DEVIATION FROM SIMPLE QUANTUM ELECTRODYNAMICS*†

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(Received 23 February 1965)

Measurements of the photoproduction from carbon of wide-angle electron-positron pairs in the energy range from 1 to 6 BeV were made at the Cambridge electron accelerator. This experiment, which was proposed by Drell[1] and discussed in detail by Bjorken, Drell, and Frautschi,[2] is a new test of quantum electrodynamics at high energies and small distances. The object of the experiment is to study the behavior of the electron propagator for large spacelike virtual momenta by measuring the cross section for the photoproduction of symmetrical electron-positron pairs. The experimental results do not agree with the predictions of quantum electrodynamics for pair production; they suggest a breakdown of the theory or the presence of other processes.

The apparatus is shown in Fig. 1. A 10-mil tungsten ribbon was used to produce the bremsstrahlung beam. A circular magnet bent charged particles away from the gamma-ray beam so that pairs with small opening angles could be detected. The electrons and positrons were detected and momentum analyzed by two mirror-image magnet-counter systems. The momentum-analyzing magnet was one-half of a conventional quadrupole to which was bolted an iron plate as an image plane. The half quadrupoles focused in the vertical plane, and they were used as spectrometers by placing lead obstacles in their centers. The smallest production angle which could be accepted was determined by the height of the lead obstacle. A brass mask at the front of each half-quadrupole defined the entrance aperture.

The particle trajectories were defined by scintillation counters placed behind the quadrupoles. On each arm a large, threshold-type, gas Čerenkov counter set below the thresholds of pions and muons was used to detect electrons. Behind the Čerenkov counters were scintillator-lead sandwiches in which electrons showered; these counters provided additional discrimination against pions and muons. The Čerenkov counter, shower counter, and certain of the fast-coincidence pulses were displayed on a fast oscilloscope and photographed for many of the events. Two methods were used to determine the contamination due to pion pairs; both methods yielded the same result. The total energy of the bremsstrahlung beam was measured with a quantameter. The calibration of the quantameter was checked against two Cornell quantameters as well as other quantameters in this laboratory.

Table I summarizes the experimental and theoretical electron pair yields. All of the yields have been normalized to the rate for a $\frac{1}{2}$-in.-thick carbon target per unit charge collected by the quantameter. The experimental data have been corrected for random coincidences, counting-rate loss, and pion contamination. The target thickness ranged from $\frac{1}{8}$ to $\frac{1}{2}$ in. and was selected so that the chance electron-pair coincidences were always less than 10% of the real rate. The average count-

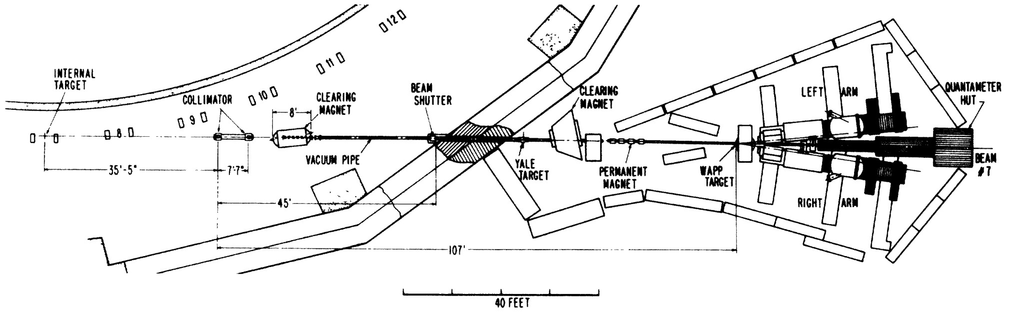

FIG. 1. A drawing showing the general layout of the apparatus and its relationship to the electron synchrotron.

