

Observation of the Dalitz Decay Modes of the K_L^0

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 (Received 17 September 1979)

Using a proportional-chamber spectrometer and an array of lead-glass photon detectors, we have observed four examples of the decay $K_L^0 \rightarrow e^+ e^- \gamma$, and one candidate for $K_L^0 \rightarrow \mu^+ \mu^- \gamma$. The corresponding branching ratios are $(17.4 \pm 8.7) \times 10^{-6}$ and $(2.8 \pm 2.8) \times 10^{-7}$, respectively. In addition we have established 90%-confidence-level upper limits of $b(K_L^0 \rightarrow e^+ e^- \pi^0) < 2.3 \times 10^{-6}$ and $b(K_L^0 \rightarrow \mu^+ \mu^- \pi^0) < 1.2 \times 10^{-6}$.

The decays $K_L^0 \rightarrow e^+ e^- \gamma$ and $K_L^0 \rightarrow \mu^+ \mu^- \gamma$ have been suggested as sites for possible anomalous effects¹ and structure,^{2,3} which would manifest themselves as deviations from the rate and matrix elements which can otherwise be calculated reliably³ given the measured $K_L^0 \rightarrow \gamma\gamma$ rate.⁴ Because of the suppression of strangeness-changing neutral currents, the decays $K_L^0 \rightarrow e^+ e^- \pi^0$ and $K_L^0 \rightarrow \mu^+ \mu^- \pi^0$ provide a window through which higher-order effects in the weak interactions may potentially be studied. The theoretical literature devoted to this subject is large and diverse⁵⁻¹²; branching ratios as high as 10^{-5} and as low as $< 10^{-13}$ have been predicted. Clearly the observation of $K_L^0 \rightarrow l^+ l^- \pi^0$ would greatly advance our

knowledge of the weak interaction.

An experiment sensitive to these decays was carried out at the Brookhaven National Laboratory alternating-gradient synchrotron as part of a program of studying K_L^0 decays into two charged particles plus any number of neutral particles. The apparatus was set up in a long-lived neutral beam essentially identical to one described previously.^{13,14} The beam contained approximately 10^6 K_L^0 and 2×10^7 neutrons per pulse. The K_L^0 momentum averaged ~ 6 GeV/c and the useful spectrum extended from 2 to 16 GeV/c.

The experimental arrangement is shown in Fig. 1. The neutral beam passed through a veto counter (D) and into a 6-m-long vacuum decay tank.

