1900 MeV in our recent work for nucleon-meson form factors.[2-4] The fact that they are heavier than the photon regulators is quite reasonable and, indeed, the regulator magnitudes lend themselves to this interpretation.

The authors would like to thank Mrs. Judy Lipofsky for carrying out the numerical calculations.

---

*Work supported in part by the U. S. Air Force Office of Scientific Research.

†Present address: Osaka University, Osaka, Japan.

[1] A. E. S. Green, Phys. Rev. 73, 519 (1948), and 75, 1926 (1949).

[2] T. Ueda and A. E. S. Green, to be published.

[3] T. Ueda and A. E. S. Green, Phys. Rev. 174, 1304 (1968).

[4] A. E. S. Green and T. Sawada, Rev. Mod. Phys. 39, 594 (1967), and Nucl. Phys. B2, 276 (1967).

[5] M. Goitein, J. R. Dunning, and R. Wilson, Phys. Rev. Letters 18, 1018 (1967).

[6] W. K. H. Panofsky, Stanford Linear Accelerator Center Report No. SLAC 370, 1967 (unpublished); R. E. Taylor, Stanford Linear Accelerator Center Report No. SLAC 372, 1967 (unpublished).

[7] T. Janssen, R. Hofstadter, E. B. Hughes, and M. R. Yearian, Phys. Rev. 142, 922 (1966).

[8] M. Goitein et al., Phys. Rev. Letters 18, 1016 (1967).

[9] K. Berkelman, M. Feldman, R. M. Littauer, G. Rouse, and R. R. Wilson, Phys. Rev. 130, 2061 (1963).

[10] W. Albrecht, H.-J. Behrend, H. Dorner, W. Flauger, and H. Hultschig, Phys. Rev. Letters 18, 1014 (1967).

[11] T. T. Wu and C. N. Yang, Phys. Rev. 137, B708 (1965).

[12] S. D. Drell, A. C. Finn, and M. H. Goldhaber, Phys. Rev. 157, 1402 (1967).

[13] V. Wataghin, Stanford Linear Accelerator Center Report No. SLAC 359, 1967 (unpublished).

[14] S. Sawada, T. Ueda, W. Watari, and M. Yonezawa, Progr. Theoret. Phys. 28, 991 (1962).

VALIDITY OF QUANTUM ELECTRODYNAMICS AT EXTREMELY SMALL DISTANCES*

H. Alvensleben, U. Becker,† William K. Bertram,† M. Binkley, K. Cohen, C. L. Jordan,†
T. M. Knasel,† R. Marshall,† D. J. Quinn, M. Rohde, G. H. Sanders, and Samuel C. C. Ting†
Deutsches Elektronen-Synchrotron, Hamburg, Germany

(Received 30 October 1968)

We have measured the yield of electron-positron pairs from the reaction $\gamma+\mathrm{C}\to e^+ + e^- + \mathrm{C}$ as a test of the validity of quantum electrodynamics at very small distances. Our results show that first-order quantum electrodynamics correctly predicts the e^+e^- pair yield up to an invariant pair mass of 900 MeV/c^2.

We have measured the yield of wide-angle electron-positron pairs produced in the reaction

$$\gamma+\mathrm{C}\to e^+ + e^- + \mathrm{C} \tag{1}$$

in order to test the validity of quantum electrodynamics (QED) at small distances. The experiment, performed at the DESY 7.5-GeV electron synchrotron, involves the use of a symmetric magnetic spectrometer and counter techniques to detect the pairs.[1] Care was taken to eliminate sources of systematic error and contributions from the e^+e^- decay of the vector mesons ρ, ω, and φ.

The three first-order diagrams contributing to Reaction (1) are shown in Fig. 1(a). The first two, the Bethe-Heitler graphs, have been calculated by Bjorken, Drell, and Frautschi.[2] The contribution of the third, the Compton graph, was reduced to $\leq 8\%$ by restricting the measurement to small opening angles. Interference between the Bethe-Heitler and Compton amplitudes vanishes when the electron and positron are observed symmetrically, as in this experiment. At symmetry, if E_+ is the energy of the positron and θ is its production angle, the momentum transfer t to the virtual electron is given by $t^2 = 2E_+{}^2\theta^2$, while the momentum transfer q to the recoil nucleus is given by $q^2 = E_+{}^2\theta^4$. The invariant pair mass is $M = \sqrt{2}\,t$. Under the kinematical conditions of this experiment, $M \leq 900\ \mathrm{MeV}/c^2$ and $\langle q^2\rangle^{1/2} \leq 90\ \mathrm{MeV}/c$. Because q is small, a heavy-nucleus target may be used; the yield is proportional to Z^2, and nuclear form-factor corrections to the yield can be accurately made.

