

Electron-Positron Elastic Scattering at 5 GeV Center-of-Mass Energy*

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We have measured the cross section, the distribution of scattering angles, and the distribution of noncoplanarity angles for electron-positron elastic scattering at 5 GeV c.m. energy. An analysis based on 230 events with scattering angles between 50 and 130° yields a ratio of the experimental to theoretical quantum-electrodynamic cross section of 1.03 ± 0.09 . The scattering-angle and noncoplanarity-angle distributions are also found to be in excellent agreement with the quantum-electrodynamic predictions.

We have extended our previous electron-positron colliding-beam studies^{1,2} at the Cambridge Electron Accelerator Laboratory to a c.m. energy of 5 GeV. We report here measurements of the cross section and angular distribution for elastic scattering carried out with electron and positron beams each with energy $E = 2.5$ GeV over a range of scattering angles $50 < \theta < 130^\circ$. Both the scattering amplitude with spacelike four-momentum transfer ($\bar{q}^2 = 8.3 \text{ GeV}^2/c^2$) and the annihilation amplitude with timelike four-momentum transfer ($q^2 = +25 \text{ GeV}^2/c^2$) contribute to the observed scattering process.

We used the same particle detector BOLD^{1,3} and the same luminosity monitor^{4,5} as in our previous measurements at 4 GeV. Improvements in luminosity-monitor electronics and shower-counter energy-calibration techniques were applied to the 5-GeV experiment; they have also yielded a better luminosity value for the 4-GeV experiment. We compare the experimental results with theoretical calculations using the more precise radiative corrections⁶ which have become available recently.

The e^+ and e^- beams collided head on. The scattered leptons were detected in the four quadrants of BOLD, a nonmagnetic array of wire spark chambers, counters, and radiators covering 2π sr. The apparatus accepts scattering angles θ between 45 and 135° with projected azimuthal angles φ covering 73% of the 2π radians (the z axis is defined by the direction of the e^- beam).

A computer scan used preliminary criteria to find about 800 Bhabha scattering candidates out of 2.3×10^6 triggers. With the aid of a computer-assisted interactive display, 225 events were then selected by applying the following require-

ments:

(1) The particle trajectories originate in the interaction region: $\Delta x \times \Delta y \times \Delta z = 2 \times 2 \times 10.8 \text{ cm}^3$. The length Δz is determined by the beam bunch length; the transverse dimensions arise mainly from multiple scattering and the precision of track reconstruction.

(2) Each particle leaves sparks in at least four of the first six low-mass gaps, produces secondary sparks in the next six high- Z gaps, and makes a large pulse corresponding to > 800 MeV in the shower-counter system.

(3) Each particle scatters into the region $50 < \theta < 130^\circ$ and its azimuthal angle φ lies within 30° of a quadrant normal. The detection efficiency for 2.5-GeV electrons and positrons satisfying these angular criteria has been shown^{4,5} to be $> 99.5\%$.

(4) The two tracks are within 15° of collinearity.

A computer rescan using less restrictive criteria than the first scan yielded about 80 000 possible events in addition to those already found. Imposition of the final criteria yielded only five additional events. The final sample, based on two scans with combined efficiency of $(99.5 \pm 0.5)\%$, thus consists of 230 ± 15.2 events. After correcting for various minor effects such as (1) contamination from cosmic rays and $e^+e^- \rightarrow \gamma\gamma$ (where both photons convert in the beam pipe), (2) loss of events due to cuts, and (3) trigger inefficiency, we obtain the corrected number of events $N_{ee} = 230.5 \pm 15.7$.

Contamination from beam-gas interactions has been shown to be negligible: In single-beam runs at increased gas pressure such that the integral of current times pressure was equivalent to seventeen data-taking runs, no acceptable events were found. Computations^{5,7} using the equivalent-

TABLE I. Typical calculation of the double-bremsstrahlung correction factor C .

