and the angular distribution in the very forward direction change very little with target size and the nuclear effects seem to come mainly from the particles produced in the backward direction but without much change in their angular distributions. Thus we see that nuclear phenomena at high energy may allow a glimpse of the underlying dynamics that cannot be seen directly in free-$p$-$p$ collisions. We are confident that nuclear studies at higher energies shall surely provide important insight into strong-interaction dynamics.

We are very grateful to Professor K. Gottfried for a useful discussion and for sending us his paper before its publication. We are also very thankful to the staff of the National Accelerator Laboratory and particularly to Dr. L. Voyvodic for their valuable help with the 200-GeV exposure.

*Work supported by the Research Corporation.

†Permanent address: Ball State University, Muncie, Ind. 47306.

[1]P. L. Jain, H. C. Glahe, J. D. Rinaldo, and P. D. Bharadwaj, Nuovo Cimento 32, 872 (1964).

[2]P. L. Jain, H. C. Glahe, G. N. Srivastova, and P. D. Bharadwaj, Nuovo Cimento 21, 859 (1961).

[3]P. L. Jain, Phys. Rev. 125, 679 (1962), and Nuovo Cimento 24, 565 (1962); A. Barkow, B. Chamany, D. Haskin, P. L. Jain, E. Lohrman, M. Teucher, and M. Schein, Phys. Rev. 122, 617 (1961).

[4]P. L. Jain, M. Kazuno, Z. Ahmad, B. Girard, G. Thomas, and H. Moses, Lett. Nuovo Cimento 8, 921 (1973), and 9, 113 (1974); P. L. Jain, *Experiments on High Energy Particle Collisions*, AIP Conference Proceedings No. 12, edited by R. S. Panvini (American Institute of Physics, New York, 1973), p. 141.

[5]$\beta = 0.7$ corresponds to pion and nucleon momenta of 150 MeV/$c$ and 1 GeV/$c$, respectively. The slower particles also include evaporation protons due to de-excitation of the nucleus. Shower tracks $n_s$ correspond to particles with $\beta \geq 0.7$.

[6]P. L. Jain, H. C. Glahe, J. D. Rinaldo, and P. D. Bharadwaj, Nucl. Phys. 67, 641 (1965), and reference quoted there.

[7]G. Charlton, Y. Cho, M. Derrick, R. Engelmann, T. Fields, L. Hyman, K. Joseph, U. Mehtani, B. Musgrave, Y. Oren, D. Rhines, P. Schreiner, H. Yuta, L. Voyvodic, R. Walker, J. Whitmore, H. B. Crawley, Z. M. Ma, and R. G. Glasser, Phys. Rev. Lett. 29, 515 (1972).

[8]J. Babecki, Z. Czachowska, B. Furmanska, J. Gicrula, R. Holynski, A. Jurak, S. Krywdzinski, G. Nowak, B. Slezak, and W. Walter, Phys. Lett. 47B, 268 (1973); Barcelona-Batavia-Belgrade-Bucharest-Lund-Lyons-Montreal-Nancy-Ottawa-Paris-Rome-Strasbourg-Valencia Collaboration, Phys. Lett. 48B, 467 (1974).

[9]K. N. Erickson, University of Michigan Report No. 03028-4-T, 1970 (unpublished); P. R. Vishwanath, A. E. Bussian, L. W. Jones, D. E. Lyon, J. G. Learned, D. D. Reeder, R. J. Wilksand, and B. Cork, Bull. Amer. Phys. Soc. 19, 445 (1974).

[10]K. Gottfried, Phys. Rev. Lett. 32, 957 (1974).

[11]P. M. Fishbane and J. S. Trefil, Phys. Rev. Lett. 31, 734 (1973); A. Dar and J. Vary, Phys. Rev. D 6, 2412 (1972).

[12]G. Calucci, R. Jengo, and A. Pignotti, Phys. Rev. (to be published).

[13]D. H. Perkins, in *Progress in Elementary Particle and Cosmic Ray Physics*, (North-Holland, Amsterdam, 1960), Vol. V.

[14]P. L. Jain and Z. Ahmad, Phys. Rev. Lett. 28, 459 (1972).

