Simultaneous Measurement of K_S and K_L Decays into $\pi^+\pi^-\gamma$

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With the E731 apparatus at Fermilab, we have simultaneously collected 6859 K_L and K_S decays into $\pi^+\pi^-\gamma$. Using our sample of over 370000 $\pi^+\pi^-$ decays for normalization we have determined that the ratio $\Gamma(K^0 \to \pi^+\pi^-\gamma)/\Gamma(K^0 \to \pi^+\pi^-)$ is $(23.0 \pm 0.7)\times 10^{-3}$ for K_L and $(7.10 \pm 0.22)\times 10^{-3}$ for K_S, for photon energies greater than 20 MeV in the kaon center of mass. After removing the inner-bremsstrahlung contribution, we find that the photon energy spectrum of the direct emission decay of the K_L is consistent with the presence of a vector meson propagator in the form factor.

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It has long been recognized [1,2] that the decays $K_{L,S} \to \pi^+\pi^-\gamma$ may hold promise for illuminating the experimentally unresolved mechanisms of CP violation. The K_L decay also provides a testing ground for models based on chiral perturbation theory [3–5] which are relevant to understanding CP violation in rare decays such as $K_L \to \pi^0 e^+ e^-$. 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 [5]. In this Letter we report the most precise results to date for the $\pi^+\pi^-\gamma$ branching ratios and demonstrate the presence of a modification to the $M1$ amplitude in this decay. In the following Letter we demonstrate K_L-K_S interference in this mode for the first time and extract new CP-violation parameters for the decay [6].

The $K_S \to \pi^+\pi^-\gamma$ decay is dominated [7] by inner bremsstrahlung (IB) in which a pion from the decay into $\pi^+\pi^-$ radiates a photon. However, for K_L decays, the IB rate is suppressed because the underlying $\pi^+\pi^-$ decay is CP violating. This permits the more interesting CP-conserving DE process, in which the photon originates from the primary decay vertex, to be significant.

The IB decay can be described very well with a pure $E1$ bremsstrahlung spectrum [7]. In contrast, previous experimental results [8] have supported the idea that the DE decay occurs through an $M1$ amplitude, modified by a form factor F which includes the effects of 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:

$$F = a_1[(M_\rho^2 - M_K^2) + 2M_K E_\gamma^*]^{-1} + a_2\,, \tag{1}$$

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 neutral rho meson and neutral kaon. The coefficient a_1 and a_2 depend on 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 than the pure $M1$ spectrum. In other models, however, 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 studies here were collected by the E731 experiment at Fermilab, which measured the direct CP violation parameter ϵ'/ϵ and concentrated on high acceptance and accurate measurement of two pion decays, both neutral and charged [9]. The apparatus, described in detail elsewhere [10], consisted of a vacuum decay vessel followed by a magnetic spectrometer. This spectrometer included four drift chambers, each incorporating four wire planes with approximately 100 μm resolution. An analyzing magnet was located between the second and third drift chambers. Following the drift chambers was an array of lead-glass blocks for photon detection, with an energy resolution for photons of $2.5\% + 5\%/\sqrt{E}$. Two K_L beams, one of which passed through a regenerator, allowed 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 traverse the detector on either side of the vertical midplane at the second drift chamber. No requirement was made on energy in the lead-glass array. In the off-line analysis, each event was required to contain two tracks of momentum between 7 and 80 GeV/c, satisfying the trigger requirement. In addition there had to be exactly one cluster of energy of at least 1.5 GeV in the calorimeter not associated with either track. The photon energy in the kaon center-of-mass system had to be at least 20 MeV. To exclude electrons from the sample, we required $E/p < 0.8$, where E is the cluster energy associated with a track and p is the momentum of that track. Each event was also required to have 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, p_T^2, of less than 250 (MeV/c)^2. To suppress the background from $\pi^+\pi^-\pi^0$ decays with one undetected photon, a cut was made on the variable

$$P_{\pi^0}^2 = \frac{(M_{K^0}^2 - M_{\pi^0}^2 - M_c^2)^2 - 4M_{\pi^0}^2 M_c^2 - 4M_{K^0}^2 (p_T)_c^2}{(pT)_c^2 + M_c^2}, \quad (2)$$

where M_c is the invariant mass of the two pions and $(p_T)_c$ is their combined transverse momentum. For $\pi^+\pi^-\pi^0$ decays this is proportional to the squared longitudinal momentum of the π^0 in the K center of mass. Barring resolution effects, $P_{\pi^0}^2$ is positive for that decay. By making our cut of $P_{\pi^0}^2 < -0.05$ the background from the $\pi^+\pi^-\pi^0$ decay was reduced 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 mass and p_T^2 spectra of the events in both beams passing all other cuts. (The events observed in the vacuum beam are mostly K_L decays, while those in the regenerator beam are mostly K_S decays.) The backgrounds are small. There are 7042 decays that pass all of the cuts, 3841 of which are associated with the regenerator beam and 3201 with the vacuum beam. The background under the mass peak was estimated to be 65 ± 10 for the vacuum beam and 25 ± 15 for the regenerator beam by using the sidebands in the p_T^2 and mass distributions. The uncertainty on these estimates accounts for the possibility that signal events are included in the sidebands.

