Measurement of the Branching Ratio and Form Factor for $K_L \to e^+e^-\gamma$

K. E. Ohl, R. K. Adair, H. B. Greenlee, H. Kasha, E. B. Mannelli,[a] M. P. Schmidt, and M. R. Vagins
Department of Physics, Yale University, New Haven, Connecticut 06511

E. Jastrzembski,[b] R. C. Larsen, L. B. Leipuner, and W. M. Morse
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973

C. B. Schwarz
Department of Physics and Astronomy, Vassar College, Poughkeepsie, New York 12601
(Received 23 May 1990)

We report on measurements of the K_L Dalitz decay $K_L \to e^+e^-\gamma$. The results are based on a sample of 919 events. Through an evaluation of the form factor, we have established evidence for a nonvanishing contribution due to the $KK^*\gamma$ coupling. We have determined the branching ratio to be $B(K_L \to e^+e^-\gamma) = (9.1 \pm 0.4^{+0.6}_{-0.5}) \times 10^{-6}$.

PACS numbers: 13.20.Eb, 13.40.Hq

The Dalitz decay $K_L \to e^+e^-\gamma$ was first observed by Carroll *et al.*[1] They determined a branching ratio $B(K_L \to e^+e^-\gamma) = (1.7 \pm 0.9) \times 10^{-5}$ based on the observation of four events. The Kroll-Wada[2] QED prediction for the branching ratio using the observed $K_L \to \gamma\gamma$ decay rate[3] is $B(K_L \to e^+e^-\gamma) = (9.1 \pm 0.4) \times 10^{-6}$. Deviations from the QED-predicted rate as well as in the e^+e^- invariant-mass spectrum can arise from vector-meson contributions through virtual photon conversion to an e^+e^- pair.

A measurement of these deviations can be used to determine the relative strength of the nonleptonic weak pseudoscalar-pseudoscalar (e.g., $K_L \to \pi, \eta, \eta'$) and vector-vector (e.g., $K^* \to \rho, \omega, \phi$) transitions. Bergström, Massó, and Singer[4] have pointed out the relevance of this measurement to understanding the $\Delta I = \frac{1}{2}$ rule in nonleptonic weak kaon decays. The $K_L \to \gamma\gamma$ decay rate is not affected by contributions from vector-vector transitions which vanish for real photons. However, these contributions can be important for K_L Dalitz decays and $K_L \to \mu^+\mu^-$.[5]

We present results on the decay $K_L \to e^+e^-\gamma$ derived from measurements made in an experiment at the Brookhaven National Laboratory Alternating Gradient Synchrotron (BNL E845). The E845 detector was optimized to search for the rare decay $K_L \to \pi^0 e^+e^-$, and has been described in Ref. 6.

The measurements were performed on K_L decays occurring in a neutral beam produced by the interactions of 24-GeV/c protons with a one-interaction-length Cu target. The neutral beam, produced at an angle of 2° with a solid angle of 35 μsr, traveled 10 m in vacuum and through a 6-Tm clearing field before entering a 6-m-long decay region. The decay region was evacuated (70 μm Hg) and terminated by a window consisting of 0.43 mm of Kevlar and 0.13 mm of Mylar.

The momenta of charged particles from K_L decays were determined in a magnetic spectrometer consisting of two upstream sets of mini-drift chambers, a magnet with a field integral of $\Delta p_t = 114$ MeV/c, and two downstream sets of mini-drift chambers. Electrons and positrons were identified by a 2-m-long hydrogen-gas threshold Čerenkov counter. Charged pions with momenta below 8 GeV/c were not registered by the Čerenkov counter. Electron and photon energies were measured in a lead-glass array consisting of 244 fiducial blocks of Schott F2 glass, each of dimension 6.4 cm × 6.4 cm × 46 cm (length). The blocks were arranged in a square (1-m^2) array with a central 12.7 cm × 38 cm hole for passage of the neutral beam. The spatial resolution of the lead glass was determined to be 13 mm for 1-GeV/c electrons, and the energy resolution was $\sigma_E/E = 7\%/E^{1/2} + 1.6\%$ (E in GeV).

