NEW RESULTS ON THE RARE DECAYS $K_L \to \pi^0 e^+ e^-$ AND $K_L \to e^+ e^- \gamma$

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Abstract

We report on results from Brookhaven AGS experiment 845. We have obtained new limits on the transition rate for the CP violating decay $K_L \to \pi^0 e^+ e^-$. We have also made a measurement of the form factor for the Dalitz decay $K_L \to e^+ e^- \gamma$ with sufficient precision to confront theoretical predictions. In addition we have performed a detailed investigation of a fundamental background to $K_L \to \pi^0 e^+ e^-$ arising from K_L Dalitz decay accompanied by hard internal bremsstrahlung (*i.e.* $K_L \to \gamma\gamma e^+ e^-$).

INTRODUCTION

The violation of charge-parity (CP) invariance remains an enigma after more than twenty-five years of investigation. Only the neutral kaon system has provided evidence for the breakdown of CP invariance, and all experimental results taken together are still consistent with Wolfenstein's superweak model of CP violation. The decay $K_L \to \pi^0 e^+ e^-$ has received considerable attention recently because of its potential for elucidating the mechanism responsible for the violation of CP invariance.

In the Kobayashi-Maskawa model of CP violation, $K_L \to \pi^0 e^+ e^-$ is expected to receive comparable CP violating contributions from a *direct* K_2^0 decay amplitude and from an *indirect* amplitude due to the CP impurity (ϵK_1^0) of the K_L state. Calculations within the Standard (KM) Model obtain very small values for the $K_L \to \pi^0 e^+ e^-$ branching ratio, typically [1] in the range 10^{-11} - 10^{-12}. A CP conserving contribution to $K_L \to \pi^0 e^+ e^-$ through a $\pi^0\gamma\gamma$ intermediate state is also expected to be small, although there is uncertainty over its importance. At levels above the Standard Model predictions, the decay $K_L \to \pi^0 e^+ e^-$ is sensitive to the existence of light scalar particles that couple to e^+e^-, as well as to CP violating amplitudes expected from nonstandard models.[2]

As the search for rare K meson decays continues, experiments also obtain the sensitivity to study some now not-so-rare decays in detail. Often these decays provide the means to study the interplay of the strong, weak and electromagnetic interactions. Decays occurring via flavor changing neutral currents, which are therefore suppressed by the GIM mechanism, can provide constraints on the KM matrix elements. Radiative decays provide a testing ground for predictions of chiral perturbation theory.

The Dalitz decay $K_L \to e^+ e^- \gamma$ occurs as a result of internal pair conversion in the decay $K_L \to \gamma\gamma$. The Kroll-Wada[3] QED prediction for the branching ratio, assuming the observed $K_L \to \gamma\gamma$ decay rate, is $B(K_L \to e^+ e^- \gamma) = (9.1 \pm 0.4) \times 10^{-6}$. Deviations from the predicted rate as well as in the e^+e^- invariant mass spectrum can arise from contributions of vector mesons through virtual photon conversion. It has been pointed out[4] that a measurement of these deviations can be used to determine the relative strength of the nonleptonic weak pseudoscalar-pseudoscalar and vector-vector transitions, which is of relevance to the $\Delta I = 1/2$ 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]

THE E-845 DETECTOR

The measurements discussed below were performed at Brookhaven on K_L decays occurring in a neutral beam produced by 24 GeV/c protons from the AGS. About 10 m of shielding and 6 Tesla-meters of sweeping field separated the production target from the beginning of a 6 m decay region. The evacuated (70μHg) decay region was terminated by a thin (0.2% radiation length) Kevlar/mylar window. Typically about 10^{12} protons per ($\sim$1 sec) pulse were directed onto the target, resulting in a neutral beam flux of 3×10^8 per pulse ($K/n \approx 1/30$).