# Observation of the Reactions $e^+e^- \to e^+e^-$, $e^+e^- \to \gamma\gamma$, and $e^+e^- \to \mu^+\mu^-$ at a Center-of-Mass Energy of 5.2 GeV*

B. L. Beron, J. F. Crawford, R. L. Ford, R. Hofstadter, E. B. Hughes, R. Kose,† P. LeCoultre,‡ T. W. Martin, L. H. O'Neill, R. E. Rand, L. Resvanis,§ R. F. Schilling, and J. W. Simpson

*High Energy Physics Laboratory and Department of Physics, Stanford University, Stanford, California 94305*

(Received 17 June 1974)

We report measurements of $e^+e^- \to e^+e^-$, $e^+e^- \to \gamma\gamma$, and $e^+e^- \to \mu^+\mu^-$ at angles close to 90°, relative to Bhabha scattering at 3.7°, at a center-of-mass energy equal to 5.2 GeV. The results are found to be consistent with the predictions of quantum electrodynamics.

We report here significant initial results from an experimental study of the reactions $e^+e^- \to e^+e^-$, $e^+e^- \to \gamma\gamma$, and $e^+e^- \to \mu^+\mu^-$ at the 2.6-GeV electron-positron storage ring (SPEAR) at the Stanford Linear Accelerator Center. The purpose of this experiment[1] was to test the validity of quantum electrodynamics for large values of the square of the invariant four momentum transfer, $q^2$, by measuring cross sections for the above reactions at angles close to 90°, relative to Bhabha scattering at 3.7°. For $e^+e^- \to e^+e^-$, which at 90° is dominated by spacelike momentum transfers, and for $e^+e^- \to \gamma\gamma$ the detected events lie in the $q^2$ range $-7$ to $-20$ $(\mathrm{GeV}/c)^2$, while for $e^+e^- \to \mu^+\mu^-$ $q^2$ is equal to 27 $(\mathrm{GeV}/c)^2$. In this Letter we present the results of an analysis of approximately 60, 30, and 85% of the total event numbers that were observed for the reactions $e^+e^- \to e^+e^-$, $e^+e^- \to \gamma\gamma$, and $e^+e^- \to \mu^+\mu^-$, respectively.

The experimental apparatus consisted of two identical spectrometers mounted in a collinear configuration about the beam interaction region. Each spectrometer consists of a multiwire proportional chamber (MWPC) at a distance of 7.5 in. from the interaction region, followed in sequence by an optional 0.25-in. lead converter, a set of two MWPC's separated by an 8-in. drift space, a plastic scintillator aperture counter, and a 20-in.-thick NaI(Tl) total-absorption detector. A complete description of the MWPC's and the read-out electronics has appeared elsewhere.[2] The NaI(Tl) total-absorption shower-counter (TASC) crystal[3] is 30 in. in diameter and serves to absorb totally electrons and $\gamma$ rays incident within its acceptance aperture. The remaining elements in each spectrometer are used solely for the identification of muons. These consist of an 8-in. iron absorber, a plastic scintillator timing counter, a plastic scintillator hodoscope (spatial resolution 1.5 in. ×1.5 in. for single particles), and a 3.5-in.-thick NaI(Tl) crystal. All of the data were obtained with the spectrometers oriented at an azimuthal angle of 45° relative to the plane of the circulating beams. This was done in order to suppress any influence on the measured cross sections of a possible transverse polarization of the circulating beams.[4]

The experiment was run in two modes. First, with the $\gamma$-ray converters removed, the apparatus was devoted to the measurement of $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$, and second, with the $\gamma$-ray converters inserted, to $e^+e^- \to \gamma\gamma$ and $e^+e^- \to \mu^+\mu^-$. The electronic signature for an event of the type $e^+e^- \to e^+e^-$ or $e^+e^- \to \gamma\gamma$ required only the detection of greater than 0.5 GeV in each of the TASC crystals in coincidence with the crossing of the beams, while that for an event of the type $e^+e^- \to \mu^+\mu^-$ required signals from the aperture and timing counters in each spectrometer in coincidence with the crossing of the beams.

The absolute luminosity of the storage ring was monitored through the measurement of Bhabha scattering at 3.7°. The operating principle of the monitor has been used before,[5] but in the application to SPEAR the design goal was to provide luminosity measurements accurate to within a systematic uncertainty ±2%. A critical examination of the response of the monitor[6] leads us to believe that this accuracy was achieved.