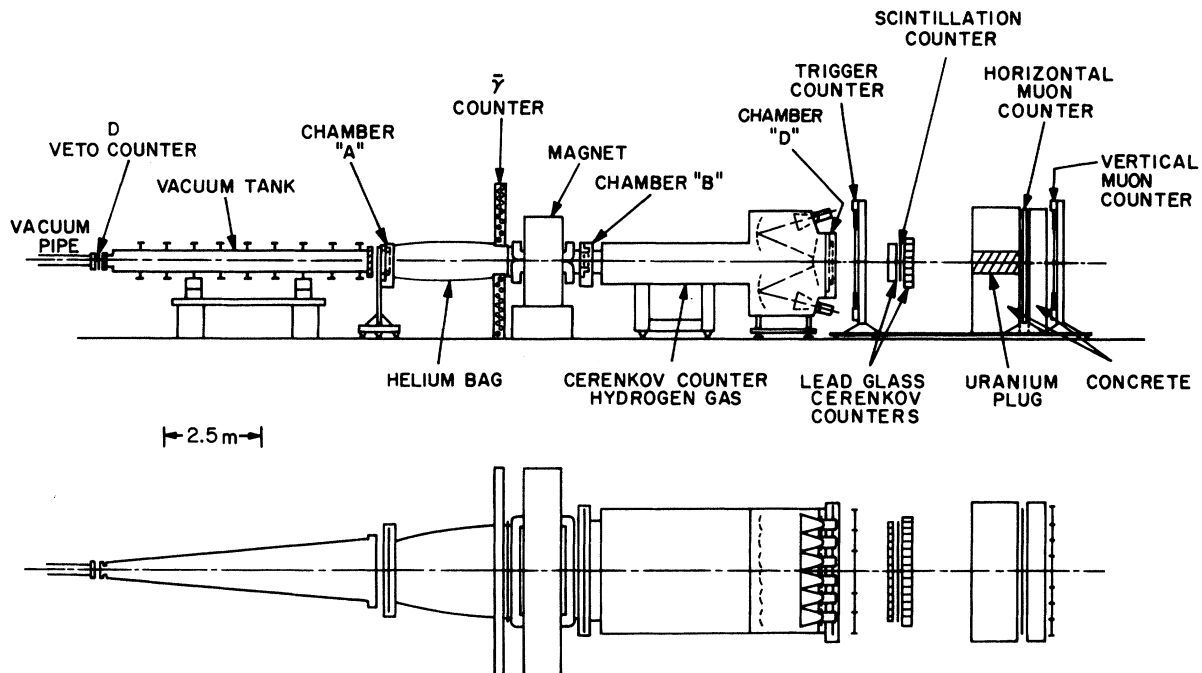


FIG. 1. Layout of the apparatus.

Charged products of the decays were detected in a three-chamber 5000-wire multiwire proportional counter (MWPC) spectrometer system which has been described previously.¹³ A hydrogen Cherenkov counter with twelve independent optical sectors (C_i) operated at atmospheric pressure distinguished electrons from pions for momenta below 8 GeV/c. Muons with momenta greater than 1.5 GeV/c were identified by their penetration to two eight-element banks of counters, μ_H after 600 and μ_V after 750 g/cm² of material.

Photons were detected in a 120×300-cm² lead-glass Cherenkov-counter array (LG).¹⁵ The array was divided into two hodoscopes: a bank of 38 transversely mounted counters presenting 2.8 radiation lengths (r.l.) to the beam, followed by an 8×20 array presenting 9.4 r.l. to the beam. A 30×30-cm² hole in the array allowed passage of the beam. A 38-element scintillation counter hodoscope (UV) situated between the front and rear walls provided 0.7-nsec timing resolution on both charged and neutral particles. Two lead-liquid scintillator shower counters (γ_{anti}) flanking the aperture of the analyzing magnet served to reduce the trigger rate due to $K_L^0 \rightarrow \pi^+ \pi^- \pi^0$ decays.

The electronic triggering requirements were

- (i) basic trigger, $\overline{D} \cdot (\overline{\gamma_{anti}}) \cdot (\text{two tracks in each spectrometer plane}) \cdot (\geq 3 \text{ clusters in UV and in LG})$;
- (ii) $e^+e^- \gamma$, (basic trigger) $\cdot C_i \cdot C_j$;
- (iii) $\mu^+ \mu^- \gamma$, (basic trigger) $\cdot (\geq 2 \mu_H) \cdot (\geq 2 \mu_V)$.

Parallel triggers were also implemented to detect $\pi^+ \pi^- \gamma$ (Ref. 16) and $K_L^0 \rightarrow \pi^+ \pi^0 e^+ \nu$ (Ref. 17) decays. In addition, many runs were taken under special triggering conditions. Altogether, approximately 2.7×10^7 events were collected. All K -decay candidates were required to satisfy (1) good decay vertex, (2) \geq one in-time γ , (3) γ and charged shower clusters separated in both LG and UV counters.

To distinguish electrons from pions and muons in the LG, the quantity $R = E(\text{LG})/p(\text{MWPC})$ is calculated for each charged particle. The cut $0.75 \leq R \leq 1.25$ accepts 0.98 of e 's, 0.01 of π 's, and 0.0006 of μ 's. The Cherenkov counter accepts 0.99 of e 's, and ~ 0.0005 of π 's and μ 's. Thus the overall π and μ rejections are $2 \times 10^5:1$ and $3.3 \times 10^5:1$, respectively.

The combination of kinematics and particle identification makes the $K_L^0 \rightarrow e^+e^- \gamma$ and $e^+e^- \pi^0$

decays extremely clean. The leading backgrounds to $K_L^0 \rightarrow e^+e^- \gamma$ are $K_L^0 \rightarrow \pi^+ e^+ \nu \gamma$ and $K_L^0 \rightarrow \pi^+ e^+ \nu$ in which the π^+ generates a spurious γ . These contribute < 0.01 event to the interval $0.48 < M_{e^+e^- \gamma} < 0.52$ GeV/c². The background to $e^+e^- \pi^0$ is negligible.

In addition to the K decay and e purity cuts, the $ee\gamma$ candidates had to satisfy (1) $0.5 < p_{\pm} < 7.5$ GeV/c, (2) $\phi_0^2 < -0.018$ (Ref. 18), (3) $\theta_{+-\gamma} < 2.45$ mrad, where $\theta_{+-\gamma}$ is the angle between the incident K_L^0 and the sum of the final-state momenta, and (4) $0.48 < M_{e^+e^- \gamma} < 0.52$ GeV/c².

