# OBSERVATION OF THE DECAY $\mathrm{K}_{\mathrm{L}}^{\mathrm{O}} \rightarrow \pi^{+} \pi^{-} \gamma \dagger$ 

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## ABSTRACT

We have measured the ratio $\Gamma\left(\mathrm{K}_{\mathrm{L}}^{\mathrm{O}} \rightarrow \pi^{+} \pi^{-} \gamma\right) / \Gamma\left(\mathrm{K}_{\mathrm{L}}^{\mathrm{O}} \rightarrow\right.$ 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.
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[^0]We report herewith the first measurement of the branching ratio and Dalitz plot of the decay $\mathrm{K}_{\mathrm{L}}^{\mathrm{o}} \rightarrow \pi^{+} \pi^{-} \gamma .^{1}$ This decay is of interest for several reasons:
(1) Both the decay rate and Dalitz plot distribution are sensitive to possible CP violation in the transition. ${ }^{2}$
(2) $\Gamma\left(\mathrm{K}_{\mathrm{L}}^{\mathrm{o}} \rightarrow \pi^{+} \pi^{-} \gamma\right)$ was the only unmeasured decay rate which is important in determining the unitarity limit for $\mathrm{K}_{\mathrm{L}}^{\mathrm{O}} \rightarrow \mu^{+} \mu^{-}$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 ${ }^{0}$ Spectrometer Facility, ${ }^{5}$ which was modified to detect $\gamma$-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 $\gamma$-rays were determined from shower tracks observed in the wire chambers, with a front (rear) resolution of $\pm 2.0(0.35) \mathrm{cm}$; they were used with the decay vertex to compute $\gamma$-ray directions. Time-of-flight (TOF) measurements for charged tracks and showers were required to be consistent, and were then combined to yield a $K_{L}^{o}$ TOF for each event with an uncertainty of $\pm 0.25 \mathrm{nsec}$.

Since the experimental problems associated with finding and reconstructing the decay modes $\mathrm{K}_{\mathrm{L}}^{\mathrm{o}} \rightarrow \pi^{+} \pi^{-} \pi^{o}$ and $\mathrm{K}_{\mathrm{L}}^{\mathrm{o}} \rightarrow \pi^{+} \pi^{-} \gamma$ 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 $3 \pi$ Monte Carlo and experimental data was used to confirm our understanding of kinematic and geometric distributions for charged tracks and $\gamma^{\prime}$ s.

