errors are correlated, the $A$-configuration counting rate being used in both; also, should these answers turn out to be significantly different from each other in an improved experiment, this might reflect a different angular distribution $d\Gamma_S{}^{3\gamma}$. Since $b \geq 0$, one can estimate from the $C$-configuration result that $b \leq 2.8\times 10^{-6}$ with a 68% confidence limit. Such an upper limit, if the Lagrangians of Eq. (1) or (2) are to be taken seriously, corresponds to $g \leq 1.08$, when using the mass of the electron for $m$.

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# PHOTOPRODUCTION OF WIDE-ANGLE ELECTRON PAIRS FROM CARBON*

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Measurements of the photoproduction of wide-angle electron pairs from carbon in the energy range 600 to 2000 MeV are reported. The results agree with the predictions of quantum electrodynamics substantially better than the previously reported results, based on part of the data presented here, which showed a discrepancy of 2.3 standard deviations.

The photoproduction of wide-angle electron pairs from carbon has been measured at the Cornell electron synchrotron, at peak bremsstrahlung energies ranging from 600 to 2000 MeV. Two series of measurements were made: The first, or "old," series[1] has already been reported; the second, "new," series was carried out since that report.

The apparatus is shown in Fig. 1. The bremsstrahlung beam from the synchrotron, produced by electrons incident on a 0.1-radiation-length tungsten target, was collimated and passed through a region of sweeping field, a thin-plate ion chamber, and the carbon target (usually 2.5 g/cm$^2$ thick), after which it was stopped in uranium. The beam spot at the target was half an inch in diameter. The ion chamber was used as a beam-intensity monitor during runs. Before and after every run it was calibrated against a thick quantameter placed in the beam at the target position. The electron and positron passed through symmetrically placed apertures defined by uranium into a region of uniform magnetic field. The trajectories were recorded in thin-plate aluminum spark chambers and a set of lead and brass "shower" chambers. A sixfold coincidence of the counters $L_1L_2L_3R_1R_2R_3$ shown in Fig. 1 triggered the spark chambers, registering a "pair." For the "new" series, some changes were made in the apparatus. Counters $L_3$ and $R_3$ were moved downstream to the center of the magnet in order to decrease the singles rates in them. In the "old" configuration, the beam intensity was limited by the instantaneous rates in $L_3$ and $R_3$, typically held to 5 Mc/sec. In both series of runs, the duty cycle of $L_3$ or $R_3$ was continuously monitored and the beam intensity adjusted to keep it constant. The shower chambers were rebuilt to record each shower of the pair in an independent chamber; the number of gaps was increased and the thick-

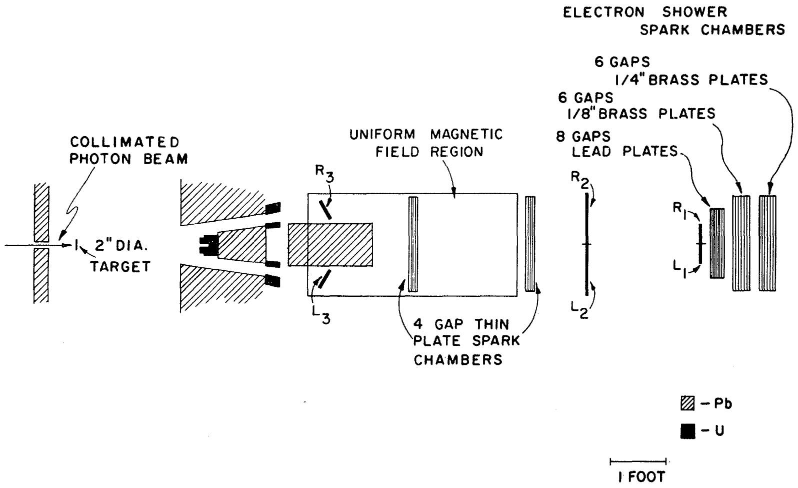

FIG. 1. Plan view of the experiment for the "old" series of data. The "new" series was taken with an improved setup, as described in the text.

ness of converter between gaps decreased. This improved the quality of the electron showers, leading to better discrimination against pions. The mean opening angle of the pairs was increased in order to increase the upper limit of $Q_M$, the invariant mass of the pair. The "old" data included pairs whose trajectories crossed before $L_1R_1$ ("crossed events") as well as those which crossed after $L_1R_1$ ("uncrossed events"). For the "new" data, the geometry was such as to eliminate the "uncrossed events" and thus increase the average bending of the trajectories.