To isolate the separate components of the K_L decay coming from 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 ρ propagator correction given in Eq. (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 sen-

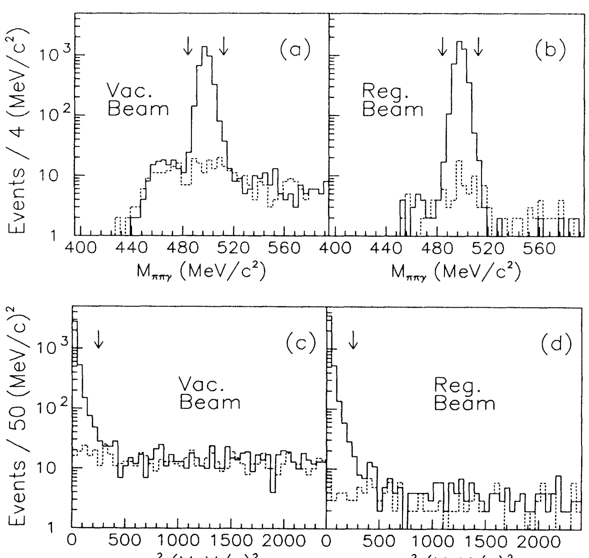

FIG. 1. (a) Mass spectrum of vacuum beam events passing all cuts except for the mass cut (solid). Shown as background (dashed) is the same distribution with the cut $250 < p_T^2 < 500$ (MeV/c)^2. (b) Mass spectrum and background of regenerator beam events. (c) p_T^2 spectrum of vacuum beam events passing all cuts except for the p_T^2 cut. The background estimate comes from the side bands on either side of the mass region $0.484 < M_{\pi\pi\gamma} < 0.512$ GeV/c^2. (d) p_T^2 spectrum and background for the regenerator beam events. (Arrows show cut values.)

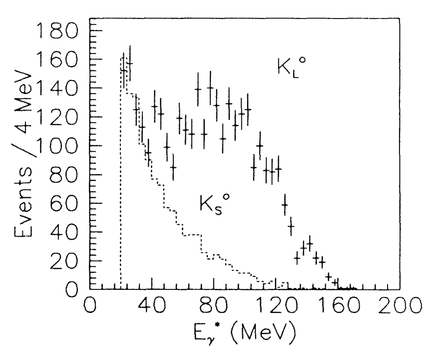

FIG. 2. The data points indicate the E_γ^* spectrum for the K_L data. The dotted line is the same spectrum for the K_S data, normalized as indicated in the text.

sitive to the IB background subtraction, within the errors we observe in the fit.

An additional 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, but is regarded as part of the K_L-K_S coherent mixture. This latter component 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. The number of DE decays downstream of the regenerator position was estimated using the vacuum beam decays and the known absorption of kaons in our regenerator. The estimate for this DE background in the regenerator beam is 93 ± 5 events.

A Monte Carlo simulation of the apparatus was used to determine the acceptance for this decay mode. The acceptance of our apparatus using the cuts detailed above was 10.1% for K_L decays and 21.1% for K_S decays. The acceptance decreases smoothly with increasing E_γ^* and has the same shape for both K_S and K_L decays, even though the vertex distribution for these decays is very different.

The numbers of reconstructed K_S and K_L decays into two charged pions from the same data set (totaling 370000 K_L decays and 1.2×10^6 K_S decays) were used to normalize the $\pi^+\pi^-\gamma$ yields after correcting for their own acceptance (approximately 25% for K_L and 44% for K_S).

A final correction was made because the requirement of having exactly one unmatched cluster in the calorimeter excludes some $\pi^+\pi^-\gamma$ events. These events contain extra clusters of energy associated with the beam or with the showering of either of the charged pions in the lead glass. We therefore required that the $\pi^+\pi^-$ normalization sample contain no extra clusters, which reduced that sample size by 9.5%.

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 I. Also shown, for comparison to a previous result [7], is the branching ratio for K_S decays where $E_\gamma^* > 50$ MeV. All errors quoted are combined statistical and systematic errors.