Counter resolution, C_1	1.045 \pm 1.5%
Counter threshold uncertainty, C_2	1.000 \pm 4.3%
Counts lost as a result of photon conversion in synchrotron-radiation absorbers, C_3	1.25 \pm 1%
Dead-time loss of veto counters, C_4	1.031 \pm 0.5%
Counts lost as a result of finite-geometric apertures, C_5	1.126 \pm 1.3%
Radiative correction, C_6	1.012 \pm < 0.1%
	$C = \prod_i C_i = 1.535 \pm 4.9\%$

photon approximation⁸ show the $e^+e^- \rightarrow e^+e^-e^+e^-$ contamination to be $\approx 0.1\%$.

The luminosity was measured using the double-bremsstrahlung (DB) process which is dominated by low momentum transfers. DB events were observed as coincidences in two lead-scintillator sandwich counters placed at 0° with respect to the e^+ and e^- beams. Accidentals due to single bremsstrahlung from the residual gas were monitored continuously and amounted to 20% of the signal. After subtraction of accidentals, $N_{2\gamma}$ (the number of measured DB events) is obtained. The time-integrated luminosity L_i is then calculated using

$$L_i = \int L dt = (N_{2\gamma} / \sigma_{2\gamma}) C,$$

where L is the luminosity, $\sigma_{2\gamma}$ is the DB cross section calculated from quantum electrodynamics (QED), and C is a correction factor dependent on the characteristics of the luminosity monitor some of which required continual monitoring. Table I details the calculation of C for a period corresponding to 20% of the data. Full details are found in Refs. 4 and 5.

The value of $\sigma_{2\gamma}$ is a function of $\epsilon_1 = k_1/E$ and $\epsilon_2 = k_2/E$ where k_1 and k_2 are the "threshold energies" of photons for which the efficiency of the two luminosity counters has risen to 50%. These threshold energies are determined to an accuracy of $\pm 2\%$ by comparing experimental spectra of single bremsstrahlung from residual gas with a theoretical spectrum calculated by folding the shower-counter resolution⁵ into the QED single-bremsstrahlung spectrum.⁹ Typical values were $\epsilon_1 = 0.340 \pm 0.007$ and $\epsilon_2 = 0.258 \pm 0.006$. The uncertainties in these energies dominate the uncertainty in the value of L_i . We find $L_i = (1.25 \pm 0.06) \times 10^{34} \text{ cm}^{-2}$.

With this value and the observed number of events N_{ee} we obtain the following value for the

experimental $e^+e^- \rightarrow e^+e^-$ integrated cross section $\sigma_{\text{exp}}(2E)$: $\sigma_{\text{exp}}(5 \text{ GeV}) = (1.85 \pm 0.16) \times 10^{-32} \text{ cm}^2$.

With our increased knowledge of the shower-counter resolution and the use of more accurate analysis techniques, we have recalculated the value of L_i for the 4-GeV experiment^{1,4} and find $L_i = (1.02 \pm 0.09) \times 10^{34} \text{ cm}^{-2}$ which is 4% less than the previously quoted number. We now obtain $\sigma_{\text{exp}}(4 \text{ GeV}) = (2.60 \pm 0.28) \times 10^{-32} \text{ cm}^2$.

To calculate σ_{QED} , the theoretical cross section for this experiment, radiative corrections must be applied to the lowest-order (α^2) cross section. A computer program developed by Berends, Gaemers, and Gastmans⁶ is used which calculates exactly to order α^3 the contributions of vertex modification, vacuum polarization, and two-proton diagrams to the cross section. The program also accounts for radiative events $e^+e^- \rightarrow e^+e^-\gamma$ lost at the edges of the accepted angular region near $\theta = 50$ and 130° . The computed radiative corrections are $(-7.7 \pm 0.8)\%$ at both energies as compared with our previous 4-GeV estimate of $(-6.1 \pm 2.2)\%$ which used the peaking approximation.

We obtain the following ratios¹⁰ $R(2E) = \sigma_{\text{exp}} / \sigma_{\text{QED}}$:

$$\begin{aligned} R(5 \text{ GeV}) &= 1.03 \pm 0.09, \\ R(4 \text{ GeV}) &= 0.93 \pm 0.10. \end{aligned} \quad (1)$$

Lower-energy measurements¹¹ of R are also generally consistent with the value 1.