The E-845 detector, shown in Figure 1, was largely constructed from the apparatus used in our previous searches (AGS E-780) for $K_L \to \mu e$, $K_L \to ee$ and $K_L \to \pi^0 e^+ e^-$. The momenta of charged particles from K_L decays were determined in a magnetic spectrometer consisting of two upstream sets of mini-drift chambers (3 mm cells), a magnet with a field integral of $\Delta p_t = 114$ MeV/c, and two downstream sets of mini-drift chambers. Electrons 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 gamma ray energies were measured in a lead glass array (15 r.l. in depth) consisting of 244 blocks arranged in a square (1 m^2) array with a central 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 were accepted by a FastBus data acquisition system if they had 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 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.

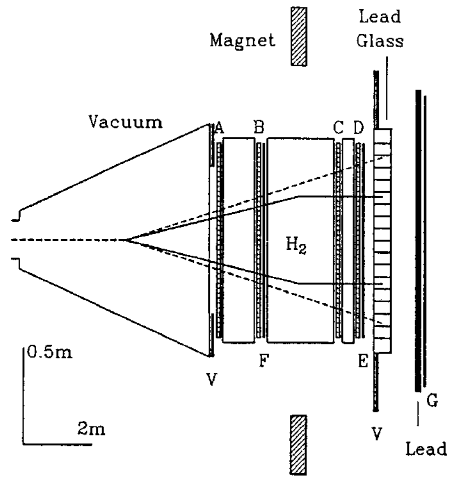

Figure 1: Schematic plan view of the E-845 detector. The neutral beam enters from the left. Note the different horizontal and vertical scales.

In addition to the two-electron trigger data, minimum bias data were collected concurrently throughout the course of the experiment. This was accomplished with a trigger that required only two charged particles passing through separate quadrants and operated with a prescale factor of 10,000. The minimum bias data contained large samples of $K_L \to \pi^+\pi^-\pi^0$ and $K_L \to \pi e \nu$ 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.

ANALYSIS AND RESULTS

About 100 million events in all were collected with the E-845 detector during February-May of 1989. In the final analysis, events were required to have two oppositely charged tracks originating from a common vertex in the decay region. Electrons were required to have momenta (p) less than 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 energy deposition in the lead glass was required to be narrow, as expected for electromagnetic showers.

Gamma rays were defined as clusters of energy in the lead glass array not associated with charged particle tracks. Only gamma ray clusters with energies greater than 500 MeV were included in the analysis. Bremsstrahlung photons were removed from the subsequent analysis by requiring gamma rays to be separated by more than 6.7 mrad in the laboratory from either charged particle. Contributions from accidental gamma rays were strongly suppressed by demanding that lead glass clusters have times within $\pm$ 5 nsec of the event time. The reconstruction of a π^0 from two γ clusters assumed the decay vertex established by the charged particle trajectories.

The resolution of the detector was determined from the study of $K_L \to \pi^+\pi^-\pi^0$ decays. Events were required to have a $\gamma\gamma$ pair with an invariant mass within 34 MeV/c^2 of the π^0 mass. With the $\gamma\gamma$ mass constrained to the π^0 mass, events were selected if the $\pi^+\pi^-\pi^0$ effective mass was within 13 MeV/c^2 of the K^0 mass, and if $\theta_K^2 < 12$ mrad^2. (θ_K^2 is the square of the angle between the line from the target to the decay vertex and the reconstructed kaon momentum vector.) The kinematic constraints constitute cuts for values three standard deviations away from the mean.

Search for $K_L \to \pi^0 e^+e^-$

For the $K_L \to \pi^0e^+e^-$ search the e^+e^- pair mass was restricted to be greater than π^0 mass in order to suppress backgrounds arising from π^0 Dalitz decays. The results of the analysis for the $\pi^0e^+e^-$ final state are presented as a scatter plot in Figure 2 of the $\pi^0e^+e^-$ effective mass and θ_K^2. Events from $K_L \to \pi^0e^+e^-$ decays are expected to be concentrated in the (3σ) bounded region shown, corresponding to a $\pi^0e^+e^-$ effective mass within 32 MeV/c^2 of the K^0 mass and $\theta_K^2 < 12$ mrad^2.

