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E. Ramberg, G. Bock, R. Coleman, J. Enagonio, Y. Hsiung, K. Stanfield, R. Tschirhart and T. Yamanaka

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

A. Barker, R. Briere, L. Gibbons, G. Makoff, V. Papadimitriou[a], J. Patterson[b], S. Somalwar, Y. Wah, B. Winstein, R. Winston, M. Woods[c] and H. Yamamoto[d]

The Enrico Fermi Institute and the Department of Physics, The University of Chicago, Chicago, Illinois 60637

E. Swallow

Department of Physics, Elmhurst College, Elmhurst, Illinois 60126 and The Enrico Fermi Institute and the Department of Physics, The University of Chicago, Chicago, Illinois 60637

G. Blair[e], G. Gollin[f], M. Karlsson[g] and J. Okamitsu[h]

Department of Physics, Princeton University, Princeton, New Jersey 08544

P. Debu, B. Peyaud, R. Turlay and B. Vallage

Department de Physique des Particules Elementaires, Centre d'Etudes Nucleaires de Saclay, F-91191 Gif-sur-Yvette Cedex, France

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Fermi National Accelerator Laboratory, Batavia, Illinois 60510

A. Barker, R.A. Briere, L.K. Gibbons, G. Makoff, V. Papadimitriou[(a)],
J.R. Patterson[(b)], S. Somalwar, Y.W. Wah, B. Winstein, R. Winston,
M. Woods[(c)] and H. Yamamoto[(d)]

The Enrico Fermi Institute and the Department of Physics,
The University of Chicago, Chicago, Illinois, 60637

E.C. Swallow

Department of Physics, Elmhurst College, Elmhurst, Illinois 60126 and
The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois, 60637

G. Blair[(e)], G.D. Gollin[(f)], M. Karlsson[(g)], and J.K. Okamitsu[(h)]

Department of Physics, Princeton University, Princeton, New Jersey 08544

P. Debu, B. Peyaud, R. Turlay, and B. Vallage

Department de Physique des Particules Elementaires, Centre d'Etudes
Nucleaires de Saclay, F-91191 Gif-sur-Yvette Cedex, France

Abstract

With the E731 apparatus at Fermilab, we have simultaneously collected 8748 K_L and K_S decays into $\pi^+\pi^-\gamma$. Using the large sample of $\pi^+\pi^-$ decays for normalization we have determined that $\Gamma(K^\circ \to \pi^+\pi^-\gamma)/\Gamma(K^\circ \to \pi^+\pi^-)$ is $(21.9 \pm 0.7) \cdot 10^{-3}$ for K_L and $(6.69 \pm 0.19) \cdot 10^{-3}$ for K_S, for photon center of mass energies greater than 20 MeV. After removing the inner-bremsstrahlung contribution, the photon energy spectrum of the direct emission decay of the K_L shows a clear distortion characteristic of the presence of a ρ propagator form factor.

It has long been recognized[1,2] that the decays $K_{L,S} \to \pi^+\pi^-\gamma$ may hold promise for illuminating the mechanisms of CP violation. The K_L decay also provides a testing ground for models based on chiral perturbation theory[3,4,5] which are relevant to disentangling CP violation in rare decays like $K_L \to \pi^0 e^+ e^-$. A critical issue in these models is whether the direct-emission (DE) photon energy distribution is characterized by a pure magnetic dipole (M1) transition or manifests some additional energy dependence.[3,4] In this letter we report the most precise results to date for the $\pi^+\pi^-\gamma$ branching ratios using the high precision E731 detector at Fermilab. For the first time decays of both K_L and K_S were seen simultaneously in the data making possible the accurate determination of the shape of the energy spectrum in question.

The $K_S \to \pi^+\pi^-\gamma$ decay is dominated[6] by inner-bremstrahlung (IB) in which a pion from the decay into $\pi^+\pi^-$ radiates a photon. However, for K_L decays, the IB rate is supressed because the underlying $\pi^+\pi^-$ decay is CP violating. This permits the more interesting DE process, in which the photon originates from the primary decay vertex, to compete successfully.