Events accepted by the data-acquisition system were required to have two charged tracks consistent with electron identification, and at least 4 GeV of energy deposited in the lead-glass array. The mean kaon momentum for accepted $K_L \to e^+e^-\gamma$ events was 10 GeV/c. The trigger requirement for an electron consisted of the activation of one quadrant of the Čerenkov counter and greater than 800 MeV of energy deposited in the corresponding quadrant of lead glass. Scintillation counters located immediately upstream and downstream of the Čerenkov counter established the timing for each event. Events with particles (e.g., pions or muons) penetrating the lead-glass array and a 15-cm lead wall were vetoed. Scintillation counters covered with 3 radiation lengths of material vetoed events with gamma rays outside the fiducial detector acceptance.

In addition to the two-electron trigger data, minimum-bias data were collected throughout the course of the experiment. This was accomplished with a minimum-bias trigger, satisfied by two charged particles passing through separate quadrants, which operated with a prescale factor of 10 000. The minimum-bias data contained large samples of $K_L \rightarrow \pi^+\pi^-\pi^0$ and $K_L \rightarrow \pi e \nu$ decays. The former were used to calibrate the kinematic resolution of the detector and establish the sensitivity of the experiment. The latter were used to monitor the electron identification capabilities of the detector.

Reconstructed events were required to have two oppositely charged tracks originating from a common vertex in the decay region. Each electron or positron track had to be uniquely associated with a signal from one quadrant of the Čerenkov counter. Electrons were required to have momenta (p) between 1 and 8 GeV/c. The energy (E) of an electron as measured in the lead glass had to be consistent with its momentum, $0.75 < E/p < 1.25$. The transverse profile of the shower in the lead glass was required to have a second (energy-weighted) moment of less than 32 cm^2.

For the purposes of event reconstruction, γ rays were defined as clusters of energy in the lead-glass array not associated with charged-particle tracks. Only γ-ray clusters with energies greater than 500 MeV were included in the analysis. The $K_L \rightarrow e^+e^-\gamma$ events were required to have a single γ-ray cluster in the lead-glass array. In addition, to suppress backgrounds induced by interactions of the neutral beam, this cluster had to be in a fiducial region of the array that excluded blocks adjacent to the beam hole. For $K_L \rightarrow \pi^+\pi^-\pi^0$ events, two γ-ray clusters were required, and clusters centered on blocks adjacent to the beam hole were accepted provided their energy was greater than 700 MeV.

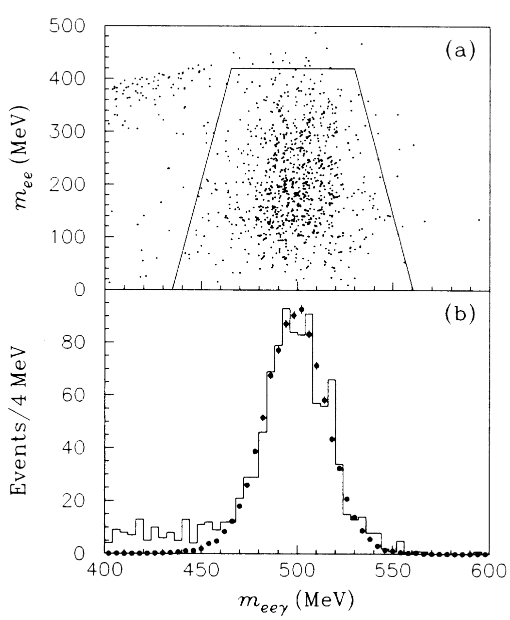

FIG. 1. (a) A scatter plot of the reconstructed events as a function of the invariant e^+e^- pair mass and the $e^+e^-\gamma$ invariant mass. Accepted events must fall within the region indicated by the solid lines. (b) The distribution of events with respect to the $e^+e^-\gamma$ invariant mass for data (solid line) and Monte Carlo simulation. The low-mass events are eliminated by the mass cut shown in (a).

Additional constraints were imposed in the analysis in order to suppress backgrounds arising from accidental coincidences and beam interactions. Events were rejected if they exhibited track segments in the upstream chambers originating at the vertex, or if charged-particle tracks were found passing through the neutral-beam hole in the lead-glass array.

