Experimental Test of Higher-Order QED and a Search for Excited Muon States

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The reactions $e^+e^-\to\mu^+\mu^-\gamma\gamma$ and $e^+e^-\to\mu^+\mu^-\gamma$ have been studied at $\sqrt{s}=29$ GeV with the MAC detector at the SLAC storage ring PEP. The measured cross sections, charge asymmetry, and invariant-mass distributions are in good agreement with the predictions of QED theory. Limits are derived for the production of excited muon states.

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The processes $e^+e^-\to\mu^+\mu^-\gamma\gamma$ and $e^+e^-\to\mu^+\mu^-\gamma$ are appropriate for direct tests of higher-order quantum electrodynamics (QED) theory at large momentum transfer and a search for excited states of the muon. The MAC detector at the electron-positron storage ring PEP at Stanford Linear Accelerator Center identifies and momentum analyzes muons and photons over 96% of 4π solid angle, thus providing a powerful tool for such studies. The results reported here are based on an integrated luminosity of 48 pb^{-1} at $\sqrt{s}=29$ GeV and include the first published measurements (and comparison with theory) of $\mu\mu\gamma\gamma$ final states and the charge asymmetry for the reaction $e^+e^-\to\mu^+\mu^-\gamma$.

High-energy e^+e^- colliding-beam experiments provide a direct test of QED at high momentum transfer and small distances. Such tests have been carried out for the lowest-order reactions such as Bhabha scattering, muon-pair, and gamma-pair productions. It is important to extend tests of this very successful theory to higher orders of perturbation theory and over as wide a kinematic range as possible. A test to order α^4 and $Q^2<100$ (GeV/c)^2 has been reported using $e^+e^-\to e^+e^-\mu^+\mu^-$.[1] The processes $e^+e^-\to\mu^+\mu^-\gamma$ and $e^+e^-\to\mu^+\mu^-\gamma\gamma$ are predicted by QED to occur at order α^3 and α^4 as a result of initial- and final-state radiation accompanying the annihilation of e^+e^- into muon pairs and probe Q^2 up to $E_{\mathrm{c.m.}}{}^2$ [841 (GeV/c)^2 for this experiment]. Furthermore, there have been many theoretical discussions of the possibility that quarks and leptons are composed of more elementary constituents,[2] in which case there may exist low-lying excited states of these particles. An excited state of the muon

(μ^*) could be produced by $e^+e^- \to \mu^{*\pm}\mu^{*\mp}$ or $e^+e^- \to \mu^{*\pm}\mu^{\mp}$ depending on the μ^* mass. If one assumes that the μ^* decays promptly via $\mu^* \to \mu\gamma$, such events would result in $\mu\mu\gamma\gamma$ or $\mu\mu\gamma$ final states but with $\mu\gamma$ invariant-mass combinations clustering at a particular value. Searches for such effects have been performed at lower energies[3] and a search at energies comparable to the present experiment has been made at PETRA.[4]

A detailed description of the MAC detector has been given elsewhere.[5] Charged particles are analyzed in a central drift chamber consisting of ten layers of drift wires inside a solenoid coil with a magnetic field of 5.7 kG, with momentum resolution $\Delta p/p \simeq 0.065 p \sin\theta$ for $25° \leq \theta \leq 155°$. The total polar angle acceptance is $17° \leq \theta \leq 163°$. Photons are detected by calorimeters surrounding the solenoid coil in the form of a central hexagonal cylinder with planar end caps. These shower detectors consist of layers of lead (central) or steel (end caps) interspersed with proportional wire chambers. The energy and angular resolutions of the central (end-cap) chambers average about $\Delta E/E \simeq 20\%/\sqrt{E}$ ($45\%/\sqrt{E}$), $\Delta\varphi \simeq 0.8°$ (2.0°), $\Delta\theta \simeq 1.3°$ (1.5°), respectively. The electromagnetic calorimeters are surrounded by hadron calorimeters, which consist of proportional wire chambers interspersed between steel plates totaling 5 absorption lengths. These steel plates are magnetized at 17 kG and surrounded by drift chambers to form a toroidal spectrometer for muons. The charged tracks reconstructed in the central drift chamber are extrapolated to the electromagnetic and hadron calorimeters and the calorimeter information associated with the charged tracks is used for particle identification. The combination of inner and outer drift chamber systems is used to determine the muon charge.