Table I. This table summarizes the measured electron-pair yields and the calculated electron-pair yields. The angle θ is the angle between each member of the pair and the direction of the incident photon beam; E is the energy of each member of the pair in BeV; k_{max} is the end-point energy of the bremsstrahlung spectrum in BeV. The experimental yields have been normalized to the rate for a $\frac{1}{2}$-in.-thick carbon target per unit charge collected by the quantameter. The theoretical yields include radiative corrections and were calculated by a Monte-Carlo integration over the acceptance of the system. The integration program used the cross-section expression of Bjorken, Drell, and Frautschi and an analytic fit to the experimental data for the carbon form factor measured in elastic electron scattering. The inelastic contributions are estimated in all cases to be less than 6%; they have not been included in the calculated theoretical yields. The radiative corrections were calculated from the formulas of Bjorken, Drell, and Frautschi.

θ (deg)	E (BeV)	k_{max} (BeV)	Experimental yield	Theoretical yield	R	$\frac{\sigma_{\text{radiative}}}{\sigma_{\text{Bethe-Heitler}}}$
4.75	0.5	1.25	$(4.40\pm1.03)\times10^{-1}$	6.08×10^{-1}	0.72 ± 0.17	0.018
		2.5	$(2.18\pm0.13)\times10^{-1}$	3.56×10^{-1}	0.61 ± 0.04	0.103
	1.0	2.5	$(5.88\pm0.34)\times10^{-2}$	7.58×10^{-2}	0.78 ± 0.05	0.021
		5.0	$(3.41\pm0.26)\times10^{-2}$	4.42×10^{-2}	0.77 ± 0.06	0.117
	1.5	5.0	$(1.47\pm0.08)\times10^{-2}$	1.73×10^{-2}	0.85 ± 0.04	0.079
	2.0	4.5[a]	$(1.21\pm0.13)\times10^{-2}$	9.97×10^{-3}	1.21 ± 0.13	−0.018
		[b]	$(1.07\pm0.09)\times10^{-2}$	9.97×10^{-3}	1.07 ± 0.09	−0.018
		5.0	$(1.05\pm0.04)\times10^{-2}$	9.10×10^{-3}	1.16 ± 0.05	0.023
		5.15	$(8.57\pm0.93)\times10^{-3}$	8.87×10^{-3}	0.97 ± 0.11	0.032
	2.25	5.5	$(6.94\pm0.96)\times10^{-3}$	6.44×10^{-3}	1.08 ± 0.15	0.017
	2.5	6.0	$(7.09\pm0.67)\times10^{-3}$	4.72×10^{-3}	1.50 ± 0.14	0.010
6.26	1.0	2.5	$(6.83\pm1.56)\times10^{-3}$	9.80×10^{-3}	0.70 ± 0.16	0.022
		4.0	$(4.13\pm3.24)\times10^{-3}$	6.76×10^{-3}	0.61 ± 0.48	0.010
		4.5	$(3.40\pm1.47)\times10^{-3}$	6.23×10^{-3}	0.55 ± 0.24	0.113
		5.0	$(4.92\pm0.72)\times10^{-3}$	5.80×10^{-3}	0.85 ± 0.12	0.123
	1.5	5.0	$(2.09\pm0.20)\times10^{-3}$	2.23×10^{-3}	0.94 ± 0.09	0.082
	2.0	4.5	$(1.29\pm0.19)\times10^{-3}$	1.26×10^{-3}	1.02 ± 0.15	−0.019
		5.0	$(1.52\pm0.14)\times10^{-3}$	1.15×10^{-3}	1.32 ± 0.12	0.024
		5.5	$(1.43\pm0.32)\times10^{-3}$	1.06×10^{-3}	1.35 ± 0.30	0.050
	2.25	5.5	$(1.09\pm0.08)\times10^{-3}$	8.09×10^{-4}	1.35 ± 0.10	0.017
	2.5	6.0	$(9.94\pm1.36)\times10^{-4}$	5.86×10^{-4}	1.70 ± 0.23	0.011
7.50	1.0	4.0	$(1.94\pm0.41)\times10^{-3}$	1.73×10^{-3}	1.12 ± 0.24	0.103
		4.5	$(2.53\pm0.51)\times10^{-3}$	1.60×10^{-3}	1.58 ± 0.32	0.116
		5.0	$(1.53\pm0.33)\times10^{-3}$	1.49×10^{-3}	1.03 ± 0.22	0.126
		5.5	$(1.37\pm0.35)\times10^{-3}$	1.39×10^{-3}	0.98 ± 0.25	0.135
	1.5	5.5	$(6.84\pm2.98)\times10^{-4}$	5.28×10^{-4}	1.30 ± 0.56	0.098
	2.25	5.5	$(2.01\pm1.09)\times10^{-4}$	1.99×10^{-4}	1.01 ± 0.54	0.018
		5.55	$(3.12\pm0.46)\times10^{-4}$	1.97×10^{-4}	1.58 ± 0.23	0.021
10.88	2.0	5.1	$-(0.27\pm1.70)\times10^{-5}$	9.67×10^{-6}	-0.28 ± 1.76	0.033
11.74	1.8	5.0	$-(0.07\pm2.08)\times10^{-4}$	6.04×10^{-6}	-0.04 ± 34.46	0.056