Experimental procedure.—A bremsstrahlung beam from the DESY 7.5-GeV electron synchrotron was incident on a carbon target. Electrons and positrons were detected in a symmetric spectrometer shown in Fig. 1(b), which has been described in detail previously.[1,3] Briefly, the apparatus had the following properties essential to the experiment:

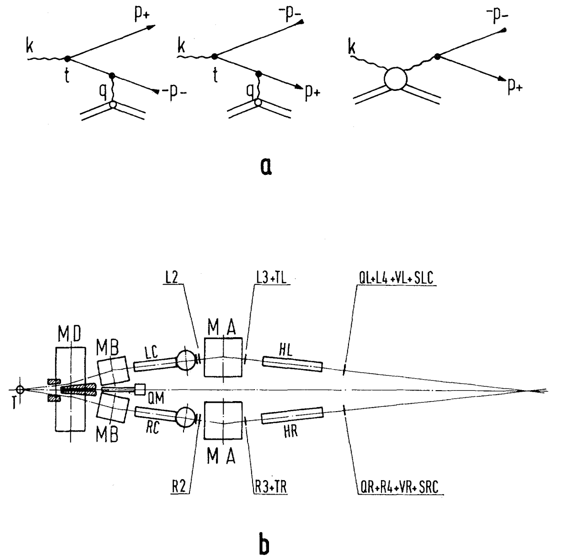

FIG. 1. (a) Feynman diagrams for electron-positron pair production. (b) Experimental arrangement, consisting of five dipole magnets (MD, MB, MA), trigger counters ($L2$-$L4, R2$-$R4$), large-aperture threshold Čerenkov counters (LC, RC, HL, HR), shower counters (SLC, SRC), and hodoscopes (TL, QL, VL, TR, QR, VR).

(1) The acceptance of the spectrometer was not limited by the edges of magnets or by shielding, being defined instead by the scintillation trigger counters L_2-L_4, R_2-R_4. All counters were located such that their surfaces were not directly exposed to the target.

(2) The spread in position and angle of the particles as they passed through all the threshold Čerenkov counters and shower counters was nearly independent of the spectrometer setting. Therefore, any slight inefficiency of these counters could not lead to a momentum-transfer-dependent effect.

(3) The spectrometer had a large acceptance but was designed to recombine rays of constant $p\theta \sim M$ and therefore had a good mass resolution. For a typical spectrometer setting, the acceptance limits were $\Delta p/p = \pm 0.25$, $\Delta\theta/\theta = \pm 0.12$, $\Delta M/M \simeq \pm 0.10$, and $\Delta\psi = \pm 8$ mrad, where ψ is the projected vertical production angle.

The single-arm electron rate was as much as 10^4 times higher than the electron-pair rate. Therefore, contributions from random coincidences were continuously monitored with circuits of different resolving times. This correction was always kept less than 2%.

The spectrometer contained four threshold Čerenkov counters. Two Čerenkov counters and two shower counters were sufficient to define an electron pair, the two remaining counters being used to check the pion rejection throughout the experiment. Even at the largest pair opening angle, pion pairs never contributed more than 1% to the measured e^+e^- pair yields. Muons as well as pions were rejected by the threshold and shower counters. The shower counters were <1% efficient on muons, as measured with cosmic rays. Muon contamination (including that from $\pi \rightarrow \mu\nu$ decay) is estimated to be <0.1%.

To eliminate possible asymmetries of the spectrometer, half of the data were taken at each polarity.

Analysis. – The e^+e^- yield predicted by QED was obtained by integrating $d\sigma_{\mathrm{BH}}$ over the spectrometer acceptance, the target position, and the bremsstrahlung spectrum. $d\sigma_{\mathrm{BH}}$ denotes the sixfold-differential Bethe-Heitler cross section[2]

$$d\sigma_{\mathrm{BH}} = d^6\sigma/dE_+ dE_- d\cos\theta_+ d\cos\theta_- d\psi_+ d\psi_- .$$

This integration was performed by a Monte Carlo technique. The effects of bremsstrahlung and multiple scattering in the target and along the spectrometer were included in the calculation. The decrease in the theoretical yield due to bremsstrahlung, while significant, varied little over the spectrometer settings, ranging from 38 to 45%. The effect of multiple scattering, a decrease in the theoretical yield, was always less than a few per cent. A sufficient number of events was treated by the Monte Carlo technique to determine the theoretical yield within an uncertainty of ±1.5%.