All candidate events for the three reactions of interest were reconstructed and displayed for off-line inspection on a graphic terminal by an IBM 360/91 computer. An interactive software system was employed, as necessary, to edit the MWPC data in order to complete the track reconstruction. Events were accepted as candidates for $e^+e^- \to e^+e^-$ provided that both reconstructed tracks intersected the respective entrance planes of the TASC crystals within a circular aperture of 22 in. diameter and that the two tracks were collinear to within 15°. Subsequently, the requirement was made that a minimum energy of 1.25 GeV be observed in each of the TASC crystals. Figure 1 shows the energy distribution observed in one of the NaI(Tl) TASC crystals for $e^+e^- \to e^+e^-$ candidate events which satisfy all of the above criteria, with the exception of the energy requirement in this one crystal. A clear

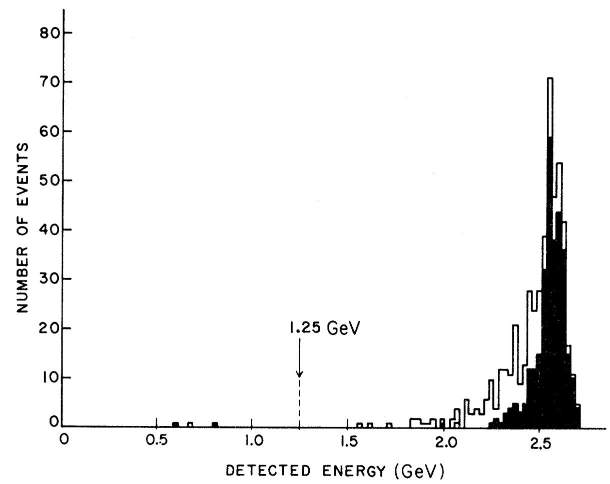


FIG. 1. Energy distribution observed in the top NaI(Tl) TASC crystal for $e^+e^- \to e^+e^-$ candidate events for two aperture diameters. (22 in. aperture diameter —502 events shown by open histogram; 18 in. aperture diameter—305 events shown by filled histogram.) At the larger diameter the peak is broadened as a result of the inclusion of particles which enter the crystal obliquely and close to its edge. 22 in. is judged to be the maximum aperture diameter for which Bhabha events can be cleanly separated from the lower-energy background events.

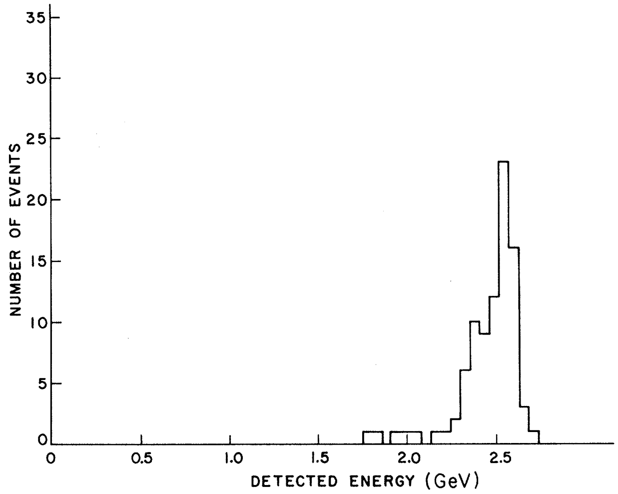


FIG. 2. Energy distribution observed in the top NaI(Tl) TASC crystal for 88 $e^+e^- \rightarrow \gamma\gamma$ candidate events for an aperture diameter of 23 in. The absence of background events at low deposited energies permits the use of a larger aperture diameter for $e^+e^- \rightarrow \gamma\gamma$ than for $e^+e^- \rightarrow \gamma\gamma$ than for $e^+e^- \rightarrow e^+e^-$.

peak due to the detection of 2.6-GeV electrons or positrons is observed together with a few events at energies less than 1 GeV. The latter events are primarily due to the detection of cosmic-ray muons. Clearly the choice of 1.25 GeV as the threshold energy for electron detection is quite uncritical. No other criteria are necessary for the identification of $e^+e^- \rightarrow e^+e^-$ events.

Events were accepted as candidates for $e^+e^- \rightarrow \gamma\gamma$ provided that both reconstructed $\gamma$-ray trajectories intersected the respective planes of the TASC crystals within a circular aperture of 23 in. diameter and that the two trajectories were collinear to within 15°. It was also required that no evidence exist for incident charged particles in the MWPC's in front of the converters in the immediate vicinity of the positions through which the $\gamma$ rays were expected to pass. Figure 2 shows the energy distribution observed in one of the NaI(Tl) TASC crystals for $e^+e^- \rightarrow \gamma\gamma$ events which satisfy the above criteria. Again, a clear peak due to the detection of 2.6-GeV $\gamma$ rays is observed. No other criteria are necessary for the identification of $e^+e^- \rightarrow \gamma\gamma$ events.