The spark chambers were used primarily to identify particles and to monitor the quality of the events. It was not necessary to measure and reconstruct all events, but representative samples of events were reconstructed and analyzed in detail to obtain kinematic plots. The trajectories were extrapolated back to the target plane. Distributions in horizontal and vertical displacements at the target agreed well with expected distributions at all energies. Thus, scattering off pole pieces, etc., was seen to be negligible, since scattered events would appear not to come from the target. The precision was then improved by assuming the particles came from the center of the target. The resulting distributions in energies and momentum transfer were in reasonable agreement with the predictions of the Bethe-Heitler theory.

Pion pairs constitute the major background in real "pair" events. Discrimination against pions was based on the characteristic showers produced by electrons and positrons in the shower chambers. Pions typically gave straight tracks, often with large-angle scattering or obvious nuclear interactions. Calibration pictures taken with pure electron and pion beams showed a negligible probability of misidentifying a pion pair as an electron pair over the range of energies used in the present experiment. The highest ratio of pion pairs to $e^+e^-$ pairs was about 10 to 1 (at the highest energy point).

An approximate form of the Bethe-Heitler formula for pair production at wide angles and near symmetry for the electron and positron is

$$d\sigma_{\text{B-H}} \cong \frac{Z^2\alpha^3}{\pi^2} \frac{1}{\theta_+^2\theta_-^2} \frac{dE_+}{k} d\Omega_+ d\Omega_- \frac{q_T^2}{q^4}, \tag{1}$$

where $Z$ is the nuclear charge; $\alpha = 1/137$; $d\Omega_+$ ($d\Omega_-$) is the positron (electron) detection solid angle centered at $\theta_+$ ($\theta_-$); $k$ is the incident photon energy (approximately equal to $E_+ + E_-$); $q$ is the momentum of the nuclear recoil, and $q_T$ is the component of $q$ transverse to the incident photon direction.

In the present experiment the geometry was kept constant. The magnet field setting and the synchrotron end-point energy, $k_0$, were scaled exactly together to obtain the different data points. A discrepancy from Eq. (1) could, in general, have very complicated dependences in the five-dimensional phase space. However, it is convenient for comparing different experiments to suppose that any discrepancy is a function solely of $Q_M$, the invariant mass of the electron positron system. For symmetric pairs, $Q_M \simeq k\theta_\pm$. The maximum attainable value of $Q_M$ in the present case was 250 MeV at the average angle $\theta_\pm = 9.2°$ and maximum synchrotron energy 2 GeV. The data from previous experiments at Cambridge Electron Accelerator (CEA)[2] and Deutsches Elektronen-Synchrotron, Hamburg (DESY)[3] extend up to $Q_M \simeq 550$ MeV.

Interpretation of the results depends crucially on a complete knowledge of the energy dependence of the bremsstrahlung beam. To study this question, the apparatus was rearranged to measure the photoproduction of 0° electron-positron pairs from a thin copper target placed well within the magnetic field. The incident-photon acceptance matched roughly the acceptance in the wide-angle experiment. At several values of the end-point energy $k_0$, the photon spectrum was traced out by varying the magnetic field, and thus $k$. A comparison of the spectra at different energies with theory, including corrections for screening, Coulomb effect, pair production from atomic electrons, etc., demonstrated that the bremsstrahlung spectrum shape is constant at low and high energies; that the beam monitor is linear to within 1% between 600 and 2000 MeV; that the absolute calibration of the beam monitor and counter efficiencies are known to within 2%; and that the scaling of the synchrotron end-point energy with the field in the spectrometer magnet is good to within 1%.

As a preliminary check, the dependence of wide-angle pair production on the target nucleus was measured at an intermediate energy ($k_0 = 1.0$ BeV). The $Z$ dependence was found to be $Z^{2.1 \pm 0.2}$ using target materials from beryllium to copper, which agrees with the $Z$ dependence of Eq. (1).

The contribution of "Compton-like" diagrams to wide-angle electron pair production has been discussed by Drell[4] and others. In a peripheral experiment,[5] we have measured the small-angle (~3°) elastic scattering of photons from carbon and tungsten. The results serve to substantiate the forward scattering cross section of high-energy photons as used by Drell. Thus the "Compton-like" terms may be neglected.