Figure 1 shows the invariant-mass distributions for events with $\theta_K^2 < 16$ mrad^2, where θ_K^2 is the square of the target angle (i.e., the angle between the reconstructed kaon momentum and the line joining the production target and the decay vertex in the laboratory). The background at high e^+e^- pair mass, seen in the upper left-hand corner of Fig. 1(a), is due to K_{e3} radiative decays, and K_{e3} decays in which the pion shower develops so as to appear as two clusters. With the pion misidentified as an electron and the neutrino not detected, the $e^+e^-\gamma$ effective mass is below the K mass. This background is largely eliminated by a cut on the $e^+e^-\gamma$ invariant mass that depends on the e^+e^- pair mass. Monte Carlo calculations motivate the (3σ) constraint $|m_{ee\gamma} - m_K| < (860 - m_{ee})/13.7$ (masses in MeV/c^2). For e^+e^- pair masses less than 420 MeV/c^2 the remaining background is found to be small (about 1%) from a study of the distribution of events with $\theta_K^2 > 16$ mrad^2. After background subtraction, 919 $K_L \rightarrow e^+e^-\gamma$ events remain with an e^+e^- pair mass of less than 420 MeV/c^2.

The e^+e^- pair-mass spectrum for the observed decays is shown in Fig. 2. This distribution extends well into large e^+e^- pair masses where the effects of the de-

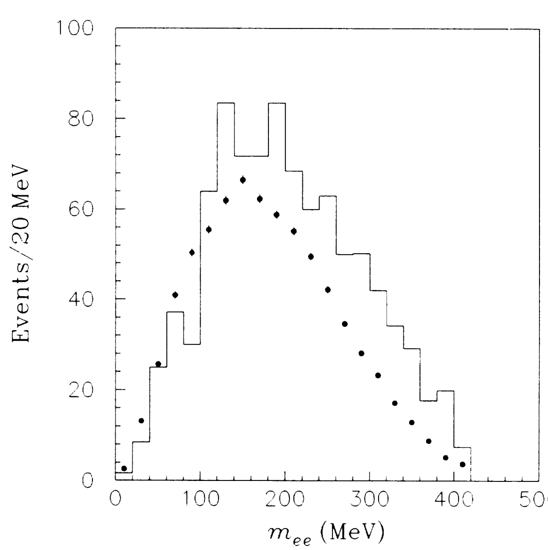

FIG. 2. The e^+e^- pair-mass distribution for the $K_L \rightarrow e^+e^-\gamma$ events (solid line). Shown also is the absolutely normalized QED prediction for a constant form factor [$f(x) = 1$].

cay form factor are important. The differential decay spectrum, in the absence of radiative corrections, is given by[2]

$$\Gamma_{\gamma\gamma}^{-1}\frac{d\Gamma}{dx}=\frac{2\alpha}{3\pi}\frac{(1-x)^3}{x}\left[1+\frac{2m_e^2}{xm_K^2}\right]\times\left[1-\frac{4m_e^2}{xm_K^2}\right]^{1/2}|f(x)|^2, \quad (1)$$

where $x=m_{ee}^2/m_K^2$. The form factor $f(x)$, defined such that $f(0)=1$, contains the structure of the K_L-γ-γ^* vertex. Note that the above expression is only an approximation in that an exact calculation of the decay rate requires the inclusion of QED radiative corrections. The calculation of these corrections was based on a computer program described in Ref. 7. The absolutely normalized Monte Carlo prediction for the e^+e^- pair-mass spectrum for $f(x)=1$ is shown in Fig. 2 superimposed on the data, where radiative corrections have been included in the calculation. The excess in the data in the high-pair-mass region indicates the presence of a nontrivial form factor.

Following the model of Bergström, Massó, and Singer[4] the form factor can be written as

$$f(x)=\frac{1}{1-0.418x}+\frac{C\alpha_{K^*}}{1-0.311x}\left[\frac{4}{3}-\frac{1}{1-0.418x}-\frac{1}{9(1-0.405x)}-\frac{2}{9(1-0.238x)}\right]. \quad (2)$$

The first term corresponds to the pseudoscalar-pseudoscalar transition where $K_L\to\pi,\eta,\eta'\to\gamma\gamma^*$. The second term corresponds to the vector-vector transition where $K_L\to K^*\gamma$ with $K^*\to\rho,\omega,\phi\to\gamma^*$. This latter term vanishes for on-shell photons ($x=0$). The parameter α_{K^*} measures the relative strength of the two terms. The dimensionless constant C is a combination of known coupling constants[8] with the value $C=2.5$.

A Monte Carlo simulation was used to determine the detector acceptance as a function of the e^+e^- pair mass, and a maximum-likelihood fit was obtained for the shape of the observed pair-mass spectrum as a function of α_{K^*}. The result of the fit was $\alpha_{K^*}=-0.280\pm0.083^{+0.054}_{-0.034}$ where the first error is statistical and the second (asymmetric) error is systematic.[9] Figure 3 displays the square of the form factor extracted from the data and the fit with $\alpha_{K^*}=-0.28$. For comparison the result of a fit with $\alpha_{K^*}=0$ is also shown. As shown in Fig. 4, the Monte Carlo prediction (with $\alpha_{K^*}=-0.28$) for the e^+e^- momentum asymmetry is in good agreement with the data.

