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Observation of the Decay $K_L{}^0 \to \pi^+\pi^-\gamma$†

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We have measured the ratio $\Gamma(K_L{}^0\to\pi^+\pi^-\gamma)/\Gamma(K_L{}^0\to\text{all})$ to be $(6.2\pm2.1)\times10^{-5}$. The rate and Dalitz-plot distribution are consistent with CP conservation in this weak-electromagnetic decay.

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

(1) Both the decay rate and Dalitz-plot distribution are sensitive to possible CP nonconservation in the transition.[2]

(2) $\Gamma(K_L{}^0\to\pi^+\pi^-\gamma)$ was the only unmeasured decay rate which is important in determining the unitarity limit for $K_L{}^0\to\mu^+\mu^-$ 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 Stanford Linear Accelerator Center (SLAC) K^0 spectrometer facility,[5] which was modified to detect γ rays and identify electrons by the addition of two 1.1-radiation-length (rl) lead sheets (Fig. 1). Showers at large (small) angles with respect to the beam direction were detected in the front (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 $K_L{}^0$ TOF for each

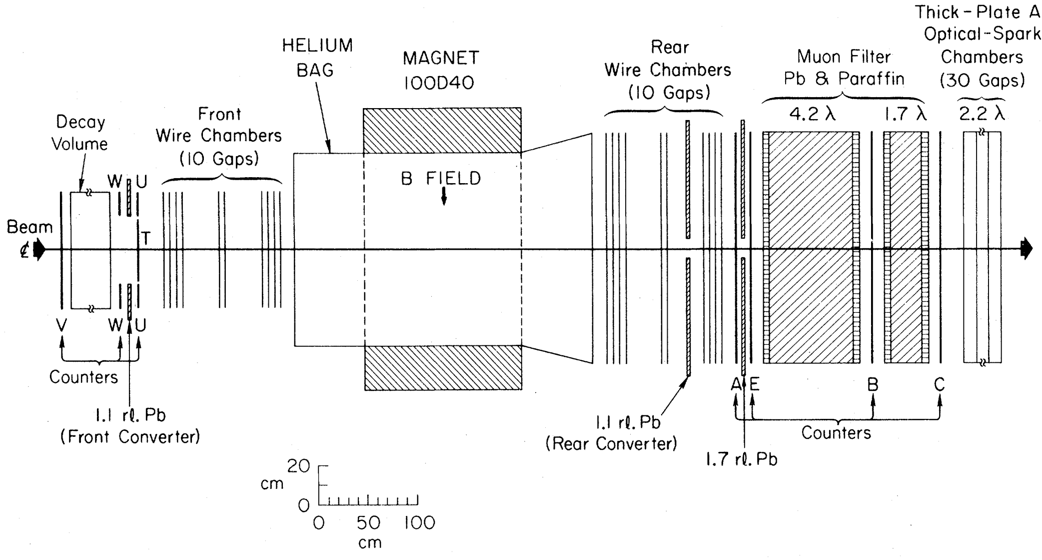

FIG. 1. Elevation view of SLAC $K_L{}^0$ spectrometer. The trigger requirement was $\overline{\mathrm{V}}$WU2T2A or $\overline{\mathrm{V}}$2T3A. λ represents absorption lengths. The E counters and Al chambers were not used in the $\pi\pi\gamma$ analysis.

event with an uncertainty of ±0.25 nsec.

Since the experimental problems associated with finding and reconstructing the decay modes $K_L{}^0 \to \pi^+\pi^-\pi^0$ and $K_L{}^0 \to \pi^+\pi^-\gamma$ 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 calculation. 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 more converted γ's, we isolated two sets of data by requiring the kinematic quantity $P_0{}'^2 < -0.014$ (GeV/c)^2 for $\pi\pi\gamma$ candidates, and $-0.002 < P_0{}'^2 < 0.01$ (GeV/c)^2 for 3π events.[6] 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) one γ (one or two γ's for 3π events); and (3) $\cos\theta_{\gamma C} \leq 0.9996$, where $\theta_{\gamma C}$ is the angle in the laboratory between the directions of the observed γ ray and either charged track at the decay vertex.

After cuts, 1074 $\pi\pi\gamma$ candidates and 165 000 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.[7]

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 $\vec{\mathrm{P}}_{\pi^+}$, $\vec{\mathrm{P}}_{\pi^-}$, and the $K_L{}^0$ direction. Specifically, the two solutions for the laboratory γ directions 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 $|\mathrm{TOF}_{\mathrm{meas}} - \mathrm{TOF}_{\mathrm{fit}}| \geq 0.7$ nsec, where $\mathrm{TOF}_{\mathrm{fit}}$ 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. 2(a) and 2(b) 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 $\Delta\varphi$ cuts of 450 (150) mrads for the front (rear) showers, where $\Delta\varphi$ is the difference between the predicted and measured γ angles 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

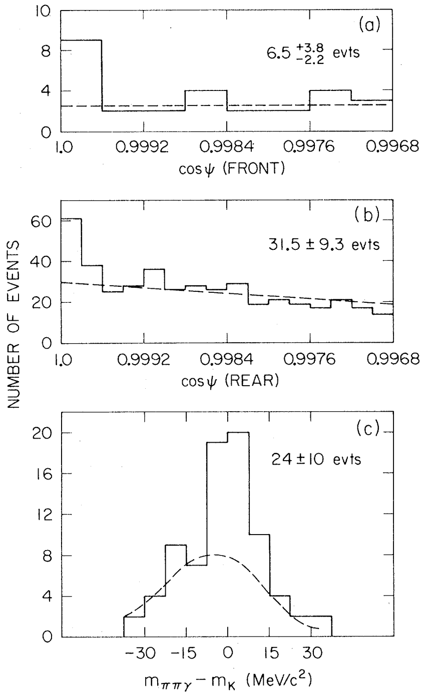

FIG. 2. (a) Cosψ, the angle between the measured and predicted γ-ray directions for $\pi\pi\gamma$ candidates with a front γ shower; (b) cosψ for $\pi\pi\gamma$ candidates with a rear γ shower; (c) $m_{\pi\pi\gamma} - m_{K^0}$. The backgrounds discussed in the text are indicated by dashed lines.