The results of the pair-production experiment are usually presented as ratios, $R$, of experimental yield to theoretically predicted yield. Various corrections have to be applied before the raw data yields can be compared with theory. Typical correction factors are listed in Table I. The "radiative" and "bremsstrahlung" corrections were evaluated using approximations closely resembling those of Lomon[6] but arrived at independently. Computer integration over experimental apertures enable these corrections to be evaluated more accurately than was done by Lomon. Table II lists the ratios $R$ for the various data points. At each point, roughly equal amounts of data were taken for each polarity of the magnet. The yields at the two polarities always agree within statistical accuracy. The systematic error in the absolute value of $R$ for each point is estimated to be ±5%. The "relative" systematic error in comparing points taken at

Table I. Correction factors for the "new" series. Corrections for the "old" series are similar. The total correction factors for individual points are shown in Table II.

| | Correction Factor | |
|---|---|---|
| Effect | $k_0 = 1$ GeV | $k_0 = 2$ GeV |
| Form factor of carbon | $1.013 \pm 0.001$ | $1.050 \pm 0.005$ |
| Beam loss in target, etc. | $1.05 \pm 0.01$ | $1.05 \pm 0.01$ |
| Dead-time loss | $1.02 \pm 0.01$ | $1.02 \pm 0.01$ |
| Multiple scattering | $0.98 \pm 0.01$ | 1.0 |
| Ionization loss in target, etc. | $1.025 \pm 0.005$ | $1.005 \pm 0.001$ |
| Radiative correction | $1.034 \pm 0.007$ | $1.041 \pm 0.007$ |
| Bremsstrahlung in target, etc. | $1.19 \pm 0.02$ | $1.19 \pm 0.02$ |
| Absolute calibration of quantameter | $1.00 \pm 0.02$ | $1.00 \pm 0.02$ |
| Calculation | $1.00 \pm 0.03$ | $1.00 \pm 0.03$ |
| Product of all corrections | $1.340 \pm 0.047$ | $1.400 \pm 0.047$ |

Table II. Results of the experiment. For the "new" series, $\theta_\pm$(average) = 9.2°; for the "old" series, $\theta_\pm$(average) = 7.8°. The average incident photon energy is obtainable from $Q_M = k\theta_\pm$.

| Point Number | $k_0$ (MeV) | $Q_M$ (MeV) | Correction factor | $R$ | Total error | Statistical error |
|---|---|---|---|---|---|---|
| | | | "New" series | | | |
| 1 | 1000 | 126 | 1.34 | 0.960 | ±0.057 | ±0.028 |
| 2(*a*) | 1900 | 241 | 1.39 | 0.985 | ±0.060 | ±0.033 |
| 2(*b*) | 2000 | 254 | 1.40 | 0.995 | ±0.090 | ±0.075 |
| | | | "Old" series | | | |
| 3(*a*) | 600 | 47 | 1.34 | 0.867 | ±0.056 | ±0.026 |
| 3(*b*) | 600 | 61 | 1.34 | 0.940 | ±0.057 | ±0.027 |
| 4(*a*) | 1800 | 140 | 1.38 | 0.908 | ±0.064 | ±0.042 |
| 4(*b*) | 1800 | 182 | 1.38 | 1.009 | ±0.065 | ±0.044 |
| 4(*c*) | 2000 | 156 | 1.39 | 0.994 | ±0.075 | ±0.057 |
| 4(*d*) | 2000 | 202 | 1.39 | 1.097 | ±0.075 | ±0.057 |
| 5 | 800 | 72 | 1.35 | 0.94 | ±0.07 | ±0.05 |
| 6 | 1000 | 90 | 1.35 | 0.98 | ±0.06 | ±0.04 |
| 7 | 1400 | 126 | 1.36 | 0.94 | ±0.07 | ±0.05 |
| 8 | 1600 | 144 | 1.37 | 1.03 | ±0.07 | ±0.05 |
| 9 | 1700 | 153 | 1.38 | 1.00 | ±0.08 | ±0.06 |

different energies but under otherwise identical conditions is estimated to be ±1.4%. This systematic error is small because, with fixed geometry, $d\sigma_{\text{B-H}}$ given by Eq. (1) varies as $1/k^2$, and thus the experimental yield times $k^2$ is expected to be constant. This result is independent of apertures, efficiencies, or calculations. To reduce the possibility of error, runs were taken alternating between matched points of high and low energy. The over-all correction factors are also listed in Table I, as are the "absolute" uncertainties.

Figure 2 shows a plot of the results, and includes the results of the CEA[2] and DESY[3] experiments in the region of $Q_M$ covered by the present experiment. For the sake of simplification the data are combined into four points; namely, high and low $Q_M$ in each of the "old" and "new" series. For the same reason the intermediate-energy points (numbered 5 to 9 in Table II) are not plotted. They are, however, completely consistent with all subsequent comments. The error bars shown are "relative." They are obtained from quadratic combination of the counting error and the 1.4% "relative" systematic error.