The effective mass of $e^+e^- \gamma$ candidates passing all other cuts is plotted in Fig. 2(a). A clear peak of four events is evident near the K^0 mass ($\langle M_{e^+e^- \gamma} \rangle = 0.502$ GeV/c², $\sigma_{M_{e^+e^- \gamma}} = 0.008$ GeV/c²). The nearest background event is > 100 MeV/c² below the peak. This result is quite insensitive to variations in the kinematic cuts; removing cuts (2) and (3) entirely introduces no additional event with $M_{e^+e^- \gamma} > 0.38$ GeV/c².

The $e^+e^- \pi^0$ candidates had to satisfy condition

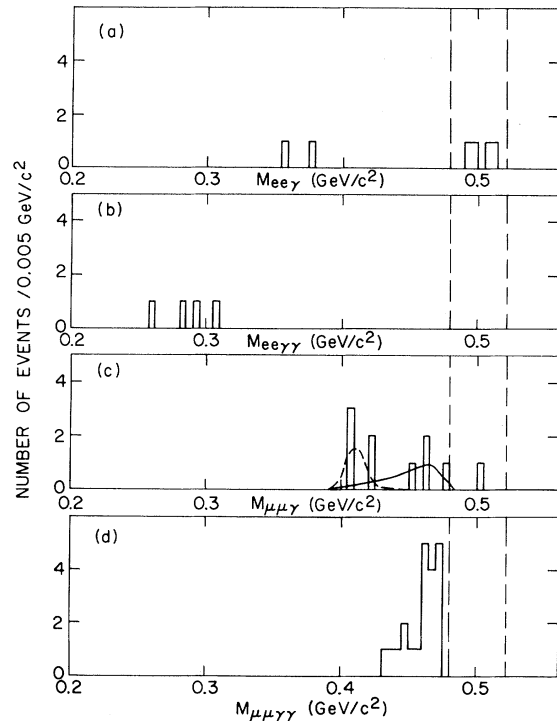


FIG. 2. Effective-mass spectra for events subject to all cuts except in mass. Vertical lines show mass cuts. (a) $e^+e^- \gamma$, (b) $e^+e^- \gamma \gamma$, (c) $\mu^+ \mu^- \gamma$ (dashed line is expected $K_L^0 \rightarrow \pi^+ \pi^- \pi^0$ background, solid line is sum of expected $K_L^0 \rightarrow \pi^+ \mu^+ \nu \gamma$ and $K_L^0 \rightarrow \pi^+ \mu^+ \nu$ backgrounds), and (d) $\mu^+ \mu^- \gamma \gamma$.

(1) above, (2) $\Phi_0^2 < -0.010$, (3) $0.105 < M_{\gamma\gamma} < 0.165$ GeV/c², (4) $\theta_{+-\gamma\gamma} < 2.45$ mrad, and (5) $0.48 < M_{e^+e^-\gamma\gamma} < 0.52$ GeV/c².

Figure 2(b) shows the effective mass distribution for $e^+e^-\gamma\gamma$ candidates satisfying all other cuts. No event lies within the K_L^0 mass interval.

To be accepted as a muon in $K_L^0 \rightarrow \mu^+\mu^-\gamma$ decay, a particle was required to be detected in the correct μ_H and μ_V and to deposit minimum-ionizing pulse height in the LG. In addition, geometrical χ^2 cuts similar to those of Ref. 13 were imposed. Muons above the absorber threshold of 1.45 GeV/c were accepted with $\sim 85\%$ probability. Studies of π^+ 's from kinematically unambiguous $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ decays show that only 3% of π^+ 's satisfy these conditions.

In addition to the K decay and μ purity cuts, $\mu^+\mu^-\gamma$ candidates had to satisfy (1) $1.5 < p_{\pm} < 7.5$ GeV/c, (2) $E_{\gamma}^{\text{lab}} > 1$ GeV, (3) $\Phi_0^2 < -0.014$, (4) $\theta_{+-\gamma\gamma} < 1.73$ mrad, and (5) $0.48 < M_{\mu^+\mu^-\gamma} < 0.52$ GeV/c².