Events were accepted as candidates for $e^+e^- \rightarrow \mu^+\mu^-$ provided that (1) the measured time difference between the pulses observed in the two timing counters did not exceed 5.3 nsec, (2) the reconstructed tracks intersected the planes of the respective timing counters within a circular aperture of 28 in. diameter, and (3) the measured

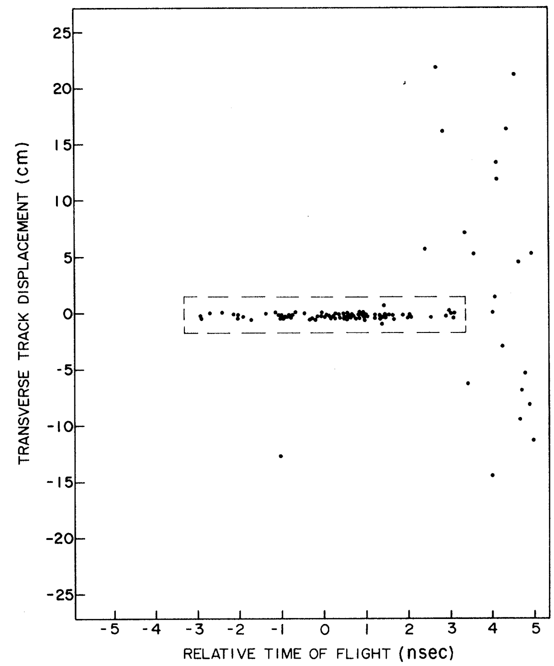


FIG. 3. Scatter plot for 102 $e^+e^- \rightarrow \mu^+\mu^-$ candidate events (aperture diameter, 28 in.) showing the average transverse distance of muon tracks from the orbit of the circulating beams versus the time difference between the pulses observed in the timing counters. The dashed rectangle indicates the acceptance area for $e^+e^- \rightarrow \mu^+\mu^-$ events.

time difference between the pulse observed in one of the timing plastic scintillators and the crossing of the beams was within ±7 nsec. For these events Fig. 3 shows the correlation between the average distance of closest approach of the tracks to the orbit of the circulating beams and the time difference between the pulses observed in the timing counters. Two types of events are clearly revealed in this plot: first, a group of events with small relative timing and tightly correlated with the beam orbit, and second, a group of events with larger timing and no correlation with the beam orbit. The former are $e^+e^- \rightarrow \mu^+\mu^-$ events, while the latter are cosmic-ray muons. Only a small fraction (~0.1%) of the cosmic-ray muons detected by the apparatus appear in Fig. 3, since the average relative timing for such events is 10.6 nsec and the measured standard deviation is 1.7 nsec.

The observed numbers of events and the numbers expected from quantum electrodynamics for the three reactions of interest are shown in Table I. This table also lists the radiative corrections applied to the expected numbers of events. All of the radiative corrections, including cor-

TABLE I. Summary of the observed and expected number of events. The principal corrections and errors are also shown, together with the lower limits set by this and earlier experiments on the cutoff parameters $\Lambda$.

| | $e^+e^- \rightarrow e^+e^-$ | $e^+e^- \rightarrow \gamma\gamma$ | $e^+e^- \rightarrow \mu^+\mu^-$ |
|---|---|---|---|
| Integrated luminosity ($10^{35}$ cm$^{-2}$) | $2.96 \pm 0.06$ | $6.41 \pm 0.13$ | $23.5 \pm 0.5$ |
| Radiative correction (to lowest-order expected rate in spectrometers) | $0.940 \pm < 0.01$ | $0.951 \pm < 0.01$ | $0.954 \pm < 0.01$ |
| Number of events expected | $521 \pm 16$ | $84.3 \pm 3.7$ | $87.1 \pm 2.7$ |
| Number of events observed | 499 | 88 | 80 |
| Ratio of observed to expected events | $0.96 \pm 0.05$ | $1.04 \pm 0.12$ | $0.92 \pm 0.11$ |
| $\Lambda_+$ (GeV), this experiment | 22.8 | 6.2 | 14.5 |
| $\Lambda_-$ (GeV), this experiment | 14.4 | 6.9 | 23.6 |
| $\Lambda_+$ (GeV), earlier experiments | 9.8 [a] | 3.9 [b] | $\sim 7$ [c] |
| $\Lambda_-$ (GeV), earlier experiments | 10.5 [a] | 5.1 [b] | $\sim 9$ [c] |