There were no event candidates consistent with the decay $K_L \to \pi^0e^+e^-$. Background events are expected from the decay modes $K_L \to \pi^0\pi^0$ and $K_L \to \pi^0\pi^0\pi^0$ with two π^0 Dalitz decays, from K_{e3} decays with pion misidentification and accidental coincidence with γs from another decay, and the Dalitz decay $K_L \to e^+e^-\gamma$ with internal radiation. The latter process is ultimately the most serious and is discussed below.

Using the number of $K_L \to \pi^+\pi^-\pi^0$ decays observed and the ratio of acceptances for the $\pi^0e^+e^-$ and $\pi^+\pi^-\pi^0$ decay modes as determined by Monte Carlo methods a 90% limit is obtained[6] $B(K_L \to \pi^0e^+e^-) < 5.5\times 10^{-9}$. This limit, the most stringent achieved in any experiment, places further constraints on non-standard model contributions to this process.

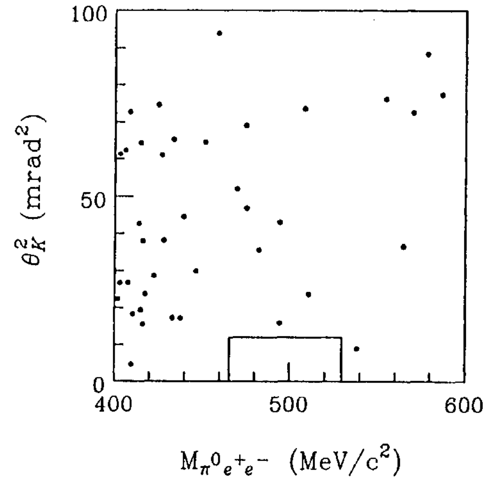

Figure 2: Event scatter plot of the square of the target reconstruction angle vs. the $\pi^0e^+e^-$ effective mass.

Study of $K_L \to e^+e^-\gamma$

The $K_L \to e^+e^-\gamma$ analysis proceeded much along the lines of the analysis in the search for $K_L \to \pi^0e^+e^-$, with the important exception that events were required to have a *single* gamma 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.

Figure 3 shows the invariant mass distributions for events with $\theta_K^2 < 16$ mrad^2. The background at high invariant e^+e^- pair mass, seen in the upper left hand corner of Figure 3(a), is understood to arise from $K_L \to \pi e\nu$ decays. 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%), providing a clean sample of 919 $K_L \to e^+e^-\gamma$ events for further study.

The e^+e^- pair mass spectrum for the observed decays is shown in Figure 4. This distribution extends well into large e^+e^- pair masses where the effects of the decay form factor are important. The differential decay spectrum, in the absence of radiative corrections, is given by:[3]

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

where $x = m_{ee}^2/m_K^2$. The form factor $f(x)$ contains the structure of the K_L-γ-γ^* vertex ($f(0) = 1$). The

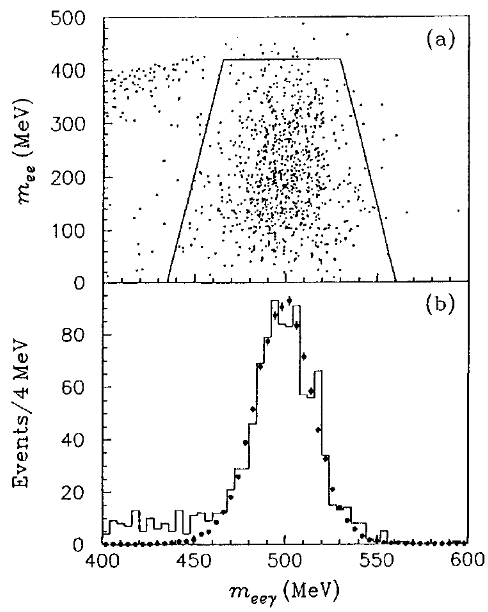

Figure 3: (a) A scatter plot of the reconstructed events as a function of the invariant e^+e^- pair mass and the $e^+e^-\gamma$ invariant mass. Accepted events must fall within the region indicated by the solid lines. (b) The distribution of events with respect to the $e^+e^-\gamma$ invariant mass for data (solid line) and Monte Carlo simulation.

absolutely normalized Monte Carlo prediction for the e^+e^- pair mass spectrum for $f(x) = 1$ is shown in Figure 4 superimposed on the data, where radiative corrections have been included[7] in the calculation. The excess in the data in the high e^+e^- pair mass region indicates the presence of a non-trivial form factor.

