SLAC-PUB-1447 June 1974

OBSERVATION OF THE DECAY $K_{L}^{0} \rightarrow \pi^{+}\pi^{-}\gamma$ †

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ABSTRACT

We have measured the ratio $\Gamma(K_{L}^{0} \rightarrow \pi^{+}\pi^{-}\gamma)/\Gamma(K_{L}^{0} \rightarrow \text{all})$ to be $(6.2 \pm 2.1) \times 10^{-5}$. The rate and Dalitz plot distribution of 24 events are consistent with CP conservation in this weak-electromagnetic decay.

(Submitted to Physical Review Letters)

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[†] Work supported in part by the U.S. Atomic Energy Commission.

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We report herewith the first measurement of the branching ratio and Dalitz plot of the decay $K_{L}^{0} \rightarrow \pi^{+}\pi^{-}\gamma$.¹ This decay is of interest for several reasons:

- Both the decay rate and Dalitz plot distribution are sensitive to possible CP violation in the transition.²
- (2) $\Gamma(K_{L}^{0} \rightarrow \pi^{+}\pi^{-}\gamma)$ was the only unmeasured decay rate which is important in determining the unitarity limit for $K_{L}^{0} \rightarrow \mu^{+}\mu^{-}$ decay.³
- (3) A measurement of the branching ratio can discriminate between several theoretical models for weak radiative decays.⁴

The experiment was conducted at the SLAC K^O Spectrometer Facility, ⁵ which was modified to detect γ -rays and identify electrons by the addition of two 1.1 rl lead sheets (Fig. 1). Wide-angle showers were detected in the front chambers and narrow-angle showers in the rear chambers. The conversion points of the γ -rays were determined from shower tracks observed in the wire chambers, with a front (rear) resolution of ± 2.0 (0.35) cm; they were used with the decay vertex to compute γ -ray directions. Time-of-flight (TOF) measurements for charged tracks and showers were required to be consistent, and were then combined to yield a K^O_L TOF for each event with an uncertainty of ± 0.25 nsec.

Since the experimental problems associated with finding and reconstructing the decay modes $K_L^0 \rightarrow \pi^+ \pi^- \pi^0$ and $K_L^0 \rightarrow \pi^+ \pi^- \gamma$ are similar, our primary measurement consists of the ratio $\Gamma(\pi\pi\gamma) / \Gamma(3\pi)$. In this way most experimental uncertainties tend to cancel, and the final result has only a weak dependence on the details of the Monte Carlo. Nevertheless, a detailed comparison of 3π Monte Carlo and experimental data was used to confirm our understanding of kinematic and geometric distributions for charged tracks and γ 's.

From those events which had two charged tracks with a vertex, plus one or

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more converted γ 's, we isolated two sets of data by requiring the kinematic quantity ${P'_0}^2 < -0.014 (\text{GeV/c})^2$ for $\pi\pi\gamma$ candidates, and $-0.002 < {P'_0}^2 < 0.01$ $(\text{GeV/c})^2$ for 3π events. Both sets of data were required to pass additional cuts, the most important being:

- (1) neither charged track be identified as an electron or a muon,
- (2) 1γ (1 or 2γ 's for 3π events),
- (3) $\cos \theta_{\gamma C} \leq 0.9996$, where $\theta_{\gamma C}$ is the angle in the laboratory between the direction of the γ -ray and either charged track at the decay vertex.

After cuts, 1074 $\pi\pi\gamma$ candidates and 165K 3π events remain. The $P_0'^2$ cut for the $\pi\pi\gamma$ candidates removed essentially all the 3π background (a maximum contamination of 5% remains). Most $\pi e\nu\gamma$ events (internal and external bremsstrahlung) were removed by the cos $\theta_{\gamma C}$ cut. The remaining background in the $\pi\pi\gamma$ sample is primarily due to K_{l3}^0 events with a random γ in which the lepton was not identified.⁶

Two methods were used to extract the number of $\pi\pi\gamma$ events. The first consisted of calculating ψ , the angle between the measured and predicted γ -ray direction. The latter was calculated using \vec{P}_{π} +, \vec{P}_{π} -, and the K_{L}^{0} direction. Specifically, the two solutions for the laboratory γ direction corresponding to forward and backward emission in the K_{L}^{0} center-of-mass were calculated, and the solution which gave the better agreement with the measured direction was selected. Events were rejected if $|\text{TOF}_{\text{measured}} - \text{TOF}_{\text{fit}}| \ge 0.7$ nsec, where TOF_{fit} corresponded to the chosen solution. After this procedure, 106 front shower and 786 rear shower events remained; their cos ψ values are shown in Figs. 2a and 2b for those events with cos $\psi > 0.9968$.

