Electron-Positron Elastic Scattering at a Center-of-Mass Energy of 4 GeV*

R. Madaras,† R. Averill, G. Hanson, A. Hofmann, J. Koch, L. Law, M. Law, J. Leong, A. Litke, R. Little, H. Mieras, H. Newman, J. M. Paterson, R. Pordes, J. Sisterson, K. Strauch, G. Tarnopolsky, G.-A. Voss, Richard Wilson, and H. Winick

Harvard University, Cambridge, Massachusetts 02138; Cambridge Electron Accelerator, Cambridge, Massachusetts 02138; Massachusetts Institute of Technology, Cambridge, Massachusetts 02139; Southeastern Massachusetts University, North Dartmouth, Massachusetts 02747; and Technion, Haifa, Israel

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We have measured the cross section for electron-positron elastic scattering at 4 GeV center-of-mass energy for scattering angles between 50° and 130°. We have calculated the theoretical (quantum-electrodynamics) cross section including a radiative correction calculated using the peaking approximation. The ratio of the experimental and theoretical cross sections is 0.88 ± 0.10. We therefore obtain new bounds on the quantum-electrodynamics breakdown parameters, $\Lambda_+ > 12$ GeV and $\Lambda_- > 6$ GeV.

We have used the electron-positron colliding-beam facility at the Cambridge Electron Accelerator (CEA) to measure Bhabha scattering ($e^+e^- \rightarrow e^+e^-$) at an energy of 4 GeV and angles $50^\circ < \theta < 130^\circ$, both in the center-of-mass system. The charge of the final-state particles was not determined.

The process occurs both by the annihilation amplitude with timelike four-momentum transfer $[q^2 = 4E^2 = 16(\text{GeV}/c)^2]$ and by the scattering amplitude with spacelike four-momentum transfer $(q^2 = -4E^2 \sin^2\theta/2)$ whose average value was -5.3 $(\text{GeV}/c)^2$. The spacelike diagram dominates the process.

2-GeV electron and positron beams collided head-on in a straight section of a bypass[1] to the main synchrotron. These beams were strongly focused by a "low beta" section to increase the probability of collision. The average current in each beam was typically 3 mA, the peak luminosity (defined as the counting rate divided by the cross section) was 3×10^{28} cm^{-2} sec^{-1} and the time-integrated luminosity was $(1.06 \pm 0.10) \times 10^{34}$ cm^{-2}.

The measurement of luminosity was based on the event rate from the double bremsstrahlung reaction $e^+e^- \rightarrow e^+e^-\gamma\gamma$. This process is dominated by low momentum transfers, where the validity of quantum electrodynamics has been verified.

The bremsstrahlung γ rays in a small angular region around the incident electron and positron beams ($\theta = 0^\circ$ and 180°) were measured by lead-scintillator sandwich counters placed outside the charged-particle trajectories. These counters had been tested, calibrated, and used in an experiment at the CEA.[2]

Random coincidences were subtracted continuously from true coincidences using the difference in arrival time for pulses from each counter. The threshold energy k_{min} for γ-ray detection was obtained by comparing the measured pulse-height distribution from gas bremsstrahlung with the theoretical distribution into which the experimentally determined resolution had been folded. The theoretical[3-5] double bremsstrahlung calculation included the geometric counter acceptance determined by carefully surveyed limiting apertures. Approximately half the experiment was complete before it was realized that uncertainty in the measurement of the luminosity would be reduced by raising the value of k_{min}. The corrections to the luminosity measurement of the first half of the experiment are detailed in Table I.

The electron-positron pair were detected in a nonmagnetic scintillation-counter–magnetostrictive wire spark-chamber assembly[6] (bypass online detector) as drawn in Fig. 1. This consisted of four quadrants. In each quadrant the first six spark-chamber gaps define the particle trajectories; the next six gaps are interleaved with lead which creates a shower. Counters in the shower region were used to trigger the apparatus as well as to measure the energy of the shower. The detector is sensitive to center-of-mass scattering angles from 45° to 135° with total coverage of 2π sr. Cosmic rays were rejected by time of flight between the outer scintillators.