$\mu\mu\gamma$ final state.—The event selection criteria required the following: (1) two charged tracks reconstructed to the interaction vertex by the central drift chamber, with an acollinearity angle greater than 10°; (2) both charged particles associated with electromagnetic shower energy less than 1.4 GeV (the minimum ionizing peak is at 0.3 GeV) with at least one of the two particles penetrating all the hadron calorimeter layers; (3) one neutral electromagnetic shower (not associated with a charged track) with energy greater than 1 GeV; and (4) the three-particle system to be fitted by the $e^+e^- \to \mu^+\mu^-\gamma$ kinematic four-constraint hypothesis with a confidence level greater than 0.5% and the invariant mass of the dimuon system to be greater than 1.5 GeV. Criterion (1) rejects collinear events such as Bhabha, mu pairs, and cosmic rays, and criterion (2) rejects radiative Bhabha events. Criteria (3) and (4) discriminate against $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ events. 282 events satisfy these requirements. From Monte Carlo studies it is estimated that 4.1 $e^+e^- \to e^+e^-\mu^+\mu^-$ and 5.3 $e^+e^- \to \tau^+\tau^-$ events remain as background in the sample.

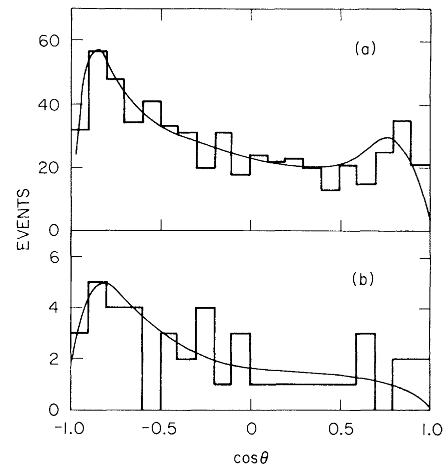

FIG. 1. (a) Polar angle distribution of muons for the $\mu\mu\gamma$ final state. The solid curve is the α^3-order QED prediction. (b) Muon angular distribution for the $\mu\mu\gamma\gamma$ final state. The curve is the α^4-order QED calculation.

The Monte Carlo program of Berends and Kleiss[6] was used to calculate the QED prediction for $e^+e^- \to \mu^+\mu^-\gamma$ to order α^3. The events generated by the program were then put through the MAC detector simulation program[7] to take account of the detector acceptance and the event selection criteria. The QED prediction is 280 events, giving $\sigma_{\rm exp}/\sigma_{\rm QED} = 0.97 \pm 0.06$.

Figure 1(a) shows the combined μ^+ and μ^- polar angle distribution as the quantity $N_{\mu^+}(\cos\theta) + N_{\mu^-}(-\cos\theta)$ plotted vs $\cos\theta$, with θ measured relative to the e^+ beam direction. A substantial asymmetry about $\cos\theta = 0$ is evident. The average charge asymmetry, defined as

$$\bar{A} \equiv \frac{N_{\mu^+}(\theta < \frac{1}{2}\pi) + N_{\mu^-}(\theta > \frac{1}{2}\pi) - N_{\mu^+}(\theta > \frac{1}{2}\pi) - N_{\mu^-}(\theta < \frac{1}{2}\pi)}{N_{\mu^+} + N_{\mu^-}},$$

is $\bar{A} = (-21.6 \pm 4.1)\%$. Such an asymmetry is expected from QED because of the interference between amplitudes corresponding to the initial- and final-state radiation of a hard proton.[8] One of the ampli-

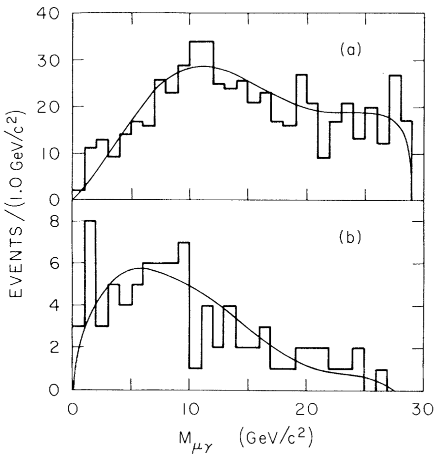

FIG. 2. (a) the $\mu\gamma$ invariant-mass distribution for the $\mu\mu\gamma$ final state. The solid curve is the α^3-order QED prediction. (b) Distribution of invariant-mass combinations for the $\mu\mu\gamma\gamma$ final state. The curve is the α^4 QED calculation.