As previously announced,[1] the "old" data appeared to corroborate the rapid energy dependence found at CEA, with a 1% probability that the resulting discrepancy from quantum electrodynamics (QED) was a fluctuation. The "old" and "new" data taken together appear

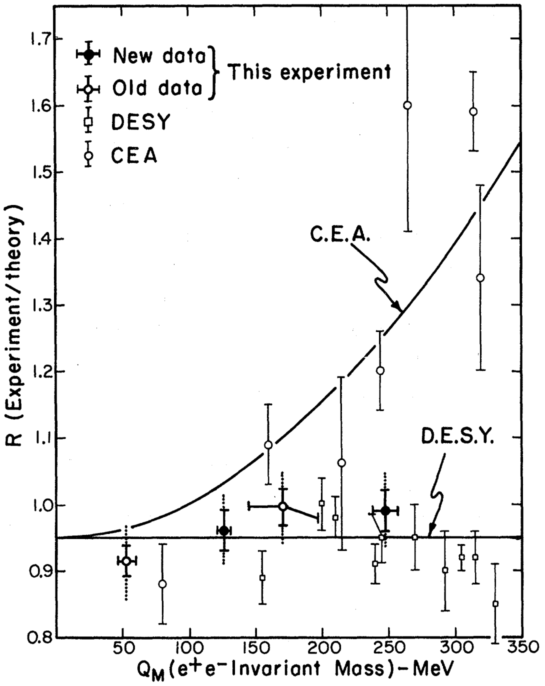

FIG. 2. Results of the present experiment and of previous experiments. The smooth curves are the published fits to the CEA and DESY results which extend up to $Q_M$ = 550 MeV. For the Cornell results, points numbered 2(*a*) and 2(*b*) in Table II are combined into a single point on the graph, as are points 3(*a*) and 3(*b*), and 4(*a*), (*b*), (*c*), and (*d*). The heavy error bars represent errors on the points "relative" to each other. The dotted error bars represent "absolute" errors.

to be in considerably better agreement with QED than with the CEA result. Ignoring the fact that the four points represent a consistent positive slope, the $\chi^2$ probability for a discrepancy from QED, as large as we measure, is 8%.

If one tests for a quadratic departure from QED, of the form $R=a(1+bQ_M^2)$, where $Q_M$ is in MeV, the best fits obtained in the three experiments are, from DESY,

$$a=0.94\pm0.02,\quad b=-(6.1\pm16.5)\times10^{-8};$$

from CEA[7],

$$a=0.67\pm0.03,\quad b=+(513\pm38)\times10^{-8};$$

and from Cornell,

$$a=0.92\pm0.05,\quad b=+(157\pm85)\times10^{-8}.$$

We would like to thank Professor D. R. Yennie for valuable discussions and Dr. G. R. Rouse and Dr. M. Tigner for their efforts on the synchrotron.

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# POSSIBLE *CP*-NONINVARIANT EFFECTS IN $\pi\pi\gamma$ DECAY OF CHARGED *K* MESONS

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Radiative $2\pi$ decays represent one of the few processes where one may reasonably hope to see relatively large *CP*-noninvariant effects. A phenomenological discussion is given of the various effects which may occur.

In this note we examine the manifestly *CP*-noninvariant, and possibly quite large, effects which may be present in radiative $2\pi$ decays of charged *K* mesons.

Measurements[1] of the rate of the decay $K_2^0\to\pi^0+\pi^0$, which prove that a superweak *CP*-noninvariant interaction[2] cannot by itself account for $K_2^0\to2\pi$ decays, encourage us to hope that *CP*-noninvariant effects may be large enough to be detectable in phenomena other than $K^0$ decays. In particular, we would like to verify that *CP*-noninvariant interactions do indeed give rise to *CP*-noninvariant effects. At the same time, we must remember that if the ratio of the $K_1^0\to2\pi$ and $K_2^0\to2\pi$ amplitudes is typical of the relative magnitudes of *CP*-conserving and *CP*-nonconserving amplitudes, one expects *CP*-noninvariant effects only of the order of 0.1%; this would account for the failure to detect *CP* noninvariance in other phenomena, notably in the decay $\Lambda^0\to p+\pi^-$.[3] This suggests that detection of *CP*-noninvariance effects would be made easier if one could either "amplify" the *CP*-nonconserving interaction or, equivalently, suppress the contribution of the *CP*-conserving interaction.

It is well known that the $2\pi$ decay of charged *K* mesons proceeds much more slowly than that of neutral *K* mesons. This is usually explained in terms of the $\Delta I=\frac{1}{2}$ rule, according to which $K^+\to\pi^++\pi^0$ is forbidden.[4] Unfortunately, *TCP* invariance alone requires that the rates for $K^+\to\pi^++\pi^0$ and $K^-\to\pi^-+\pi^0$ should be equal, apart from electromagnetic interactions of order $\alpha$,[5] and there are no other variables in these decays. Thus one cannot expect to see large effects here. We next consider the radiative processes.