If any possible deviation from QED is ascribed to the existence of a massive photon with either a positive (Λ_+) or a negative (Λ_-) metric, the photon propagator is modified by a factor $F(q^2) = 1 \pm q^2 / (q^2 - \Lambda_\pm^2)$, where q^2 is the square of the four-momentum of the virtual photon. The quoted values of R then determine $\Lambda_+ > 9.8 \text{ GeV}$, $\Lambda_- > 10.5 \text{ GeV}$ at $2E = 5 \text{ GeV}$ and $\Lambda_+ > 9.7 \text{ GeV}$, $\Lambda_- > 10.5 \text{ GeV}$ at $2E = 4 \text{ GeV}$.

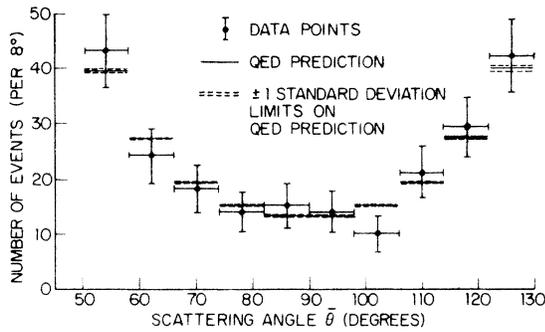


FIG. 1. Angular distribution of scattered particles in elastic $e^+e^- \rightarrow e^+e^-$ scattering at the energy $2E = 5$ GeV, and the prediction of QED normalized to the total number of observed events.

> 4.7 GeV at $2E = 4$ GeV at the 95% confidence level.

In addition to the experimental integrated-cross-section values, the observed distributions in scattering angle and noncoplanarity angle also provide tests of predictions of QED.

Figure 1 shows the 5-GeV experimental distribution in the scattering angle $\bar{\theta}$, where $\bar{\theta}$ is the average of the two θ values measured for the scattered e^+ and e^- . This distribution is compared to the predictions of QED taking into account radiative corrections⁶ and the geometric acceptance: The data are fitted by the theoretical distribution with $\chi^2 = 3.7$ (9 degrees of freedom) corresponding to a probability > 90%.

The α^3 term in the QED calculation can be checked directly by comparing the experimental $e^+e^- \rightarrow e^+e^-\gamma$ distribution in the noncoplanarity angle¹² Ψ with the predictions of QED. The complete sample of noncoplanar events is obtained by relaxing criterion (4) for event selection.

As in other recent experiments¹¹ we calculate the ratio

$$\eta_{\text{exp}}(\Psi_{\text{min}}) = N(\Psi)/N_{\text{tot}}, \quad (2)$$

where $N(\Psi)$ is the number of events with $\Psi > \Psi_{\text{min}}$ and N_{tot} is the total number of events in the $e^+e^- \rightarrow e^+e^-$ sample. The corresponding theoretical ratio $\eta_{\text{QED}}(\Psi_{\text{min}})$ was calculated using another computer program developed by Berends, Gaemers, and Gastmans,⁶ which is exact to order α^3 . The results displayed in Table II show excellent agreement between experiment and theory.

TABLE II. Noncoplanarity-angle distribution.

Ψ_{min} (deg)	η_{exp} (%)	η_{QED} (%)
5	3.5 ± 1.3	3.6 ± 0.3
10	2.6 ± 1.1	2.1 ± 0.3
20	1.7 ± 0.9	1.1 ± 0.3

This experiment has been made possible by the outstanding efforts of the staff of the Cambridge Electron Accelerator Laboratory, in particular, G.-A. Voss and A. Hofmann. They raised the beam energy from 2.0 to 2.5 GeV and then ran the colliding-beam system for our experiment under difficult circumstances. We are also indebted to G. Hanson, J. Koch, A. Litke, R. Madaras, and J. M. Paterson for their very great contribution to the entire BOLD system. The help of the Harvard Cyclotron Laboratory staff is gratefully acknowledged.

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¹² Ψ is defined as the angle between two planes each of which contains the beam axis and either the scattered electron or positron.