The IB decay can be described very well with a pure E1 bremsstrahlung spectrum. In contrast, previous experimental results[7] have supported the idea that the DE decay occurs through an M1 amplitude, modified by a factor, F, containing vector meson intermediaries. One chiral perturbation model of the decay[3] suggests that F is a sum of two terms, one of which contains the ρ meson propagator:

$$F = a_1 \cdot ((M_\rho^2 - M_K^2) + 2M_K E_\gamma^*)^{-1} + a_2 \qquad (1)$$

where E_γ^* is the energy of the photon in the center-of-mass system. The constants M_ρ and M_K are the masses of the rho meson and neutral kaon. The coefficients a_1 and a_2 depend strongly on the the mixing angle $\theta_{\eta-\eta'}$ for the SU(3) nonet members η and η'. This formulation leads to an energy spectrum for the emitted photon that is shifted lower in energy. Other models, however, suggest that F consists of a sum of amplitudes which results in no net shift in the DE photon energy spectrum.[4,5]

The $\pi^+\pi^-\gamma$ decays studied here were obtained in a 1987-1988 experiment at Fermilab which measured the direct CP violating parameter $\frac{\epsilon'}{\epsilon}$ and concentrated on high acceptance and accurate measurement of two pion decays, both neutral and charged.[8] The apparatus, described in detail previously.[9]

consisted of a vacuum decay vessel followed by a charged particle, magnetic spectrometer including four sets of four-plane drift chambers with approximately 100 micron resolution, two sets on either side of an analyzing magnet. Following the drift chambers is an array of lead glass blocks for photon detection, with an energy resolution for photons of $2.5\% + 5\%/\sqrt{E}$. Two neutral K_L beams, one of which passed through a regenerator, allowed both K_S and K_L decays to be collected simultaneously.

The trigger for charged decays, of which the $\pi^+\pi^-\gamma$ decays are a subset, demanded that two charged tracks traversed the detector on either side of the vertical midplane. No requirement was made on the presence or absence of energy in the lead-glass array. Offline, each event was required to contain two tracks of at least 7 GeV/c in momentum and have exactly one cluster of energy of at least 1.5 GeV in the calorimeter not associated with either track. The photon energy in the center of mass system had to be at least 20 MeV. To exclude electrons from the sample, we required $\frac{E}{p} < 0.8$, where E is the cluster energy associated with a track and p is the momentum of that track. Each event was also required to pass the same cuts as for analyzing the $\pi^+\pi^-$ events, which included a total kaon energy between 30 and 160 GeV, a reconstructed mass between 484 and 512 MeV/c^2 and a total transverse momentum squared of less than 250 (MeV/c)^2. To suppress the background from $\pi^+\pi^-\pi^o$ decays with one undetected photon, a cut was made on the variable

$$P^2_{\pi^o} = \frac{[(M^2_{K^o} - M^2_{\pi^o} - M^2_c)^2 - 4M^2_{\pi^o}M^2_c - 4M^2_{K^o}(p_T)^2_c]}{[(p_T)^2_c + M^2_c]} \qquad (2)$$

where M_c is the invariant mass of the two pions and $(p_T)_c$ is their combined transverse momentum. For $\pi^+\pi^-\pi^o$ decays this is the squared longitudinal momentum of the π^0 in the K center of mass. Barring resoulution effects this is positive. Our cut of $P^2_{\pi^o} < -.05$ reduces the background from the $\pi^+\pi^-\pi^o$ decay by approximately a factor of 80, while retaining 86% of the $\pi^+\pi^-\gamma$ decays, as determined from Monte Carlo simulations.

Figure 1 shows the resulting kaon mass and p^2_T spectra of the events in both beams passing all other cuts. (The events arising from the vacuum beam are mostly K_L decays, while events arising from the regenerator beam are mostly K_S decays.) The backgrounds are small. There are 9031 decays that pass all of the cuts, 4860 of which are associated with the regenerator beam and 4171 from the vacuum beam. The background under the mass peak was estimated to be 137 ± 10 for the vacuum beam and 50 ± 20 for the regenerator beam by studying the p_T^2 distribution of events on either side of the mass peak.