Systematic errors include the errors in background subtraction quoted above, and an uncertainty of 0.3% due to the relative effects of accidental activity between the $\pi^+\pi^-\gamma$ sample and the normalization sample. An uncertainty of 0.25% exists in the normalization of the $\pi^+\pi^-$ decays, consisting of equal parts arising from the statistical uncertainty of the sample and from the acceptance of the $\pi^+\pi^-$ decay. Finally, an estimate for the error in the acceptance correction for the $\pi^+\pi^-\gamma$ decays of 1.5% was obtained from the maximum variance seen in the Monte Carlo simulation after varying the cut values in the analysis.

Previous experimental results include $(1.52 \pm 0.16) \times 10^{-5}$ for the K_L IB decay with $E_\gamma^* > 20$ MeV and $(2.89 \pm 0.28) \times 10^{-5}$ for the K_L DE decay [8]. 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

$$\Gamma(K_S \to \pi^+\pi^-\gamma)/\Gamma(K_S \to \pi^+\pi^-) = (2.68 \pm 0.15) \times 10^{-3}$$

[7]. The QED prediction for this ratio is 2.56×10^{-3} for $E_\gamma^* > 50$ MeV and 7.01×10^{-3} for $E_\gamma^* > 20$ MeV [7]. 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 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 of K_L decays with $E_\gamma^* > 20$ MeV that are DE decays is 0.685 ± 0.041.

A comparison of the shape of the K_L DE photon energy spectrum to the one predicted by Eq. (1) is shown in Fig. 3. Also shown in this figure is the comparison of the data to the DE energy spectrum of a pure $M1$ amplitude, one without the ρ propagator form factor. The data are consistent with the energy-dependent modification to the standard $M1$ amplitude given in Eq. (1). The fit of theory to the K_L DE spectrum gives a χ^2 per degree of freedom of 72.7/38 with the ρ propagator term and 142.1/38 without this term. (The fit of the K_S data to the IB expectation gives 32.4 for 34 d.o.f.) Changing the cut values used in the analysis does not change this conclusion. The best fit to the data using the model from Ref. [3] gave $-20° \pm 1°$ for $\theta_{\eta-\eta'}$, in good agreement

TABLE I. Measured branching ratios (BR) for $K_{L,S} \to \pi^+\pi^-\gamma$. All errors are combined statistical and systematic. $E_\gamma^* > 20$ MeV except where noted.

Decay mode	No. of events	$\frac{\Gamma(K \to \pi^+\pi^-\gamma)}{\Gamma(K \to \pi^+\pi^-)}$	BR
K_L	3136 ± 58	$(23.0 \pm 0.06) \times 10^{-3}$	$(4.66 \pm 0.15) \times 10^{-5}$
K_L (DE only)	1937 ± 65	$(15.7 \pm 0.7) \times 10^{-3}$	$(3.19 \pm 0.16) \times 10^{-5}$
K_L (IB only)	1199 ± 58	$(7.31 \pm 0.38) \times 10^{-3}$	$(1.49 \pm 0.08) \times 10^{-5}$
K_S	3723 ± 64	$(7.10 \pm 0.16) \times 10^{-3}$	$(4.87 \pm 0.11) \times 10^{-3}$
K_S ($E_\gamma^* > 50$ MeV)	1286 ± 39	$(2.56 \pm 0.09) \times 10^{-3}$	$(1.76 \pm 0.06) \times 10^{-3}$

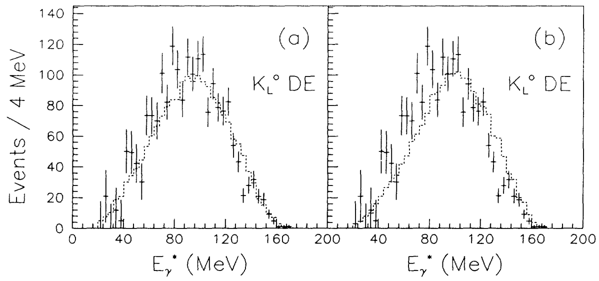

FIG. 3. (a) The DE E_γ^* spectrum for K_L decays (data points) compared to the prediction with an energy-dependent modification to the $M1$ amplitude (dashed). (b) Same spectrum compared to the prediction without the modification.

with the commonly accepted value [11]. In the notation of Eq. (1) this gives $a_1/a_2 = -1.8 \pm 0.2\ \mathrm{GeV}^2$.

Most models assume that the radiative decays occur strictly through a dipole transition. Higher multipole transitions may lead to a CP-violating 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 these data.

In conclusion, we have measured branching ratios for $K_{L,S} \to \pi^+\pi^-\gamma$ with improved precision. Our measurement of the K_S photon energy spectrum enabled us to separate the IB and DE components in the K_L decays. Our results agree both with previous measurements and with calculations of the IB component. The DE photon spectrum in K_L decays shows clear evidence of additional energy dependence beyond the basic $M1$ shape.

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