Electron-positron elastic scattering events were identified by the following criteria: (1) The particle trajectories intersect in the interaction region (9.5 cm long, 2 cm high and wide) which is small because of the high (475 MHz) rf frequency and strong magnetic focusing. (2) Each

TABLE I. Results, counts, cross sections, and correction factors (correction factors multiplicative; errors in percent).

Luminosity - Experiment		
Number of double bremsstrahlung counts (Run 1)	190,468	± 0.3%
Background subtraction error	1.00	± 0.5%
Uncertainty in counter threshold (k/E = 0.123)	1.00	± 8.9%
Counter resolution correction	1.06	± 3.9%
Losses due to γ ray conversion before veto counter	1.27	± 1.5%
Dead time losses	1.01	± 0.6%
C_1 = Corrected double bremsstrahlung counts (Run 1)	259,000	± 9.8%
Luminosity - Theory		
Cross section - infinite aperture	5.968×10^{-29} cm^2	
Losses due to finite geometric aperture	0.827	± 2.8%
Radiative correction	0.976	± 0.5%
Contamination from $e^+e^- \to \gamma\gamma$	1.001	± 0.1%
Corrected cross section = $\sigma(k/E = 0.123)$	4.82×10^{-29} cm^2	± 2.8%
Run 1: $\int L\,dt\ (k_{\min}/E = 0.123) = C_1/\sigma$	5.36×10^{33} cm^2	±10.4%
Run 2: $\int L\,dt\ (k_{\min}/E = 0.327) = C_2/\sigma$	5.28×10^{33} cm^2	± 8.1%
Sum: $\int L\,dt$	1.06×10^{34} cm^2	± 9%
Cross Section - Experimental		
Number of events	260	± 6.2%
Correction for cosmic rays and other background	0.99	± 0.9%
ee events lost in cuts and veto	1.007	± 0.4%
Trigger, scan, track efficiencies	1.007	± 1%
Absorption in pipe, fibre holder, etc.	1.01	± 1%
θ uncertainty and resolution	1.00	± 1.5%
Beam polarization	1.00	± 1%
N = corrected number of events	263.5	± 6.7%
$\sigma_{\text{exp}} = N/\int L\,dt = (2.49 \pm 0.28) \times 10^{-32}$ cm^2		
Cross Section - Theory		
Cross section with no radiative correction and $50^\circ < \theta < 130^\circ$, $\Delta\phi = 0.7 \times 2\pi$	3.04×10^{-32} cm^2	
Geometrical acceptance	0.99	± 0.4%
Radiative correction	0.97	± 2.0%
Increase of radiative correction at edges	0.97	± 1.0%
$\sigma_{\text{theory}} = (2.82 \pm 0.07) \times 10^{-32}$ cm^2		

particle produces a large pulse in the shower counter system. (3) The angle in space between the two tracks is less than 15°.

Figure 1(a) shows a typical $e^+e^- \to e^+e^-$ event satisfying these three criteria. The view is a projection perpendicular to the beam line. Figure 1(b) shows superimposed projected views at 75° and 105° to the beam direction which were used for three-dimensional reconstruction of tracks and for resolution of multitrack ambiguities.

260 events with scattering angles between 50° and 130° were accepted for data analysis. This angular region, somewhat smaller than the geometric acceptance, was chosen to ensure >99% detection efficiency for electrons and positrons. Corrections and experimental cross sections are listed in the table.

Because neither cosmic rays nor electron-gas scattering events give tracks whose intersection point bunches in the interaction region, their contribution is easily estimated. A search was also made for electron-gas scattering by operation with both e^- and e^+ single beams at higher intensity and with a high gas pressure. No events were found in single beam runs with a product of current and gas pressure equal to 50% of the running with luminosity.