The leading potential backgrounds to $K_L^0 \rightarrow \mu^+\mu^-\gamma$ are (1) $K_L^0 \rightarrow \pi^+\pi^-\pi^0$, (2) $K_L^0 \rightarrow \pi^+\mu^-\nu\gamma$, and (3) $K_L^0 \rightarrow \pi^+\mu^-\nu$ with spurious γ . Process (1) can contribute in the event that both charged pions are misidentified as muons and one γ evades both the LG and the γ_{anti} . However, Monte Carlo studies indicate that when $\mu\mu\gamma$ cuts 1-4 are imposed, this background peaks at $M_{\mu^+\mu^-\gamma} \sim 0.4$ GeV/c² [see Fig. 2(c)] and contributes < 0.01 events with $M_{\mu^+\mu^-\gamma} > 0.48$ GeV/c². In processes (2) and (3) only one pion need be mistaken for a muon for contamination of $K_L^0 \rightarrow \mu^+\mu^-\gamma$ to result. Monte Carlo samples of (2) and (3) have been generated¹⁹ and subjected to the $\mu^+\mu^-\gamma$ cuts. The calculated contribution to the $\mu^+\mu^-\gamma$ spectrum after all cuts save (5) have been imposed is indicated in Fig. 2(c) and in Table I. In the region $0.43 < M_{\mu^+\mu^-\gamma} < 0.48$ GeV/c², 6.7 events are expected and 4 are observed, suggesting that the calculation does not underestimate the contamination. As a further test we have varied the cuts and compared the predicted and observed numbers of events in this mass region. The result

TABLE I. Backgrounds to $K_L^0 \rightarrow \mu^+\mu^-\gamma$ in $0.43 < M_{\mu^+\mu^-\gamma} < 0.48$ GeV/c².

	$K\mu 3\gamma$	$K\mu 3$	Sum	Data
Normal cuts	6.4	0.3	6.7	4
$E_{\gamma} > 0.3$ GeV	10.4	1.2	11.6	13
$\Phi_0^2 < -0.008$	6.4	0.3	6.7	4
$\theta_{+-\gamma\gamma} < 2.45$ mrad	8.8	0.4	9.2	7

of three such tests are shown in Table I. In all cases the predicted and observed numbers agree within statistics.

Above $M_{\mu^+\mu^-\gamma} = 0.48$ GeV/c², where 0.1 background event is expected, one event is observed.

The $\mu^+\mu^-\pi^0$ candidates have to satisfy $\mu\mu\gamma$ cut (1) above, (2) $0.11 < M(\gamma\gamma) < 0.16$ GeV/c², (3) $\Phi_0^2 < -0.004$ (Ref. 18), $\theta_{+-\gamma\gamma} < 1.73$ mrad, and (5) $0.48 < M_{\mu^+\mu^-\gamma\gamma} < 0.52$ GeV/c². The only significant background to this decay mode is expected to be $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ decay in which both charged pions are mistaken for μ^+ 's. This was verified by plotting $M_{\pi^+\pi^-\gamma\gamma}$ for events passing all cuts except (3) and (5). Virtually all events clustered in a narrow peak centered at the K_L^0 mass. Requiring that Φ_0^2 be < -0.004 (Ref. 18) reduced the $\mu^+\mu^-\pi^0$ candidates by a factor ~ 50 . Figure 2(d) shows the effective-mass distribution for the remaining $\mu\mu\pi^0$ candidates. No event falls within $0.48 < M_{\mu^+\mu^-\gamma\gamma} < 0.52$ GeV/c². This null result is insensitive to reasonable variations in the cuts. The cut on $\theta_{+-\gamma\gamma}$, which is the most critical after that on the mass, may be relaxed by 50% without introducing background events into the K_L^0 mass interval.

Normalization for this experiment was provided by $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ decays. $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ events with one γ detected provide an ideal normalization for $l^+l^-\gamma$ and $\pi^+\pi^-\gamma$ since they are topologically nearly identical, allowing many potential systematic errors to cancel in their ratio.

Normalization events were required to satisfy the K -decay cuts and (1) $\Phi_0^2 > -0.006$, (2) (γ missing mass)² < 0.004 GeV²/c⁴, and (3) $3 < P_K < 20$ GeV/c. Applying these cuts to Monte Carlo $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ events as well and using $b(K_L^0 \rightarrow \pi^+\pi^-\pi^0) = 0.1239$,⁴ we calculate that a total of 1.09×10^{10} K_L^0 's ($P_K > 3$ GeV/c) decayed in our fiducial volume. This normalization is not sensitive to reasonable variations in the cuts. As a check on the normalization and other systematics we also analyzed special runs of $K_L^0 \rightarrow \pi^+\pi^-$ and of $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ with no γ 's required. The agreement of these rates, as well as that of the $K_L^0 \rightarrow \pi^+\pi^-\pi^0 - 2\gamma$ sample, with the expectation given by the $K_L^0 \rightarrow \pi^+\pi^-\pi^0 - 1\gamma$ normalization leads us to assign a normalization uncertainty of $\pm 7\%$ to our results.