[a] Target thickness = $\frac{1}{8}$ in.

[b] Target thickness = $\frac{1}{2}$ in.

ing-rate loss for electron pairs was 20%; the range was 10 to 30%. The largest correction for pion-pair contamination was 10%. The errors quoted in Table I include the statistical errors and the errors due to the uncertainties in the various corrections. At each data point approximately half of the measurements were made with all the magnet polarities normal, and the other half with all the magnets reversed. The yields for the two polarities were equal within the statistical errors.

Due to the sharp dip at symmetry in the Bethe-Heitler cross section, it was necessary to use a Monte-Carlo method to calculate the theoretical yields. The differential cross section given by Bjorken, Drell, and Frautschi[2] and the results of an independent calculation of the magnet acceptance were folded together. An analytic expression was used to represent the elastic carbon form factor.[3,4] Table I summarizes the calculated yields and the radiative corrections.[2]

The correction due to inelastic pair production was estimated from the sum rules for inelastic electron scattering[5] and the general formulas of Drell and Walecka.[6] For those points in this experiment at which the momentum transfer to the nucleus was largest, the inelastic contributions increased the theoretical yield by less than 6%; this additional contribution from inelastic processes has not been included in the calculated yields. The experimental results indicated that inelastic processes were not important.

The ratios of experiment to theory for data which differed only in $k_{\max}$ were combined by calculating the weighted mean. These results are presented in Table II. Figure 2(a) shows these data plotted as a function of the square of the mass of the virtual electron, $-Q_F^2$, and the square of the mass of the electron-positron system, Q_M^2. Figure 2(b) shows the data as a function of the square of the total energy, $k^2=(E_+ + E_-)^2$, of the electron-positron pair.

It is apparent from Fig. 2 that the experimental yields do not agree with the theoretical calculations. An equation which gives a least-squares representation of the ratio, R, of the experimental yield to the theoretical yield, is

$$R = 0.66\left\{(1 \pm 0.038) - \frac{Q_F^2}{(310\ \text{MeV})^2(1 \pm 0.08)}\right\},$$

where Q_F^2 is in $(\text{MeV})^2$. There are two distinct aspects of the disagreement—one is the absolute normalization, and the other is the variation of the ratio R when the spectrometer arms are kept at a fixed angle and the momentum is varied. Some of the errors which can enter the absolute normalization and an estimate of their magnitude are these: synchrotron energy, ±1%; quantameter calibration, ±5%; theoretical calculation of the yield, ±10%; Čerenkov counter efficiency. The efficiency of each Čerenkov counter was measured to be greater than 94%. One can use these unknowns to partially explain the failure to obtain the expected value for the absolute cross section at low momenta. It is more difficult to explain the variation of the observed rate with the momentum of the electrons.[7]

One process which could give additional electrons is the formation of ρ^0's and the subsequent decay of the ρ^0 into an electron-positron pair.[8]

Table II. This table summarizes the combined electron-pair results. The entries in this table were obtained by combining the results of Table I for electron pairs of a given half-angle θ and energy E. $[-Q_F^2]^{1/2}$ is the mass of the virtual fermion, $[Q_M^2]^{1/2}$ is the mass of the outgoing electron-positron system, $[-Q_N^2]^{1/2}$ is the momentum transfer to the nucleus for symmetrical pairs, and $[-\langle Q_N^2\rangle_{\text{Av}}]^{1/2}$ is the average momentum transfer to the nucleus. The average momentum transfer was obtained by weighting the momentum transfer with the cross section and then integrating over the acceptance of the system. The ratios, R, of experiment to theory are based on calculations using only the carbon elastic-scattering form factor, and they contain no correction for inelastic processes.