a typical γ ray of momentum 1 GeV/c, this gave $|\Delta P_\gamma / P_\gamma| \leq 5\%$. Events were rejected if $|\mathrm{TOF}_{\mathrm{meas}} - \mathrm{TOF}_{\mathrm{fit}}| \geq 0.7$ nsec, where $\mathrm{TOF}_{\mathrm{fit}}$ was obtained from $\vec{\mathrm{P}}_{\pi^+}$, $\vec{\mathrm{P}}_{\pi^-}$, and $\vec{\mathrm{P}}_\gamma$. The mass of the $\pi\pi\gamma$ system is plotted in Fig. 2(c) for the 79 surviving events.

The Monte Carlo program generated raw data tapes of $\pi\pi\gamma$ and 3π events[8] 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 one and two showers in the Monte Carlo program and experimental data.[9] 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%[10]; 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. 2(c) peaks with a full width at half-maximum of 15.0 MeV/c^2 about the $K_L{}^0$ 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 $K_L{}^0 \to \pi^+\pi^-\gamma$ branching ratio. After background subtraction, Figs. 2(a)–2(c) yield a branching ratio $\Gamma(\pi\pi\gamma)/\Gamma(3\pi) = (5.3^{+3.1}_{-1.8}) \times 10^{-4}$, $(5.8 \pm 1.6) \times 10^{-4}$, and $(3.8 \pm 1.6) \times 10^{-4}$, respectively. The weighted average of these results, combined with the value[11] $\Gamma(K_L{}^0 \to \pi^+\pi^-\pi^0)/\Gamma(K_L{}^0 \to \mathrm{all}) = 0.126$, yields $\Gamma(K_L{}^0 \to \pi^+\pi^-\gamma)/\Gamma(K_L{}^0 \to \mathrm{all}) = (6.2 \pm 2.1) \times 10^{-5}$.

Figure 3 shows a folded Dalitz plot of events with $|m_{\pi\pi\gamma} - m_K| < 7.5$ MeV/c^2. The signal-to-background ratio is roughly 3:2 and the background is evenly distributed in this plot. The observed $E_\gamma{}^*$ distribution was such that no cut was necessary to obtain the branching ratio. If the $K_L{}^0 \to \pi^+\pi^-\gamma$ decay proceeds via the CP-nonconserving mode $K_L{}^0 \to \pi^+\pi^-$ 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 Rockmore-Wong calculations as quoted.[12] However, if one takes the Rockmore-Wong theoretical value for $\Gamma(K_L{}^0 \to \pi^+\pi^-\gamma)$ without renormalizing to $\Gamma(K_L{}^0 \to \gamma\gamma)$, one obtains agreement with our result. Thus, the zero-free-parameter fermion loop model appears to give excellent predictions for both the $K_L{}^0 \to \pi^+\pi^-\gamma$ and $K^+ \to \pi^+\pi^0\gamma$ decay modes.[13] The

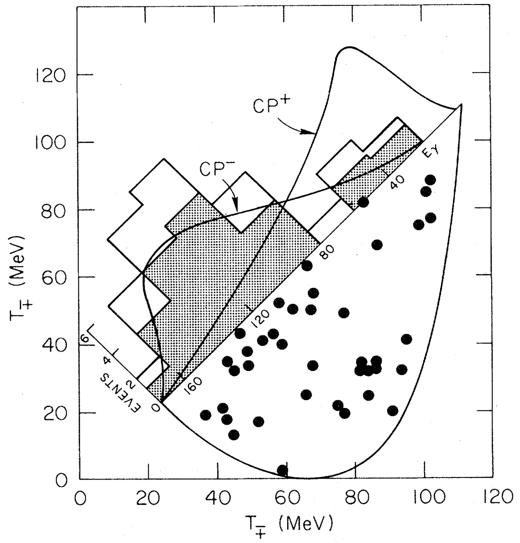

FIG. 3. Dalitz plot (folded about the γ energy axis) and projected γ-ray energy spectrum. The shaded portion is the difference between the observed distribution and the expected background. The smooth curves show the predicted spectra including experimental acceptance for $L_{\pi\pi}=1$, CP-conserving (−) and -nonconserving (+) matrix elements.

current-algebra treatment[14] 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 $K_L^0 \to \mu^+\mu^-$ is less than 2%.

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$$P_0'^2 = [(m_K^2 - m_{+-}^2 - m_{\pi^0}^2)^2 - 4(m_{+-}^2 m_{\pi^0}^2 + m_K^2 P_\perp^2)]/4(P_\perp^2 + m_{+-}^2),$$

in which m_{+-} represents mass of the (π^+, π^-) system, and $P_\perp$ its transverse momentum relative to the K_L^0 axis.

[7] The 3π events with more than two γ's indicate a front (rear) accidental γ probability of 0.3% (2.6%).

[8] 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 $|m|^2 \sim 1 - 5.2(Q/m_K)Y + 4.64(Q/m_K)^2Y^2$, where $Y = 3T_{\pi^0}/Q - 1$ [R. Messner *et al.*, in Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972 (unpublished), paper No. 882].

[9] This was confirmed by comparing 3π events having zero, one, and two γ's in a data sample taken with a $\overline{V}$2T2A trigger (i.e., having no γ requirement).

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