A background for the regenerator beam which passes the event cuts is due to the K_L DE component which decays downstream of the regenerator. The K_L IB component which decays downstream of the regenerator is not considered a background. It is regarded as part of the K_L–K_S coherent mixture and will be accounted for because all results for branching ratios are normalized with respect to the two charged pion decay, where the same mixture occurs. Scaling the number of DE vacuum beam decays downstream of the regenerator position by an absorption factor of 15.7 gives an estimate for this additional number of background events in the regenerator beam to be 96 ± 4. (The absorption factor, due to K_L absorption in the regenerator and a moveable absorber, was obtained from an analysis of a high statistics sample of $K_L \rightarrow 3\pi^o$ decays.) All estimates for numbers of background events were subtracted from the data sample.

To isolate the separate components of the K_L decay into DE and IB, the shape of the photon energy spectrum was used. Figure 2 shows the center of mass photon energy spectrum for the K_L decays with the K_S decay spectrum superimposed. The K_S spectrum is shown plotted with the normalization determined by fitting the K_L data to a linear combination of the K_S spectrum and a pure DE spectrum obtained from a Monte Carlo simulation containing the rho propogator correction given in Equation 1. This normalized K_S spectrum can then be associated with the IB component of the K_L decays. When subtracted from the total spectrum the DE component for K_L decays is then determined. The shape of the DE spectrum obtained in this way is not sensitive to the IB background subtraction, within the errors we observe in this fit.

A Monte Carlo simulation of the apparatus was used to determine the acceptance for the decay mode under study and each decay mode was corrected for this acceptance. The acceptance of our apparatus using the cuts detailed above was 12.6% for K_L decays and 26.7% for K_S decays. (The difference is due to the lower acceptance for K_L decays upstream of the regenerator position.) The number of reconstructed K_S and K_L decays into 2 charged pions from the same data set (totalling 370 thousand K_L decays and 1.2 million K_S decays) were used to normalize the $\pi^+\pi^-\gamma$ yields to a known decay channel after correcting for their own acceptance (approximately 25%

for K_L and 44% for K_S).

A final correction was made to the data because the requirement of having exactly one unmatched cluster in the calorimeter excludes some events. Extra clusters of energy can show up from accidental photons or hadronic showering of either of the two pions. An estimate of the number of these types of events that were lost was obtained by including any number of extra clusters in the event and accepting that event if any of these clusters gave a good reconstructed kaon mass together with the charged pions. The fraction of events that had exactly one cluster was $.974 \pm .020$ for K_L and $.960 \pm .020$ for K_S. The number of events of each type were corrected for this effect. (These extra cluster events were not included in the final data sample because of the difficulty of modeling noise and hadronic showers in the detector simulation.)

The final results for the numbers of events (after all selection cuts and background subtractions) and branching ratios of neutral kaons into $\pi^+\pi^-\gamma$ are given in Table 1. Also shown, for comparison to a previous result[6], is the branching ratio for K_S decays where $E^*_\gamma > 50$ MeV. All errors quoted are combined statistical and systematic. Systematic errors include the errors in background subtraction and extra cluster correction quoted above, an error of 1.0% in the normalization of the $\pi^+\pi^-$ decays, and an estimate for an error in acceptance correction of approximately 1.0% obtained from the maximum variance seen in the acceptance of Monte Carlo data after varying the cut values in the analysis, including the energy cut for the photon, the cut on the decay vertex position, the minimum track energy, the transverse momentum cut and the cut on the variable $P^2_{\pi^0}$.

Previous experimental results include $(1.52 \pm 0.16) \cdot 10^{-5}$ for the K_L IB decay and $(2.89 \pm 0.28) \cdot 10^{-5}$ for the K_L DE decay[7]. No previous results exist for the branching ratio of the K_S IB decay above 20 MeV photon energy, but above 50 MeV, the best previous result was $\Gamma(K_S \to \pi^+\pi^-\gamma)/\Gamma(K_S \to \pi^+\pi^-) = (2.68 \pm 0.15) \cdot 10^{-3}$.[6] The QED prediction for this ratio is $2.56 \cdot 10^{-3}$ for $E^*_\gamma > 50$ MeV and $7.01 \cdot 10^{-3}$ for $E^*_\gamma > 20$ MeV.[6] All of these results are consistent with the data presented here.