From those events which had two charged tracks with a vertex, plus one or
more converted $\gamma^{\prime}$ s, we isolated two sets of data by requiring the kinematic quantity $\mathrm{P}_{0}^{2}<-0.014(\mathrm{GeV} / \mathrm{c})^{2}$ for $\pi \pi \gamma$ candidates, and $-0.002<\mathrm{P}_{0}^{2}<0.01$ $(\mathrm{GeV} / \mathrm{c})^{2}$ for $3 \pi$ 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) $1 \gamma$ ( 1 or $2 \gamma^{\prime}$ s for $3 \pi$ events),
(3) $\cos \theta_{\gamma \mathrm{C}} \leq 0.9996$, where $\theta_{\gamma \mathrm{C}}$ is the angle in the laboratory between the direction of the $\gamma$-ray and either charged track at the decay vertex.
After cuts, $1074 \pi \pi \gamma$ candidates and $165 \mathrm{~K} 3 \pi$ events remain. The $\mathrm{P}_{0}^{\prime 2}$ cut for the $\pi \pi \gamma$ candidates removed essentially all the $3 \pi$ background (a maximum contamination of $5 \%$ remains). Most $\pi e \nu \gamma$ events (internal and external bremsstrahlung) were removed by the $\cos \theta{ }_{\gamma \mathrm{C}}$ cut. The remaining background in the $\pi \pi \gamma$ sample is primarily due to $\mathrm{K}_{\ell 3}^{0}$ events with a random $\gamma$ 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 $\psi$, the angle between the measured and predicted $\gamma$-ray direction. The latter was calculated using $\overrightarrow{\mathrm{P}}_{\pi^{+}}, \overrightarrow{\mathrm{P}}_{\pi^{-}}$, and the $\mathrm{K}_{\mathrm{L}}^{\mathrm{o}}$ direction. Specifically, the two solutions for the laboratory $\gamma$ direction corresponding to forward and backward emission in the $\mathrm{K}_{\mathrm{L}}^{0}$ center-of-mass were calculated, and the solution which gave the better agreement with the measured direction was selected. Events were rejected if $\left|\mathrm{TOF}_{\text {measured }}-\mathrm{TOF}_{\text {fit }}\right| \geq 0.7 \mathrm{nsec}$, where $\mathrm{TOF}_{\text {fit }}$ corresponded to the chosen solution. After this procedure, 106 front shower and 786 rear shower events remained; their $\cos \psi$ 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
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 $\gamma$ angle in the plane perpendicular to the $K_{L}^{o}$ direction. $P_{\gamma}$ was obtained from the expression $\mathrm{P}_{\gamma}=\mathrm{P}_{\perp}^{+-} / \sin \theta{ }_{\gamma \mathrm{K}}$, where $\mathrm{P}_{\perp}^{+-}$is the transverse momentum of the charged pion pair, and $\theta_{\gamma \mathrm{K}}$ is the laboratory angle between the $\gamma$ and $\mathrm{K}_{\mathrm{L}}^{\mathrm{o}}$. Events with $\sin \theta_{\gamma \mathrm{K}}<0.03$ were rejected, since they gave a poor determination of $\mathrm{P}_{\gamma}$. For a typical $\gamma$-ray of momentum $1 \mathrm{GeV} / \mathrm{c}$, this gave $\left|\Delta \mathrm{P}_{\gamma} / \mathrm{P}_{\gamma}\right| \leq 5 \%$. Fvents were rejected if $\mid T O F$ measured $-\mathrm{TOF}_{\mathrm{fit}} \mid \geq 0.7 \mathrm{nsec}$, where $\mathrm{TOF}_{\text {fit }}$ was obtained from $\overrightarrow{\mathrm{P}}_{\pi^{+}}, \overrightarrow{\mathrm{P}}_{\pi^{-}}$and $\overrightarrow{\mathrm{P}}_{\gamma}$. 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 $3 \pi$ events ${ }^{7}$ with unit $\gamma$ conversion efficiency. The tapes were processed by the same reconstruction and analysis programs used for the data. The probability of converting and detecting a $\gamma$-ray was calculated by comparing ratios of $3 \pi$ events having 1 and 2 showers in the Monte Carlo and data. ${ }^{8}$ Using those $3 \pi$ events with both $\gamma^{\prime}$ s converted, we have found no measurable energy dependence in the conversion efficiency for $\mathrm{P}_{\gamma}>150 \mathrm{MeV} / \mathrm{c}$. Below this momentum the conversion efficiency was poorly determined. A cut was therefore made removing $\pi \pi \gamma$ candidates with $P_{\gamma}<150 \mathrm{MeV} / \mathrm{c}$ to enable a distinction between CP odd and even matrix elements. This cut was not applied to the $3 \pi$ data where $P_{\gamma}$ 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

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 $15.0 \mathrm{MeV} / \mathrm{c}^{2}$ about the $\mathrm{K}_{\mathrm{L}}^{\mathrm{o}}$ 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 $3 \pi$ events observed, provide three correlated determinations of the $\mathrm{K}_{\mathrm{L}}^{\mathrm{O}} \rightarrow \pi^{+} \pi^{-} \gamma$ branching ratio. After background subtraction, Fig. 2a, b, c yield a branching ratio $\Gamma(\pi \pi \gamma) / \Gamma(3 \pi)=\left(5.3_{-1.8}^{+3.1}\right) \times 10^{-4}$, $(5.8 \pm 1.6) \times 10^{-4}$, and $(3.8 \pm 1.6) \times 10^{-4}$ respectively. The weighted average of these results, combined with the value ${ }^{10} \Gamma\left(\mathrm{~K}_{\mathrm{L}}^{\mathrm{o}} \rightarrow \pi^{+} \pi^{-} \pi^{\mathrm{o}}\right) / \Gamma\left(\mathrm{K}_{\mathrm{L}}^{\mathrm{o}} \rightarrow\right.$ all $)=0.126$, yields $\Gamma\left(\mathrm{K}_{\mathrm{L}}^{\mathrm{o}} \rightarrow \pi^{+} \pi^{-} \gamma\right) / \Gamma\left(\mathrm{K}_{\mathrm{L}}^{\mathrm{o}} \rightarrow\right.$ all $)=(6.2 \pm 2.1) \times 10^{-5}$.

