primary, $e^{-,+}$. For this process one of the photons is deeply virtual. These events, first observed at Adone by the "$\gamma\gamma$" group[6] and interpreted as above by Caribbo and Parisi,[7] occur in a kinematical configuration with both the forward-emitted particles scattered towards the same tagging counter.

The remaining twelve events cannot be classified unambiguously since, because of the experimetal error $\pm\,\delta K$, we cannot establish whether the quantity $E - (K \pm \delta K)$ is positive or negative, giving a systematical error that adds to the statistical one.

The angular acceptance of the tagging counters sets an upper limit of nearly 10 MeV/c for the transverse momentum of the recorded $e^{+,-}$. This implies that for DT events of any type it is not possible to have acoplanarity angles $\Delta\varphi$ larger than $\sim 3°$. The $\Delta\varphi$ distribution of all recorded DT events is reproduced in Fig. 3(b) and it is seen to be essentially within the expected limit.

By a Monte Carlo simulation of the experiment based on the EPA, we have deduced the expected numbers of DT and ST μ and e events reported in Table II. For the ST e events with a deeply virtual photon, a "hand" calculation gives the results reported in the last line of the table.

We conclude that the experimental observations of the processes (2) and (3) are in good agreement with those expected on the basis of EPA and that the $\gamma\gamma$ interaction can be efficiently studied with electron storage rings.

We wish to thank the Adone group for efficient collaboration during the running time.

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[7]N. Cabibbo and G. Parisi, private communication.