[a]Ref. 7. [b]Ref. 8. [c]Ref. 9.

rections of 2.2% to the observed luminosities, were calculated according to Berends *et al.*[10,11] There are no other corrections of any significance to either the observed or the expected event numbers. The estimated background due to collinear hadron pair production is negligible ($\lesssim 0.1$ event) for both $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$. A search was made for the occurrence of events of all three types with the circulating beams displaced in the vertical direction so that they do not collide but none were found. Various sources of systematic error are included in the errors assigned to the expected event numbers.

We conclude from Table I that the rates we observe for the three reactions of interest are consistent with the predictions of quantum electrodynamics. If, in addition, we anticipate that possible breakdowns of theory can be described by propagator modifications in the lowest-order Feynman diagrams of the form $1/q^2 \rightarrow (1/q^2)[1 \pm q^2/(q^2 - \Lambda_\pm^2)]$ for $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$,[12,13] and $1/(q^2 - m^2) \rightarrow [1/(q^2 - m^2)](1 \pm q^4/\Lambda_\pm^4)$ for $e^+e^- \rightarrow \gamma\gamma$,[14] then our results can be used to place lower limits (95% confidence level) on the cutoff parameters $\Lambda$ for each of the three reactions. These values, together with the limits set by earlier experiments, are given in Table I.

We are grateful to Dr. R. Gastmans of the University of Leuven for assistance in adapting his computer codes to the calculation of our radiative corrections.

*Work supported in part by the National Science Foundation under Grants No. GP-22880 and No. GP-38611.

†Visitor from Physikalisches Institut, Universität Bonn, Bonn, Germany.

‡Visitor from Universität Bern, Bern, Switzerland.

§Visitor from University of Pennsylvania, Philadelphia, Pa. 19104 (work supported by the U. S. Atomic Energy Commission).

[1]B. L. Beron *et al.*, in Proceedings of the Sixth International Symposium on Electron and Photon Interactions at High Energies, Bonn, Germany, 27–31 August 1973 (to be published).

[2]R. E. Rand *et al.*, High Energy Physics Laboratory, Stanford University, Report No. 720, 1973 (to be pusblished).

[3]E. B. Hughes *et al.*, IEEE Trans. Nucl. Sci. 19, No. 3, 126 (1972).

[4]See for example, W. T. Ford, A. K. Mann, and T. Y. Ling, SLAC Report No. 158, 1972 (unpublished).

[5]G. Barbiellini *et al.*, Atti Accad. Naz. Lincei, Cl. Sci. Fis., Mat. Natur., Rend. 44, 233 (1968).

[6]J. F. Crawford *et al.*, High Energy Physics Laboratory, Stanford University, Report No. 730 (unpublished).

[7]H. Newman *et al.*, Phys. Rev. Lett. 32, 483 (1974).

[8]G. Hanson *et al.*, Lett. Nuovo Cimento 7, 587 (1973). The breakdown model assumed by Hanson *et al.* does not admit a modification equivalent to that provided by $\Lambda_-$, but their data can be seen to be consistent with the value of $\Lambda_-$ shown in Table I.

[9]B. Borgia *et al.*, Lett. Nuovo Cimento 3, 115 (1972); V. Alles-Borelli *et al.*, Nuovo Cimento 7A, 330 (1972). These authors do not quote values for $\Lambda_\pm$ (excepting Borgia *et al.*, who give 9 GeV for $\Lambda_-$) but their data can be seen to be consistent with the values of $\Lambda_\pm$ shown in Table I.

[10]F. A. Berends, K. J. F. Gaemers, and R. Gastmans, Nucl. Phys. B68, 541 (1974), and B57, 381 (1973).

[11]F. A. Berends and R. Gastmans, Nucl. Phys. B61, 414 (1973).

[12]S. D. Drell, Ann. Phys. (New York) 4, 75 (1958).

[13]T. D. Lee and G. C. Wick, Nucl. Phys. B9, 209 (1969).

[14]N. M. Kroll, Nuovo Cimento 45A, 65 (1966).