The ratio of the IB branching ratio to the two charged pion decay is consistent for both K_L and K_S decays. Any deviations from this expectation would be a possible sign of direct CP violation in this decay mode. The fraction K_L decays with $E^*_\gamma > 20$ MeV that are DE decays is $.685 \pm .041$.

A comparison of the shape of the K_L DE photon energy spectrum to the one predicted by Equation 1 is shown in Figure 3, using the value -20°

Table 1: Measured Branching Ratios for $K_{L,S} \to \pi^+\pi^-\gamma$. All errors are combined statistical and systematic. E^*_γ >20 MeV except where noted.

Decay Mode	No. of Evts.	$\frac{\Gamma(K\to\pi^+\pi^-\gamma)}{\Gamma(K\to\pi^+\pi^-)}$	B.R.
K_L	4034 ± 66	$(21.9 \pm 0.7) \cdot 10^{-3}$	$(4.44 \pm .17) \cdot 10^{-5}$
K_L-DE only	2490 ± 70	$(15.0 \pm 0.6) \cdot 10^{-3}$	$(3.04 \pm .14) \cdot 10^{-5}$
K_L-IB only	1544 ± 24	$(6.90 \pm 0.21) \cdot 10^{-3}$	$(1.40 \pm .05) \cdot 10^{-5}$
K_S	4714 ± 73	$(6.69 \pm 0.20) \cdot 10^{-3}$	$(4.59 \pm .14) \cdot 10^{-3}$
K_S-($E^*_\gamma > 50$ MeV)	1662 ± 43	$(2.49 \pm 0.10) \cdot 10^{-3}$	$(1.71 \pm .07) \cdot 10^{-3}$

for $\theta_{\eta-\eta'}$. Also shown in this figure is the comparison of the data to the DE energy spectrum without the ρ propogator form factor in Equation 1. The data clearly supports a modification to the standard M1 amplitude that includes a ρ propogator form factor. The χ^2 for the fit of the Monte Carlo curve to the data is 49/38 dof with the energy dependent ρ propagator form factor and 95/38 dof without it.

Using a chiral perturbation model [3] and this measurement of the K_L DE branching ratio yields $\theta_{\eta-\eta'} = -21.0^\circ \pm .5^\circ$, in good agreement with the commonly accepted value of -20°.

Most models assume that the radiative decays occur strictly through a dipole transition. If any higher multipole transitions occur this may show up as an asymmetry of the photon direction in the $\pi^+\pi^-$ decay frame.[1] For the K_L data sample, we measured the average value of $\cos(\theta)$ as a function of E^*_γ, where θ is defined as the angle between the photon and the positive pion in the pion-pion rest frame. No statistically significant departure from the dipole expectation was seen in this data.

In conclusion, we have measured branching rations for $K_{L,S} \to \pi^+\pi^-\gamma$ with improved precision. Our technique of using two beams, one with K_S regeneration and the other with a pure K_L beam, provides a powerful means for separating the IB and DE components in K_L decays. Excellent agreement is obtained with previous measurements and with the highly reliable theoretical calculations for the IB component. The DE photon spectrum in K_L decays shows clear evidence of additional energy dependence beyond the basic M1 shape. This poses a significant challenge for models which predict a nearly pure M1 distribution.

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References

[a]Current address: Fermi National Accelerator Laboratory, Batavia, IL 60510

[b]Current address: Cornell University, Ithaca, NY 14853

[c]Current address: SLAC, Stanford, P.O. Box 4349, CA 94305

[d]Current address: Harvard University, Boston, Mass.

[e]Current address: Oxford University, Oxford, U.K.