With α_{K^*} determined, the branching ratio is calculated using the expression

$$B(e^+e^-\gamma)=B(K_L\to\pi^+\pi^-\pi^0)B(\pi^0\to\gamma\gamma)\times\frac{N(ee\gamma)}{N(\pi\pi\pi)}\frac{A(\pi\pi\pi)}{A(ee\gamma)}\frac{1}{E}, \quad (3)$$

where $N(ee\gamma)=919$ and the number of $K_L\to\pi^+\pi^-\pi^0$ events,[10] including the prescale factor, was $N(\pi\pi\pi)=14990\times10000$. The known branching ratios for the normalization decay are $B(K_L\to\pi^+\pi^-\pi^0)=0.1237$ and $B(\pi^0\to\gamma\gamma)=0.98798$. The acceptances, determined by Monte Carlo methods, were $A(ee\gamma)=0.125\%$ and

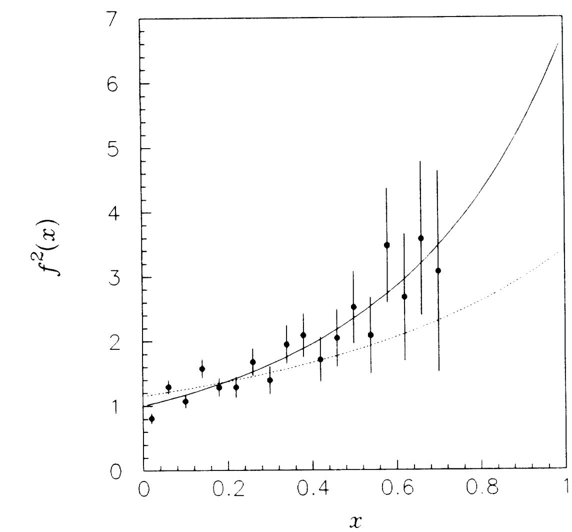

FIG. 3. The square of the decay form factor $f^2(x)$, ($x=m_{ee}^2/m_K^2$) extracted from the data (solid circles) and the fit with $\alpha_{K^*}=-0.28$ (solid line). For comparison the result of a fit with $\alpha_{K^*}=0$ (dotted line) is also shown. The normalization has been chosen such that the $\alpha_{K^*}=-0.28$ curve has $f(0)=1$.

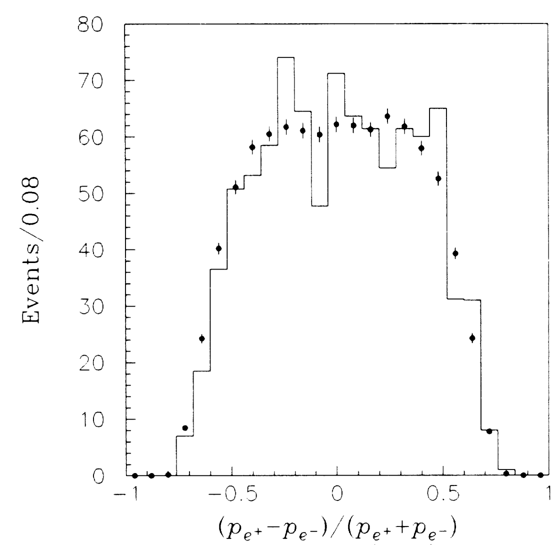

FIG. 4. A comparison of the data (solid line) with Monte Carlo simulation ($\alpha_{K^*}=-0.28$) for the e^+e^- momentum symmetry.