θ (deg)	E (BeV)	$[-Q_F^2]^{1/2}$ (MeV)	$[Q_M^2]^{1/2}$ (MeV)	$[-Q_N^2]^{1/2}$ (MeV)	$[-\langle Q_N^2\rangle_{\text{Av}}]^{1/2}$ (MeV)	R
4.75	0.5	59	83	3.4	7.5	0.62 ± 0.04
	1.0	117	166	6.8	15.1	0.77 ± 0.04
	1.5	176	248	10.3	22.7	0.85 ± 0.04
	2.0	234	331	13.7	30.0	1.12 ± 0.04
	2.25	264	373	15.4	33.6	1.08 ± 0.15
	2.5	293	414	17.2	37.0	1.50 ± 0.14
6.26	1.0	154	218	11.9	20.4	0.75 ± 0.09
	1.5	232	327	17.9	30.6	0.94 ± 0.09
	2.0	309	436	23.8	40.5	1.21 ± 0.09
	2.25	347	491	26.8	45.4	1.34 ± 0.10
	2.5	386	545	29.8	50.3	1.69 ± 0.23
7.50	1.0	185	261	17.1	25.2	1.13 ± 0.13
	1.5	277	392	25.7	37.6	1.30 ± 0.57
	2.25	416	587	38.5	56.0	1.50 ± 0.21
10.88	2.0	536	755	71.9	83.7	−0.28 ± 1.76
11.74	1.8	521	733	75.3	85.5	−0.04 ± 34.46

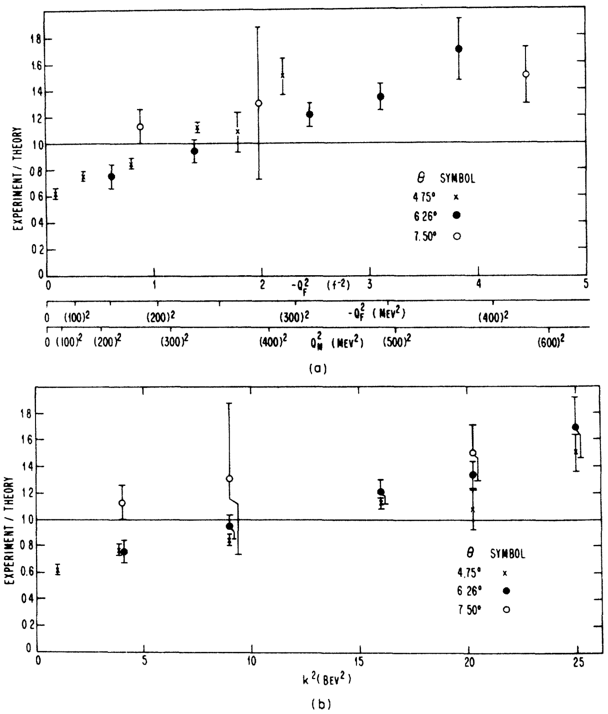

FIG. 2. This figure summarizes the ratio, R, of the experimental yields to the calculated yields. (a) R as a function of the mass of the virtual fermion $(-Q_F^2)$ and the mass of the outgoing electron-positron system (Q_M^2). (b) R as a function of the square of the total energy $(k = E_+ + E_-)$ of the electron-positron pair. The assigned error in the ratio, R, is due entirely to the errors in the measured yields and contains no estimates of the theoretical uncertainty. The theoretical yields were calculated using only the elastic form factor for the carbon, and they do not include any correction for inelastic processes. It is estimated that the increase in the yield due to inelastic contributions is less than 6 % at those points at which the momentum transfer to the nucleus is largest.