In calculating the theoretical yield we used an analytic expression for the carbon elastic form factor. The inelastic contribution was also taken into account.[4]

Contributions from $\rho \rightarrow e^+e^-$ were calculated using our previous measurement[5] of the ρ leptonic decay obtained with the same apparatus. In the present measurement, these contributions were reduced to $\leq 8\%$ by taking data at half-angles $\theta \leq 7.7°$. Contributions from ω and φ decay were negligible at all settings.

To keep radiative corrections and bremsstrahlung losses constant, the ratio k/k_{max} was held fixed.

Results and Conclusions. – Figure 2 shows our results, plotted as a function of the invariant mass of the e^+e^- pair, together with our previous measurements.[1] Corrections have been made for the dead time of the electronics, accidental coincidences, beam attenuation in the

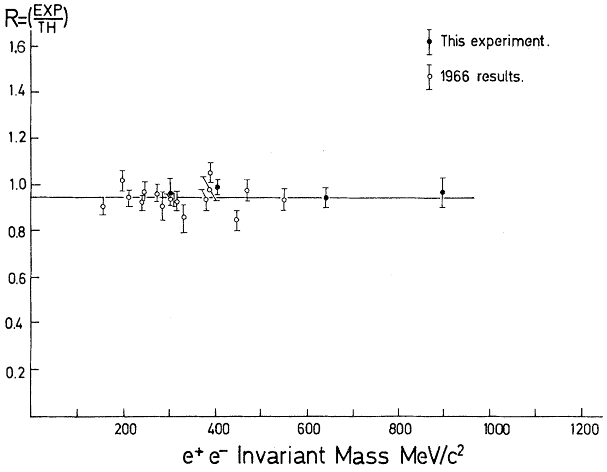

FIG 2. The ratio R of experiment to theory is shown for this measurement together with our earlier results. The normalization uncertainty of ≃5 % is not included.

target, and target-out rates. As discussed earlier, pion contamination was measured to be less than 1%, and the contribution of the process $\rho \rightarrow e^+e^-$ to the data was removed.

It has been shown by Kroll[6] that a breakdown of QED consistent with very general requirements must be of at least fourth power in M. The best fit of our combined data with R = (experimental yield/theoretical yield) $= A(1 \pm M^4/\Lambda^4)$ is

$$R = 0.94[1 \pm 0.01 + (0.3 \pm 1.1) \times 10^{-13} M^4],$$

where M is expressed in MeV/c^2. The uncertainty in the normalization, estimated to be 5%, is not included.

This fit, which is consistent with a straight line of zero slope, yields the constraints on the cutoff parameter Λ shown in Table I.

In conclusion, this experiment shows that first-order QED correctly predicts the e^+e^- pair rate over a region from 150 to 900 MeV/c^2 in pair invariant mass. It is seen in Table I that this experiment provides the most sensitive test of the electron propagator in the space-like region to date.

Table I. Constraints on the cutoff parameter Λ (in GeV/c^2).

	Most likely	68% confidence	95% confidence
(a) $R = A(1 + M^4/\Lambda^4)$	2.4	>1.8	>1.6
(b) $R = A(1 - M^4/\Lambda^4)$	∞	>2.1	>1.7

We are grateful for the support of Professor W. Jentschke, Professor M. W. Teucher, Professor V. F. Weisskopf, Professor P. Demos, Professor A. G. Hill, Professor H. O. Wuester, Professor H. Joos, and Professor G. Weber, who made this collaboration possible. We thank also Dr. D. Lublow and Mr. H. Kumpfert for technical help.

---

*Accepted without review under policy announced in Editorial of 20 July 1964 [Phys. Rev. Letters 13, 79 (1964)].

†Also Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts.

[1] J. G. Asbury, William K. Bertram, U. Becker, P. Joos, M. Rohde, A. J. S. Smith, S. Friedlander, C. L. Jordan, and Samuel C. C. Ting, Phys. Rev. 161, 1344 (1967).

[2] J. D. Bjorken, S. D. Drell, and S. C. Frautschi, Phys. Rev. 112, 1409 (1958).

[3] For this measurement, the angle of bend in the dipole magnets MA was reduced to −12.93° to enable detection of particles of higher momentum.

[4] J. H. Fregeau, Phys. Rev. 104, 225 (1956); S. D. Drell and C. L. Schwartz, Phys. Rev. 112, 568 (1958); W. L. Faissler, F. M. Pipkin, and K. C. Stanfield, Phys. Rev. Letters 19, 1202 (1967).

[5] J. G. Asbury et al., Phys. Rev. Letters 19, 869 (1967).

[6] For a discussion of possible modifications of QED, see N. M. Kroll, Nuovo Cimento 45A, 65 (1966).