Figure 3 shows a folded Dalitz plot of events with $\left|M_{\pi \pi \gamma}-M_{K}\right|<7.5 \mathrm{MeV} / \mathrm{c}^{2}$. The signal to background ratio is roughly $3: 2$ and the background is evenly distributed in this plot. The observed $\mathrm{E}_{\gamma}^{*}$ distribution was such that no cut was necessary to obtain the branching ratio. If the $\mathrm{K}_{\mathrm{L}}^{\mathrm{o}} \rightarrow \pi^{+} \pi^{-} \gamma$ decay proceeds via the CP violating mode $\mathrm{K}_{\mathrm{L}}^{0} \rightarrow \pi^{+} \pi^{-}$followed by inner bremsstrahlung, one would expect a branching ratio $\sim 1 \times 10^{-5}\left(\mathrm{E}_{\gamma}^{*}>20 \mathrm{MeV}\right)$ and the bremsstrahlung $\gamma-$ ray energy distribution in Fig. 3. In contrast we show also the $\gamma$ spectrum produced by a CP conserving, $\mathrm{L}_{\pi \pi}=1$ (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 $\sim 5$ times lower than the Moshe-Singer and

Rockmore-Wong calculations as quoted. However, if one takes the R-W theorettcal value for $\Gamma\left(\mathrm{K}_{\mathrm{L}}^{\mathrm{o}} \rightarrow \pi^{+} \pi^{-} \gamma\right)$ without renormalizing to $\Gamma^{\prime}\left(\mathrm{K}_{\mathrm{L}}^{o} \rightarrow \gamma \gamma\right)$, one obtains agreement with our result. Thus, the zero-free-parameter fermion loop model appears to give excellent predictions for both the $\mathrm{K}_{\mathrm{L}}^{\mathrm{o}} \rightarrow \pi^{+} \pi^{-} \gamma$ and $\mathrm{K}^{+} \rightarrow \pi^{+} \pi^{\mathrm{o}} \gamma$ decay modes. ${ }^{12}$ The current algebra treatment ${ }^{13}$ 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 $\mathrm{K}_{\mathrm{L}}^{\mathrm{o}} \rightarrow \mu^{+} \mu^{-}$ is less than $2 \%$.

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6. The $3 \pi$ events with $>2 \gamma^{\prime}$ s indicate a front (rear) accidental $\gamma$ probability of $0.3(2.6) \%$.
7. The Monte Carlo $\pi \pi \gamma$ events were generated according to an $\mathrm{L}_{\pi \pi}=1, \mathrm{CP}$ gdd matrix element, while the $3 \pi$ events were generated with the matrix element $\mid \mathrm{M}^{2} \sim 1-5.2\left(\mathrm{Q} / \mathrm{M}_{\mathrm{K}}\right) \mathrm{Y}+4.64\left(\mathrm{Q} / \mathrm{M}_{\mathrm{K}}\right)^{2} \mathrm{Y}^{2}$, where $\mathrm{Y}=3 \mathrm{~T}_{\pi \mathrm{o}} / \mathrm{Q}-1$ (R. Messner et al., paper No. 882 submitted to the XVI International Conference on High Energy Physics, Chicago (1972)).
8. This was confirmed by comparing $3 \pi$ events having 0,1 and $2 \gamma^{\prime} s$ in a data sample taken with a $\overline{\mathrm{V}} 2 \mathrm{~T} 2 \mathrm{~A}$ trigger (i. e. , having no $\gamma$ requirement).
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## FIGURF CAPTIONS

1. Elevation view of SLAC $\mathrm{K}_{\mathrm{L}}^{0}$ Spectrometer. The trigger requirement was $\overline{\mathrm{V}} \overline{\mathrm{W}} \mathrm{U} 2 \mathrm{~T} 2 \mathrm{~A}$ or $\overline{\mathrm{V}} 2 \mathrm{~T} 3 \mathrm{~A}$. $\lambda$ represents absorption lengths. The E counters and $\mathrm{A} \ell$ chambers were not used in the $\pi \pi \gamma$ analysis.
2. (a) $\cos \psi$, the angle between the measured and predicted $\gamma$-ray directions for $\pi \pi \gamma$ candidates with a front $\gamma$ shower, (b) $\cos \psi$ for $\pi \pi \gamma$ candidates with a a rear $\gamma$ shower. (c) $\mathrm{M}_{\pi \pi \gamma}-\mathrm{M}_{\mathrm{K}^{\mathrm{O}}}$. The backgrounds discussed in the text are indicated by dashed lines.
3. Dalitz plot (folded about the $\gamma$ energy axis) and projected $\gamma$-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 $L_{\pi \pi}=1, \mathrm{CP}$ conserving ( - ) and violating ( + ) matrix elements.


Fig. 1


Fig. 2


Fig. 3


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