With the above normalization, assuming a Kroll-Wada type (structureless) matrix element,³ the four $e^+e^-\gamma$ and one $\mu^+\mu^-\gamma$ (Ref. 20) events imply $b(K_L^0 \rightarrow e^+e^-\gamma) = (17.4 \pm 8.7) \times 10^{-6}$ and $b(K_L^0 \rightarrow \mu^+\mu^-\gamma) = (2.8 \pm 2.8) \times 10^{-7}$.²¹ These results agree within statistics with the expectations of 7.8×10^{-6} and 2.0×10^{-7} based on a Kroll-Wada-type calcu-

lation.³ Sehgal² has derived t dependences in various reasonable models and found changes in the predicted $b(K_L^0 \rightarrow l^+ l^- \gamma)$ of $\leq 30\%$ which are below our level of sensitivity. Our small samples also do not allow us to contradict the CP -nonconserving model of Ref. 1. However, our agreement with the structureless electromagnetic calculation rules out large contributions from intermediate states such as those discussed in Ref. 3.

In the absence of candidates for $K_L^0 \rightarrow l^+ l^- \pi^0$, we calculate²² 90%-confidence-level upper limits of $b(K_L^0 \rightarrow e^+ e^- \pi^0) < 2.3 \times 10^{-6}$ and $b(K_L^0 \rightarrow \mu^+ \mu^- \pi^0) < 1.2 \times 10^{-6}$, corresponding to the observation of 2.3 events. The $\mu^+ \mu^- \pi^0$ result represents an improvement of a factor of 50 upon the previous limit.²³ We know of no previous limit on the $e^+ e^- \pi^0$ branching ratio.

This work was supported in part by the U. S. Department of Energy under Contract No. EY-76-C-02-0016.

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¹⁴The beam differed from that of Ref. 13 only in that 8 r.l. of U rather than of Pb was used to convert photons.

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¹⁶A. S. Carroll *et al.*, following Letter [Phys. Rev. Lett. 44, 529 (1980)].

¹⁷A. S. Carroll *et al.*, to be published.

¹⁸ $\mathcal{G}_0^2 = \frac{1}{4} [(M_{K^0} - M_{\pi^0} - M_c)^2 - 4 M_{\pi^0}^2 M_c^2 - 4 M_{K^0}^2 p_c^2] / (p_c^2 + M_c^2)$, where M_{K^0} (M_{π^0}) is the K^0 (π^0) mass, M_c is the invariant mass of the two charged tracks if they are assumed to be pions, and p_c^2 is the transverse momentum of the charged tracks. The numerator equals $M_{K^0}^2 (p_{\pi^0}^{*2} - p_c^2)$, where $p_{\pi^0}^*$ is the c.m. π^0 momentum, so that \mathcal{G}_0^2 must be > 0 for a well-measured $K\pi 3$ decay.

¹⁹Since $K_L^0 \rightarrow \pi^\pm \mu \nu \gamma$ has not been observed, we use the theory of H. W. Fearing, *et al.*, Phys. Rev. D 2, 542 (1970), in our calculations. The characteristics of π^\pm -generated γ 's were readily determined from the large sample of $\pi\pi\gamma$ triggers in which the charged tracks fit $K_L^0 \rightarrow \pi^+ \pi^-$.

²⁰There is a 10% probability that this is a background event. In this case one would obtain $b(K_L^0 \rightarrow \mu^+ \mu^- \gamma) < 9 \times 10^{-7}$ (90%-confidence-level).

²¹Previous upper limits are $b(K_L^0 \rightarrow e^+ e^- \gamma) < 2.7 \times 10^{-5}$ of V. V. Barmin *et al.*, Yad. Fiz. 15, 1149 (1972) [Sov. J. Nucl. Phys. 15, 636 (1972)], and $b(K_L^0 \rightarrow \mu^+ \mu^- \gamma) < 7.8 \times 10^{-6}$ of G. Donaldson *et al.*, Phys. Rev. D 14, 2839 (1976).

²²We have assumed a phase-space kinematic distribution in calculating the acceptances here.

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