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

$$f(x) = f(s/m_K^2) = \frac{1}{1 - s/m_\rho^2} + \frac{\alpha_K A_{K^*}(s)}{1 - s/m_{K^*}^2},$$

with

$$\frac{A_{K^*}(s)}{C} = \left[\frac{4}{3} - \frac{1}{1 - s/m_\rho^2} - \frac{1/9}{1 - s/m_\omega^2} - \frac{2/9}{1 - s/m_\phi^2}\right]$$

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 with the value $C = 2.5$.

A Monte Carlo simulation was used to determine the detector acceptance as a function of e^+e^-

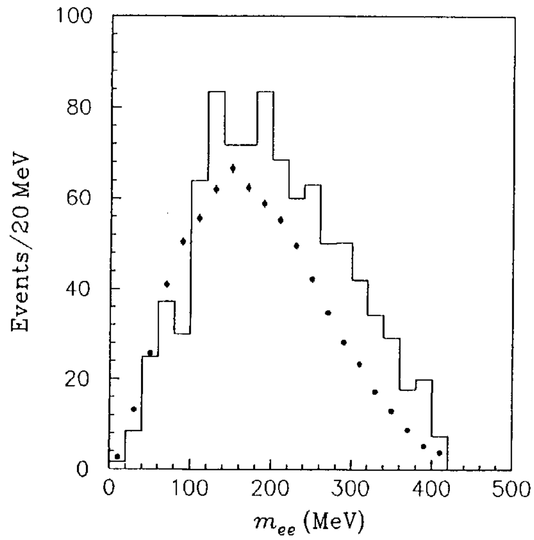

Figure 4: The e^+e^- pair mass distribution for the $K_L \to e^+e^-\gamma$ events (solid line). Shown also is the expected distribution for a constant form factor ($f(x) = 1$).

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 obtained[8] is $\alpha_K = -0.280 \pm 0.083\ ^{+0.054}_{-0.034}$ where the first error is statistical and the second (asymmetric) error is systematic. This result is evidence for a non-vanishing contribution from the nonleptonic weak vector-vector interaction to the $K_L \to e^+e^-\gamma$ decay. The value obtained $\alpha_K = -0.280\ ^{+0.099}_{-0.090}$ for the $KK^*\gamma$ amplitude is to be compared with the quark model calculation of Bergström, Massó, and Singer[4] which yields $|\alpha_K| \simeq 0.2 - 0.3$.

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 theoretical prediction for the $K_L \to e^+e^-\gamma$ branching ratio for $\alpha_K = -0.28$, including radiative corrections, is $B(K_L \to e^+e^-\gamma) = (9.6 \pm 0.4) \times 10^{-6}$.

Study of $K_L \to \gamma\gamma e^+e^-$

The rare process $K_L^0 \to \gamma\gamma ee$ is a potentially serious background in experiments searching for the still rarer process $K_L^0 \to \pi^0 ee$. The QED predictions for the background process $K_L^0 \to \gamma\gamma ee$ and the implications for $K_L^0 \to \pi^0 ee$ experiments have been considered in detail by one of us.[9] The results of this study suggested that the data collected in E-845 was of sufficient sensitivity to observe[10] the decay $K_L^0 \to \gamma\gamma ee$.

The decays $K_L \to \pi^0 e^+e^-$ and $K_L^0 \to \gamma\gamma ee$ give rise to strikingly different kinematic distributions for the e^+e^- and $\gamma\gamma$ pair masses and the e^+e^- and $\gamma\gamma$ momentum asymmetries. There is however, a non-negligible isotropic component of the internal bremsstrahlung in $K_L^0 \to \gamma\gamma ee$ decays which must be taken into account.