[f]Current address: Department of Physics, U. of Illinois, Urbana, IL 61801

[g]Current address: CERN, CH-1211, Geneva 23, Switzerland

[h]Current address: Princeton Combustion Research Laboratories, Monmouth Junction, NJ 08852

[1]G. Costa and P.K. Kabir, Nuovo Cimento **A 51**, 564 (1967)

[2]L.M. Sehgal and L. Wolfenstein, Phys. Rev. **162**, 1362 (1967)

[3]Y.C.R. Lin and G. Valencia, Phys. Rev. **D 37**, 143 (1988)

[4]C. Picciotto, Laboratoire National Saturne Preprint, **LNS/Ph/91-15U** (1991)

[5]P. Ko and T.N. Truong, Phys. Rev. **D 43**, R4 (1991)

[6]H. Taureg *et al.*, Phys. Lett. **B 65**, 92 (1976)

[7]A. Carroll *et al.*, Phys. Rev. Lett. **44**, 529 (1980)

[8]J.R. Patterson *et al.*, Phys. Rev. Lett. **64**, 1491 (1990)

[9]M. Woods *et al.*, Phys. Rev. Lett. **60**, 1695 (1988) ; see also the J.R. Patterson thesis, University of Chicago, (1990)

[10]A.S. Carroll *et al.*, Phys. Rev. Lett. **44**, 525 (1980)

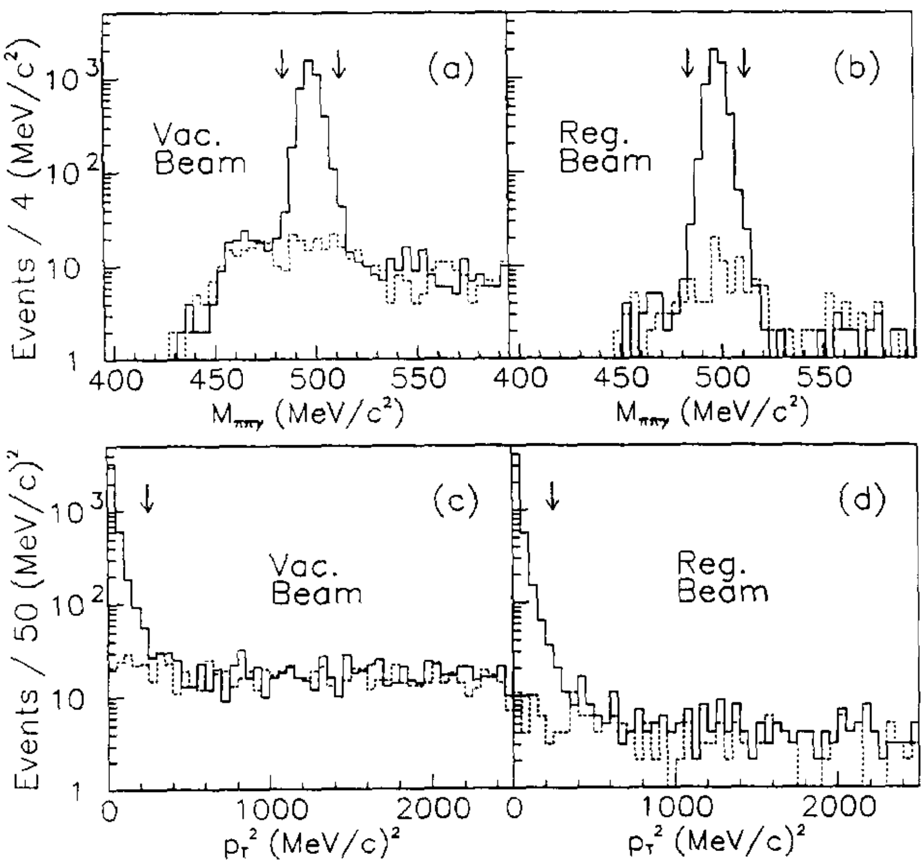

Figure 1: a) Mass spectrum of vacuum beam events passing all cuts except for the mass cut (solid). Shown as background (dashed) is the same distribution with the cut $250 < p_T^2 < 500$ (MeV/c)^2 b) Mass spectrum and background of regenerator beam events. c) p_T^2 spectrum of vacuum beam events passing all cuts except for the p_T^2 cut. The background estimate comes from the sidebands on either side of the mass region $.484 < M_{\pi\pi\gamma} < .512$ (GeV/c^2). d) p_T^2 spectrum and background for the regenerator beam events. (Arrows show cut values.)