In a run taken to observe pairs with the mass of the rho, 27 500 pion pairs[9] and only one electron pair were observed, where 1.5 electron pairs were expected from Bethe-Heitler pair production, and 1.6 from contamination. Thus we find that

$$\frac{\rho^0 \to e^+ + e^-}{\rho^0 \to \pi^+ + \pi^-} < 10^{-4},$$

and that the electromagnetic decay of the rho cannot explain our results. The difference between the theory and experiment could also be due to an insufficiency of the present theory of quantum electrodynamics, a Compton process,[2] or to the presence of some new particle which is coupled to an electron and a gamma ray.[10]

We would like to thank the staff of the Harvard cyclotron for their aid in the design, construction, and setting up of the apparatus. We thank the staff of the Cambridge electron accelerator for their many services. We gratefully acknowledge the assistance of C. Friedberg, E. Petraske, K. Randolph, J. J. Russell, and J. Tenenbaum. We wish to thank Professor J. D. Bjorken and Professor S. D. Drell for several illuminating discussions of the theory. We are indebted to the Harvard Computation Center and the Atomic Energy Commission Computing and Applied Mathematics Center at New York University for making their facilities available to us.

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*Research supported by the U. S. Atomic Energy Commission.

†Part of the work reported in this Letter was submitted by one of the authors (R.B.B.) to Harvard University in partial fulfillment of the requirements for the Doctor of Philosophy degree.

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[1] S. D. Drell, Ann. Phys. (N.Y.) 4, 75 (1958).

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[6] S. D. Drell and J. D. Walecka, Ann. Phys. (N.Y.) 28, 18 (1964).

[7] It should be pointed out that the results of this experiment are not necessarily in contradiction with those of the wide-angle mu-pair experiment [J. K. de Pagter, A. Boyarski, G. Glass, J. I. Friedman, H. W. Kendall, M. Gettner, J. F. Larrabee, and R. Weinstein, Phys. Rev. Letters 12, 739 (1964)]. In that experiment all of the mu pairs observed had nearly the same total energy; for these pairs the ratio of the experimental to the theoretical yield was not a function of the mass of the virtual fermion. If we select from our data electron-positron pairs of the same total energy, we find that the ratio of the theoretical to the experimental yield does not depend upon the mass of the virtual fermion.

[8] S. M. Berman and S. D. Drell, Phys. Rev. 133, B791 (1964).

[9] In a subsequent experiment we have shown that at least 90 % of these pion pairs come from the decay of rho mesons.

[10] F. E. Low has suggested that the pair anomaly could be explained without contradicting other experiments by postulating a heavy electron which can decay into an ordinary electron and a gamma ray. Another possible explanation is a massive photon which can decay into an electron-positron pair [F. E. Low, Phys. Rev. Letters 14, 238 (1965)].

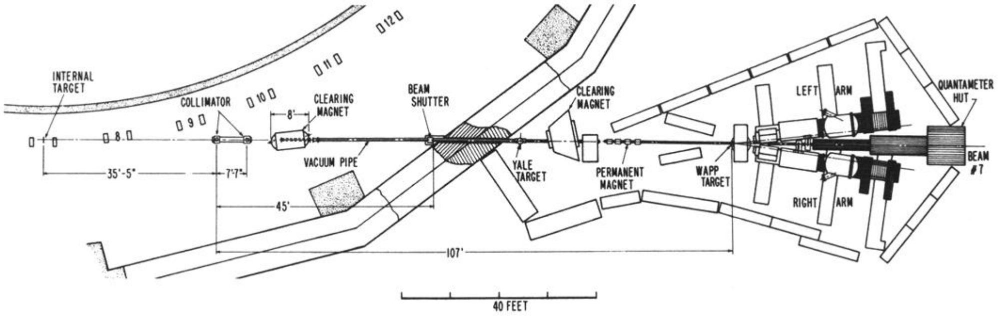

FIG. 1. A drawing showing the general layout of the apparatus and its relationship to the electron synchrotron.