Backgrounds to $K_L \to \pi^0 e^+e^-$ from π and K Dalitz decays are strongly suppressed by the requirements: $m_{e^+e^-} > m_{\pi^0}$ and $m_{\gamma\gamma} \cong m_{\pi^0}$. Nevertheless, the effective background branching ratio due to $K_L^0 \to \gamma\gamma ee$ is 8×10^{-9} even if the gamma-gamma invariant mass is required to be within 5 MeV of the π^0 mass. A search through the remaining phase space reveals that the single best point on the Dalitz plot yields an effective background at the level of 2×10^{-11} in branching ratio; inclusion of any other portion of the Dalitz plot leads to an increase in the background level. Figure 5 shows the $K_L^0 \to \gamma\gamma ee$ background branching ratio as a function of the Dalitz plot efficiency for $K_L \to \pi^0 e^+e^-$ (assuming a vector matrix element for the $K_L \to \pi^0 e^+e^-$ decay).

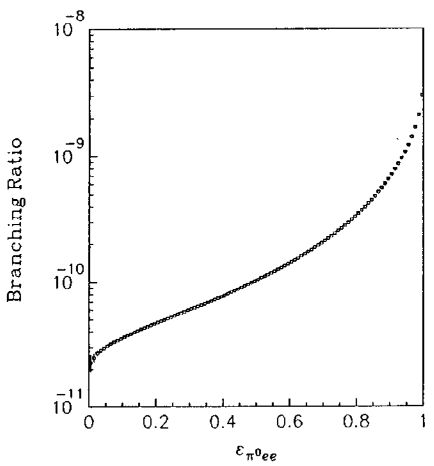

Figure 5: Effective branching ratio for $K_L^0 \to \gamma\gamma ee$ as a function of the Dalitz plot efficiency for $K_L \to \pi^0 e^+e^-$ ($m_{ee} > m_{\pi^0}; m_{\gamma\gamma} = m_{\pi^0} \pm 5$ MeV).

The effective background rate depends linearly on the gamma-gamma (π^0) mass resolution, so that improvements in photon detection (energy and position) technology (*e.g.* barium fluoride, pure cesium iodide, etc.) may offer considerable improvement. However, the discovery that $K_L^0 \to \gamma\gamma ee$ is likely to result in background at or above the rate predicted by the Standard Model for the decay $K_L \to \pi^0 e^+e^-$, has forced a serious re-examination of the ultimate prospects for this avenue of attack on the mystery of CP violation.

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REFERENCES

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[1] C.O. Dib, I. Dunietz, and F.J. Gilman, *Phys. Rev.* **D39** (1989) 2639, and references therein.
[2] L.J. Hall and L.J. Randall, *Nucl. Phys.* **B274** (1986) 157; J. Flynn and L.J. Randall, *Nucl. Phys.* **B326** (1989) 31.
[3] N.M. Kroll and W. Wada, *Phys. Rev.* **98** (1955) 1355.
[4] L. Bergström, E. Massó and P. Singer, *Phys. Lett.* **131B** (1983) 229.
[5] L. Bergström, E. Massó, P. Singer, and D. Wyler, *Phys. Lett.* **134B** (1984) 373; L. Bergström, E. Massó and P. Singer, CERN preprint CERN-TH.5803/90, 1990.
[6] K.E. Ohl *et al., Phys. Rev. Lett.* **64** (1990) 2755; see also the result from FNAL E731, Y. Wah, these proceedings.
[7] The analysis of the radiative corrections was accomplished with a program adapted from that used for a similar analysis of π^0 Dalitz decays. See L. Roberts and J. Smith, *Phys. Rev.* **D33** (1986) 3457. We are indebted to Prof J. Smith of Stony-Brook for providing us with the original code and guidance in its usage.
[8] K.E. Ohl *et al.*, Yale University preprint YAUG-A-90/5, 1990, to be published; see also the result from CERN NA31, K. Kleinknecht, these proceedings.
[9] H.B. Greenlee, Yale University preprint YAUG-A-90/3, 1990, to be published.
[10] W.M. Morse *et al.*, Yale University preprint YAUG-A-90/4, 1990, to be published.