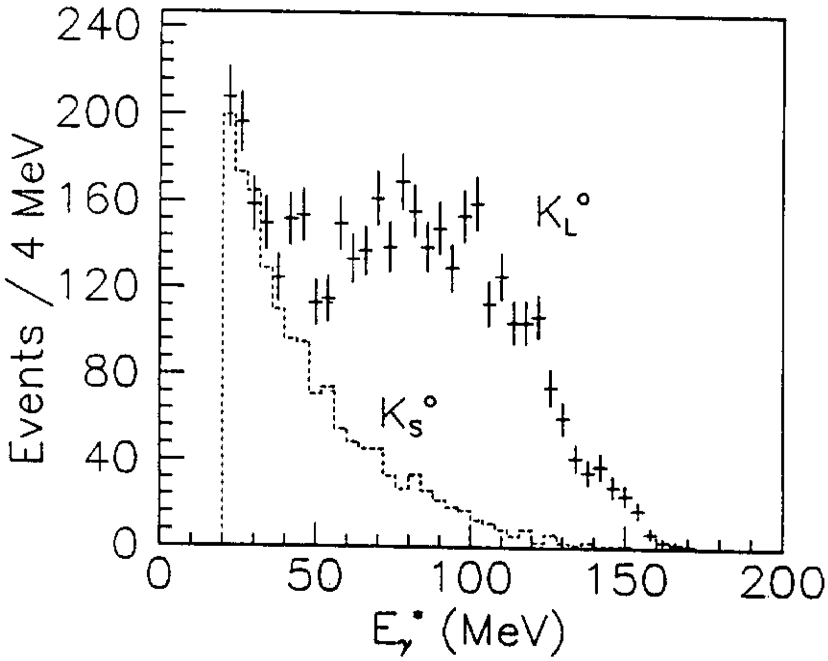

Figure 2: The data points indicate the E_γ^* spectrum for the K_L data. The dotted line is the same spectrum for the K_S data, normalized as indicated in the text.

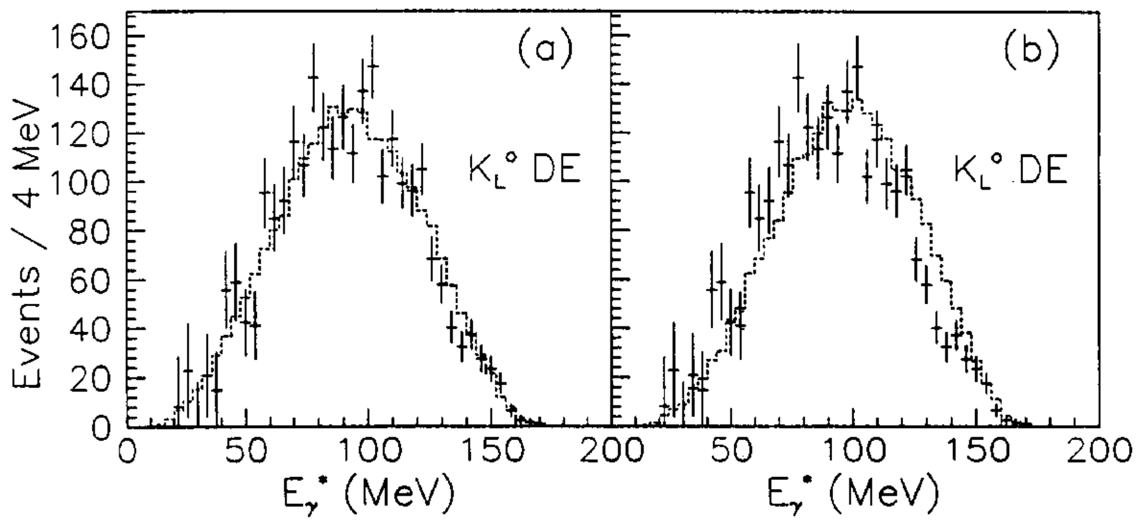

Figure 3: a) The DE E_γ^* spectrum for K_L decays (data points) compared to the prediction with intermediate vector states (dashed). b) Same spectrum compared to the prediction without those states. Fitting to the predicted curves gives a χ^2/D.O.F. of 1.3 for a) and 2.5 for b).