The theoretical cross section was corrected for radiative effects according to a formula of Tavernier[7] as used also in the similar work at Orsay and Frascati.[8,9] This calculation[10] uses the "peaking approximation," which predicts that the azimuthal angle between the scattered particles differs from 180° by $\Delta\varphi = 0$. In fact we find that $(94.8 \pm 1.4)\%$ of the tracks have $\Delta\varphi < 5^\circ$ [with criterion (3) above not applied].

This is in qualitative agreement with similar

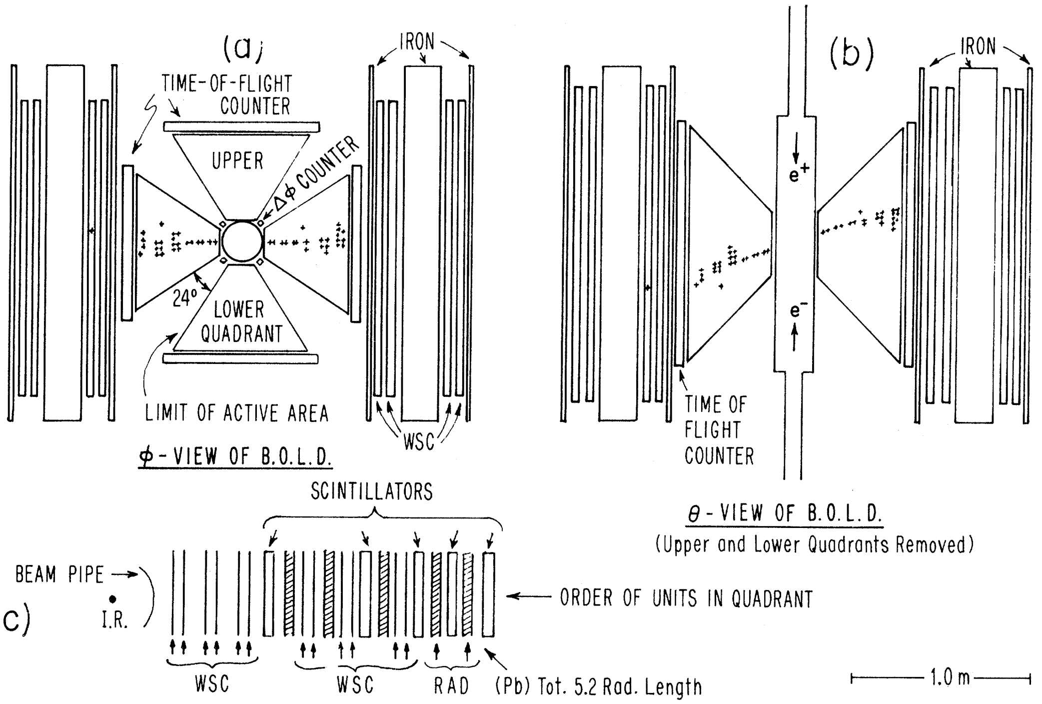

FIG. 1. Layout of the bypass on-line detector, showing a typical event.

data from Frascati,[8] and we consider the clear clustering of events around $\Delta\varphi = 0$ as evidence that the peaking approximation is adequate to correct the total cross section. A more complete calculation is being made by Berends *et al.*[11]

When the measured cross section is compared to the cross section calculated from quantum electrodynamics, including the radiative correc-