The second method consisted of reconstructing the mass of the $\pi\pi\gamma$ system. The events were required to be consistent with transverse momentum conservation

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by applying $\Delta \phi$ cuts of 450 (150) mrads for the front(rear) showers, where $\Delta \phi$ is the difference between the predicted and measured γ angle in the plane perpendicular to the K_L^0 direction. P_{γ} was obtained from the expression $P_{\gamma} = P_{\perp}^{+-}/\sin \theta_{\gamma K}$, where P_{\perp}^{+-} is the transverse momentum of the charged pion pair, and $\theta_{\gamma K}$ is the laboratory angle between the γ and K_L^0 . Events with $\sin \theta_{\gamma K} < 0.03$ were rejected, since they gave a poor determination of P_{γ} . For a typical γ -ray of momentum 1 GeV/c, this gave $|\Delta P_{\gamma}/P_{\gamma}| \leq 5\%$. Events were rejected if $|\text{TOF}_{\text{measured}} - \text{TOF}_{\text{fit}}| \geq 0.7$ nsec, where TOF_{fit} was obtained from \vec{P}_{π^+} , \vec{P}_{π^-} and \vec{P}_{γ} . The mass of the $\pi\pi\gamma$ system is plotted for the 79 surviving events in Fig. 2c.

The Monte Carlo program generated raw data tapes of $\pi\pi\gamma$ and 3π events⁷ with unit γ conversion efficiency. The tapes were processed by the same reconstruction and analysis programs used for the data. The probability of converting and detecting a γ -ray was calculated by comparing ratios of 3π events having 1 and 2 showers in the Monte Carlo and data.⁸ Using those 3π events with both γ 's converted, we have found no measurable energy dependence in the conversion efficiency for $P_{\gamma} > 150$ MeV/c. Below this momentum the conversion efficiency was poorly determined. A cut was therefore made removing $\pi\pi\gamma$ candidates with $P_{\gamma} < 150$ MeV/c to enable a distinction between CP odd and even matrix elements. This cut was not applied to the 3π data where P_{γ} was undetermined. This introduced a negligible bias in the normalization. We find the overall detection efficiency for front(rear) showers to be $45.0 \pm 1.1\%$ ($46.1 \pm 0.9\%$). This is close to the measured maximum of 51%;⁹ the difference is due in part to TOF cuts and in part to a small software inefficiency for locating showers in the data. A study of Monte

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Carlo generated $\pi\pi\gamma$ events indicates that 73% (82%) of front (rear) $\pi\pi\gamma$ events have $\cos\psi > 0.9996$ (0.9998), and that the signal in Fig. 2c peaks with a FWHM 15.0 MeV/c² about the K⁰_L mass. The contributions of the previously described background sources were found to be smooth, and in no case were they peaked at M_K or at $\cos\psi = 1$. The backgrounds in Fig. 2 were obtained from unrenormalized fits to the same data after substituting a random photon from another event.

The three distributions of Fig. 2, when combined with the Monte Carlo efficiency calculations and the number of 3π events observed, provide three correlated determinations of the $K_{L}^{0} \rightarrow \pi^{+}\pi^{-}\gamma$ branching ratio. After background subtraction, Fig. 2a, b, c yield a branching ratio $\Gamma(\pi\pi\gamma)/\Gamma(3\pi) = (5.3 + 3.1) \times 10^{-4}$, $(5.8 \pm 1.6) \times 10^{-4}$, and $(3.8 \pm 1.6) \times 10^{-4}$ respectively. The weighted average of these results, combined with the value 10 $\Gamma(K_{L}^{0} \rightarrow \pi^{+}\pi^{-}\pi^{0})/\Gamma(K_{L}^{0} \rightarrow all) = 0.126$, yields $\Gamma(K_{L}^{0} \rightarrow \pi^{+}\pi^{-}\gamma)/\Gamma(K_{L}^{0} \rightarrow all) = (6.2 \pm 2.1) \times 10^{-5}$.