$A(\pi\pi\pi) = 1.35\%$. $A(ee\gamma)$ was calculated assuming the measured value of α_{K^*} and includes the spatial variations of the Čerenkov-counter efficiency. The efficiency factor $E = 0.89$ is a correction for the differences between the two decay modes. The requirements on veto counters and additional lead-glass clusters, which are applied only to the $K_L \to e^+e^-\gamma$ mode, are the main source of these differences. A correction for the photon-detection efficiency is also necessary because the two decay modes have a different number of final-state γ rays. The experimental result for the branching ratio is $B(K_L \to e^+e^-\gamma) = (9.1 \pm 0.4 ^{+0.6}_{-0.5}) \times 10^{-6}$ where the statistical error includes the statistical uncertainty in α_{K^*}. The systematic error derives mainly from a 5% uncertainty in the ratio of acceptances $A(\pi\pi\pi)/A(ee\gamma)$. The theoretical prediction for the $K_L \to e^+e^-\gamma$ branching ratio for $\alpha_{K^*} = -0.28$, including radiative corrections, is $B(K_L \to e^+e^-\gamma) = (9.6 \pm 0.4) \times 10^{-6}$.

In conclusion, we have established evidence for a $K_L \to e^+e^-\gamma$ decay form factor which includes a nonvanishing contribution from the nonleptonic weak vector-vector interaction. The result $\alpha_{K^*} = -0.280^{+0.099}_{-0.090}$ requires a contribution from the $KK^*\gamma$ amplitude. This agrees with the quark-model calculation of Bergström, Massó, and Singer[4] which obtains $|\alpha_{K^*}| \simeq 0.2$–$0.3$. Our result is consistent with a recent CERN measurement.[11]

We wish to thank the management and staff at Brookhaven for the strong support that made this experiment possible. We thank M. Lenz and J. Yelk for their technical contributions to the experiment. We also acknowledge the important contributions to E845 by M. Mannelli and S. F. Schaffner resulting from their efforts on E780. This research is supported by the U.S. Department of Energy under Contracts No. DE-AC02-76-ER03075 and No. DE-AC02-76CH00016. One of us (M.P.S.) received additional support from the Alfred P. Sloan Foundation.

(a)Present address: Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Via Livornese, 582/A, San Piero a Grado, 56010 Pisa, Italy.

(b)Present address: Continuous Electron Beam Accelerator Facility, Newport News, VA 23606.

[1]A. S. Carroll *et al.*, Phys. Rev. Lett. **14**, 525 (1980).

[2]N. M. Kroll and W. Wada, Phys. Rev. **98**, 1355 (1955).

[3]Particle Data Group, G. P. Yost *et al.*, Phys. Lett. B **204**, (1988).

[4]L. Bergström, E. Massó, and P. Singer, Phys. Lett. **131B**, 229 (1983).

[5]L. Bergström, E. Massó, P. Singer, and D. Wyler, Phys. Lett. **134B**, 373 (1984).

[6]K. E. Ohl *et al.*, Phys. Rev. Lett. **64**, 2755 (1990).

[7]L. Roberts and J. Smith, Phys. Rev. D **33**, 3457 (1986).

[8]Specifically, $C = \sqrt{8\pi\alpha} G_{\rm NL} f_{K^*K\gamma} m_\rho^2 / f_{K^*} f_\rho^2 f_{K\gamma\gamma}$, where α is the fine structure constant, $G_{\rm NL} = 1.1 \times 10^{-5}/m_p^2$,

$$f^2_{K^*K\gamma} = \frac{96\pi\Gamma(K^* \to K^0\gamma) m^3_{K^*}}{(m^2_{K^*} - m^2_K)^3}, \quad f^2_\rho = \frac{4\pi\alpha^2 m_\rho}{3\Gamma(\rho \to e^+e^-)},$$

$$f_{K^*} = \frac{m_{K^*}}{m_\rho} f_\rho, \quad f^2_{K\gamma\gamma} = \frac{64\pi\Gamma(K_L \to \gamma\gamma)}{m^3_K},$$

giving $f_{K^*K\gamma} = 3.90 \times 10^{-4}$ MeV^{-1}, $f_\rho = 4.99$, $f_{K^*} = 5.78$, $f_{K\gamma\gamma} = 3.44 \times 10^{-12}$ MeV^{-1}, and $C = 2.5$. Experimental values for $\Gamma(K^* \to K^0\gamma)$, $\Gamma(\rho \to e^+e^-)$, and $\Gamma(K_L \to \gamma\gamma)$ are from Ref. 3. Further information can be found in Ref. 4, and references contained therein.

[9]Neglecting radiative corrections the result would be $\alpha_{K^*} = -0.18$.

[10]In order to minimize systematic effects associated with changes made to the apparatus, the analyses reported here are based on a restricted sample of the data used for the $K_L \to \pi^0 e^+e^-$ search described in Ref. 6.

[11]G. D. Barr *et al.*, Phys. Lett. B **240**, 283 (1990).