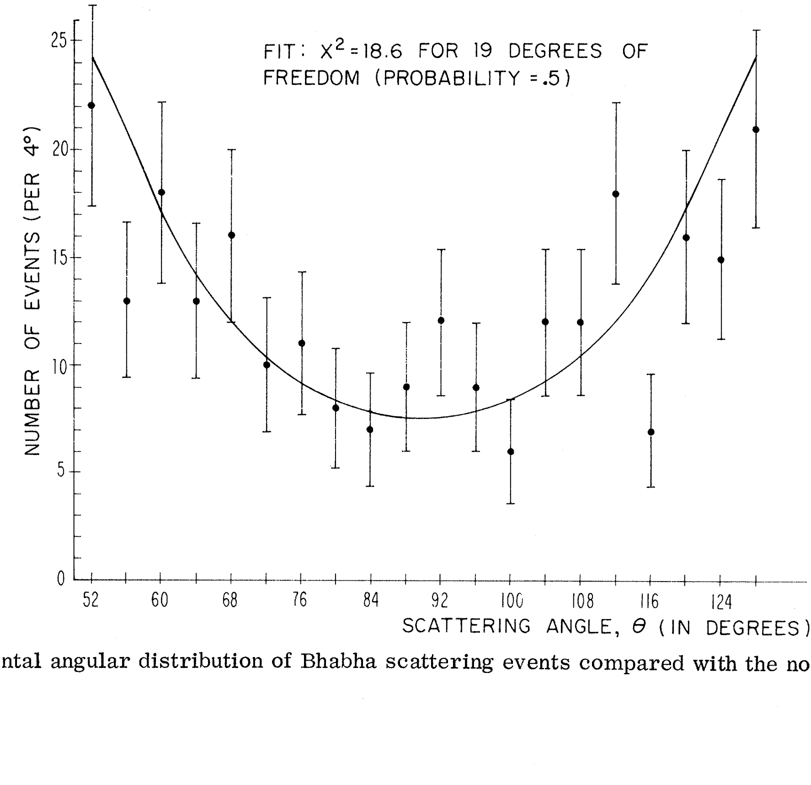

FIG. 2. Experimental angular distribution of Bhabha scattering events compared with the normalized prediction of QED.

tion as noted above, we find

$$\sigma_{\text{expt}}/\sigma_{\text{theor}} = 0.88 \pm 0.10.$$

We do not, therefore, see a significant deviation from quantum electrodynamics (QED). One way of determining the significance of this result is to assign any possible deviation from QED to a heavy photon of mass Λ with either a positive (Λ_+) or negative metric (Λ_-). This model leads to a modification of the photon propagator by a factor of $F(q^2) = 1 \pm q^2/(q^2 - \Lambda_+^2)$, where q^2 is the square of the four-momentum of the virtual photon.

With 95% confidence we find $\Lambda_+ > 12$ GeV, $\Lambda_- > 4.5$ GeV. If $\Lambda^2 \gg 4E^2$ ($= q^2$), we find $F(q^2) = 1 \mp q^2/\Lambda_\pm^2$ which is the conventional parametrization. Then we find $1/\Lambda_+^2 = -0.011 \pm 0.009$ and with 95% confidence $\Lambda_+ > 12$ GeV, $\Lambda_- > 6$ GeV. We note that modifications of QED by factors of this type and magnitude will not affect the theoretical cross section for the monitoring reaction.

The previous best verifications of the validity of quantum electrodynamics at large momentum transfers come from similar measurements at Frascati.[8,9] These authors find $\Lambda_+ > 3.9$ GeV, and $\Lambda_- > 5.4$ GeV.

We have also investigated the angular distribution in this reaction. For each event the angle θ was obtained by averaging the two values measured for the individual electron and positron tracks. The experimental distribution is shown in Fig. 2 where it is compared with the QED predictions modified to take into account the geometric acceptance and radiative corrections.[12] The theoretical curve is normalized to give the best fit to the data. We find a $\chi^2 = 18.6$, with nineteen degrees of freedom, corresponding to a probability of 50%.

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†Now at Laboratoire de l'Accélérateur Linéaire, 91 Orsay, France.

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[11] F. Berends *et al.*, to be published.

[12] Five events were excluded from this figure because extra sparks made the information difficult to recover from tape.