Figure 3 shows a folded Dalitz plot of events with $|M_{\pi\pi\gamma} - M_K| < 7.5 \text{ MeV/c}^2$. The signal to background ratio is roughly 3:2 and the background is evenly distributed in this plot. The observed E_{γ}^* distribution was such that no cut was necessary to obtain the branching ratio. If the $K_L^0 \rightarrow \pi^+\pi^-\gamma$ decay proceeds via the CP violating mode $K_L^0 \rightarrow \pi^+\pi^-$ followed by inner bremsstrahlung, one would expect a branching ratio $\sim 1 \times 10^{-5}$ ($E_{\gamma}^* > 20$ MeV) and the bremsstrahlung γ ray energy distribution in Fig. 3. In contrast we show also the γ spectrum produced by a CP conserving, $L_{\pi\pi} = 1$ (M1) matrix element. Thus both our measured branching ratio and crude Dalitz plot distribution of these events are consistent with a CP conserving transition dominating this decay.

Our measured branching ratio is ~ 5 times lower than the Moshe-Singer and

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Rockmore-Wong calculations as quoted. However, if one takes the R-W theoretical value for $\Gamma(K_{L}^{0} \rightarrow \pi^{+}\pi^{-}\gamma)$ without renormalizing to $\Gamma(K_{L}^{0} \rightarrow \gamma\gamma)$, one obtains agreement with our result. Thus, the zero-free-parameter fermion loop model appears to give excellent predictions for both the $K_{L}^{0} \rightarrow \pi^{+}\pi^{-}\gamma$ and $K^{+} \rightarrow \pi^{+}\pi^{0}\gamma$ decay modes. ¹² The current algebra treatment¹³ relating the $\pi\pi\gamma$ to the $\gamma\gamma$ rate is also in agreement with our value. Our branching ratio implies that the contribution of the $\pi\pi\gamma$ intermediate state to the unitarity limit for $K_{L}^{0} \rightarrow \mu^{+}\mu^{-}$ is less than 2%.

We thank R. Coombes, S. Hertzbach, R. Piccioni, D. Porat, M. Schwartz and E. D. Uggla for their contributions to this experiment. We also acknowledge the excellent support of the Accelerator Operations, Experimental Facilities and Computer Operations Groups of the Stanford Linear Accelerator Center.

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- 6. The 3π events with > 2γ 's indicate a front (rear) accidental γ probability of 0.3 (2.6)%.

- 7. The Monte Carlo $\pi\pi\gamma$ events were generated according to an $L_{\pi\pi} = 1$, CP odd matrix element, while the 3π events were generated with the matrix element $|M|^2 \sim 1 - 5.2 (Q/M_K) Y + 4.64 (Q/M_K)^2 Y^2$, where $Y = 3T_{\pi 0}/Q-1$ (R. Messner <u>et al.</u>, paper No. 882 submitted to the XVI International Conference on High Energy Physics, Chicago (1972)).
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FIGURE CAPTIONS

- 1. Elevation view of SLAC K_L^0 Spectrometer. The trigger requirement was $\nabla \overline{W} U2T2A$ or $\overline{V}2T3A$. λ represents absorption lengths. The E counters and A ℓ chambers were not used in the $\pi\pi\gamma$ analysis.
- 2. (a) $\cos \psi$, the angle between the measured and predicted γ -ray directions for $\pi\pi\gamma$ candidates with a front γ shower, (b) $\cos \psi$ for $\pi\pi\gamma$ candidates with a a rear γ shower. (c) $M_{\pi\pi\gamma} - M_{K0}$. The backgrounds discussed in the text are indicated by dashed lines.

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Dalitz plot (folded about the γ energy axis) and projected γ -ray energy spectrum. The shaded portion is the difference between the observed distribution and the expected background. The smooth curves show the predicted spectra including experimental acceptance for $L_{\pi\pi} = 1$, CP conserving (-) and violating (+) matrix elements.

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Fig. 2



Fig. 3