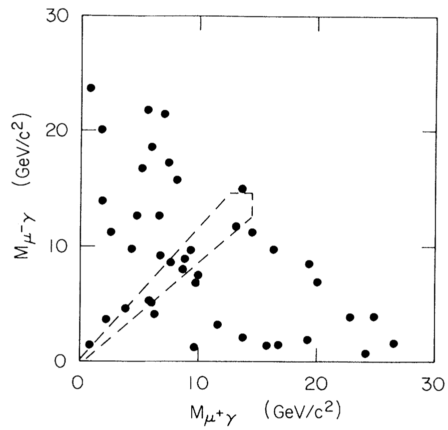

FIG. 3. Scatter plot of the invariant masses of $\mu^+\gamma$ and $\mu^-\gamma$ combinations for the $\mu\mu\gamma\gamma$ final state. Dashed lines indicate a range of two standard deviations of the $\mu\gamma$ mass resolution about the 45° line.

tudes represents Compton scattering of a proton from a muon, a process not accessible by direct measurement. The asymmetry due to QED becomes quite large for the hard-photon case compared to the relatively small value ($\simeq$2–3%) expected for the collinear $\mu^+\mu^-$ final state. The angular distribution predicted by the QED Monte Carlo method is shown as the solid curve in Fig. 1(a) and yields a charge asymmetry $\bar{A} = (-21.1 \pm 1.3)\%$, where the error is due to the statistical uncertainty of the Monte Carlo calculation. An additional contribution to the asymmetry is expected from the interference with the weak-interaction terms, and has been calculated[9] to be $\bar{A} \simeq -2\%$. The measured value is in good agreement with these predictions.

Figure 2(a) shows the muon-photon invariant-mass distribution (two entries per event) with a solid curve representing the QED prediction. The observed events are in good agreement with the calculated distribution.[10] A similar conclusion has been reached by other experiments.[4]

$\mu\mu\gamma\gamma$ final state.—The event selection criteria are as described above for the $\mu\mu\gamma$ final state except that (1) one more photon with $E_\gamma > 1$ GeV is required; (2) the angle between a muon and a photon or between the two photons must be greater than 10°; and (3) the four-particle system must be fitted by the $\mu^+\mu^-\gamma\gamma$ hypothesis. Twenty-one events satisfy these requirements, and the sample is estimated to contain four background events coming from the $e^+e^- \rightarrow \tau^+\tau^-$ final state. The QED prediction is fourteen events, as determined from the Monte Carlo program of Rek and Schmitt,[11] which evaluates the α^4-order contribution to hard-photon production. The result is $\sigma_{\rm exp}/\sigma_{\rm QED} = 1.2 \pm 0.3$.

Figure 1(b) shows the combined μ^+ and μ^- angular distribution as defined above. The solid curve is the α^4-order QED prediction, normalized to the observed events, and is in good agreement with the data. The measured average charge asymmetry is $\bar{A} = (-38 \pm 14)\%$ and the QED prediction is $\bar{A} = (-36.6 \pm 4.8)\%$. Figure 2(b) shows the distribution of muon-photon invariant-mass combinations (four entries per event). Again the observed distribution agrees with the QED calculation, shown as the solid curve.

Limits on μ^* production.—Figure 3 shows the scatter plot of $\mu\gamma$ mass combinations for $\mu\mu\gamma\gamma$ events (two entries per event). If μ^*'s were pair produced, the corresponding events would form a cluster around a point on the 45° line, within the mass resolution indicated by the dashed lines. No indication of μ^* production is observed: The distribution of points is consistent with QED within statistics [see Fig. 2(b)]. The acceptance for μ^*'s was calculated by a Monte Carlo method assuming that the μ^* couples to the virtual photon in the same manner as the muon, except for a possible form factor, and decays isotropically. The acceptance is about 66% for $M_{\mu^*} > 10$ GeV/c^2 and decreases at lower masses. This yields a 90%-C.L. upper limit on $\sigma_{\mu^*\mu^*}$ relative to the point cross section $\sigma_{\mu\mu}$, modified by the threshold factor $(3\beta - \beta^3)/2$, of between 1 and 2×10^{-3} in the mass region between 2 and 14 GeV/c^2.

Events from single μ^* production would appear as a narrow peak in the invariant-mass distribution of Fig. 2(a) (mass resolution from the kinematic fits averages about 0.3 GeV/c^2). The acceptance for this case was calculated under the assumption of a tensor coupling,[12] and ranges between 50% and 75% for 2.5 GeV/$c^2 < M_{\mu^*} <$ 27 GeV/c^2. This yields a 90%-C.L. upper limit for $\sigma_{\mu^*\mu}/\sigma_{\mu\mu}$ between 1 and 2×10^{-3} over this mass region. A similar analysis with the MARK-*J* detector at PETRA gave somewhat higher limits.[4]

In conclusion, a study of the reactions $e^+e^- \rightarrow \mu^+\mu^-\gamma$ and $e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$ has been carried out as a test of QED for hard-photon radiation up to order α^4 and to momentum transfers of 841 GeV/c^2. Total cross sections and various kinematic distributions agree with the predictions of QED. No evidence for excited-muon production, either singly or in pairs, has been found.

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