PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

New experimental upper limit for the decay $K^{\pm} \to \pi^{\pm}\gamma\gamma$ †

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(Received 3 November 1975; revised manuscript received 18 October 1976)

We have searched for the rare decay mode $K^{\pm} \to \pi^{\pm}\gamma\gamma$ using scintillation counters, optical spark chambers, and a wire-spark-chamber spectrometer. After background subtraction we obtain a branching ratio of $(-4.2 \pm 5.2) \times 10^{-5}$. The result is somewhat model-dependent. The quoted branching ratio, which comes from a fit to the phase-space model, is the highest value obtained from the various models considered.

In recent years a number of theoretical models have been constructed to calculate an expected rate for the decay $K^{\pm} \to \pi^{\pm}\gamma\gamma$. These models are of four general classes: pole models in which virtual π^0, η^0, and σ intermediate states decay to two γ's[1-5]; vector and axial-vector dominance models[2,6]; models using SU_3 which relate this decay to other radiative decays[7]; and the coupling of two pions to two γ's in $K^{\pm} \to \pi^+\pi^+\pi^-$ decays.[8] A model-independent unitarity bound for this decay has also been calculated.[9] The charged-pion c.m. kinetic energy ($T_{\text{c.m.}}$) distributions for two of these models are illustrated in Fig. 1, together with phase-space distribution as a comparison. The predicted branching ratios for $K^{\pm} \to \pi^{\pm}\gamma\gamma/(K^{\pm} \to \text{all})$ vary from ~10^{-8} to ~3×10^{-4}. Earlier experiments[10,11,12] have ruled out some of the larger predictions. In an experiment whose prime objective was a study of $K^{\pm} \to \pi^{\pm}\pi^0\gamma$,[13] we periodically collected additional events for calibration purposes for which the trigger required only two γ's. For the few hours of total running time, however, our sensitivity for $K^{\pm} \to \pi^{\pm}\gamma\gamma$ is greater than previous experiments.

The experimental layout is shown in Fig. 2. A partially separated beam at the Brookhaven National Laboratory Alternating Gradient Synchroton provided approximately 4×10^4 kaons per pulse at 1.8 GeV/c. In a core-readout wire-chamber spectrometer the incident kaon direction, the decay angle of the charged decay particle, and its momentum were determined. The conversion points of the γ's from the decay were recorded in a γ detector[14] which consisted of eight layers, each comprising lead, an optical spark chamber, and a 32-element scintillator hodoscope. An incident kaon, two or more γ's in the γ detector, and a charged particle at the end of the spectrometer were required by the trigger. Approximately 65% of the 1.6×10^5 photographs taken were K^+ decays and 35% were K^- decays.

For those events with a decay vertex (determined by the wire chambers) within the fiducial volume, the wire-chamber information was used to calculate the kinetic energy, $T_{\text{c.m.}}$, of the charged decay particle in the kaon rest frame (assuming it to be a pion). This distribution is shown in Fig. 3. (The peak at 108 MeV is due to $K^{\pm} \to \pi^{\pm}\pi^0$ decays.) The acceptance of the apparatus as calculated by the Monte Carlo method is also shown.[15]

The 31 000 events with $T_{\text{c.m.}} < 100$ MeV were scanned, and ~80% had two or more visible showers (defined as two or more sparks not necessarily consecutive) within the regions defined by the scintillators which triggered the event. The conversion point and length of each gamma shower was measured; the conversion point together with the decay vertex gave the γ direction. In addition, a random 10% sample of $K^{\pm} \to \pi^{\pm}\pi^0$ ($100 < T_{\text{c.m.}} < 117$ MeV) were scanned and measured for normalization purposes.

The principal backgrounds in this experiment were the decays $K^{\pm} \to \pi^{\pm}\pi^0$, $K^{\pm} \to \mu^{\pm}\pi^0\nu$, $K^{\pm} \to e^{\pm}\pi^0\nu$, and $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ where only two γ's were detected. Some events with more than two γ's were rejected by γ-sensitive anticoincidence counters around the decay region. From a study of the $K^{\pm} \to \pi^{\pm}\pi^0$ decays it was determined that excluding all events with $T_{\text{c.m.}} > 92$ MeV would reduce any $K^{\pm} \to \pi^{\pm}\pi^0$ con-

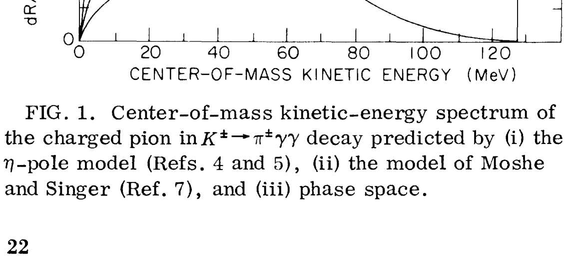

FIG. 1. Center-of-mass kinetic-energy spectrum of the charged pion in $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay predicted by (i) the η-pole model (Refs. 4 and 5), (ii) the model of Moshe and Singer (Ref. 7), and (iii) phase space.

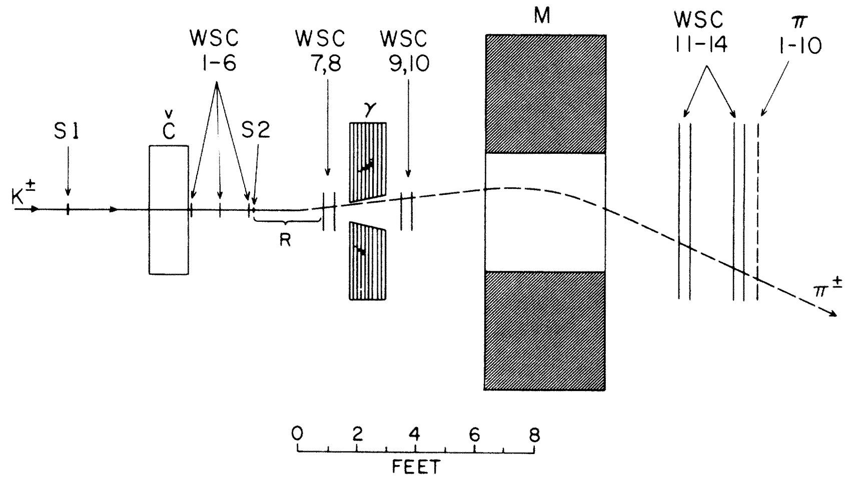

FIG. 2. Plan view of experimental layout, with a superimposed event. S_1, S_2, π_{1-10} are scintillation counters; WSC_{1-14} are wire spark chambers; $\check{C}$ is a differential Čerenkov counter to identify incident kaons; R is the kaon decay region; γ is the γ detector; M is a magnet (aperture 4 ft. wide by 4 ft. long by 3 ft. high, with a field of 5 kG).

tamination in our final answer to a negligible level. For the remaining events a two-constraint fit to the hypothesis $\pi^{\pm}\gamma\gamma$ was made, using only the directions of the γ's. As shown in Ref. 14 the length of a γ shower in our detector can be predicted from the γ energy to an accuracy of ~±40%. The γ-shower lengths predicted from the γ energies given by the two-constraint fit were then compared to the observed shower lengths. For each event, a χ^2 for four degrees of freedom is then obtained, two degrees from the 2C fit and two degrees from the shower lengths.

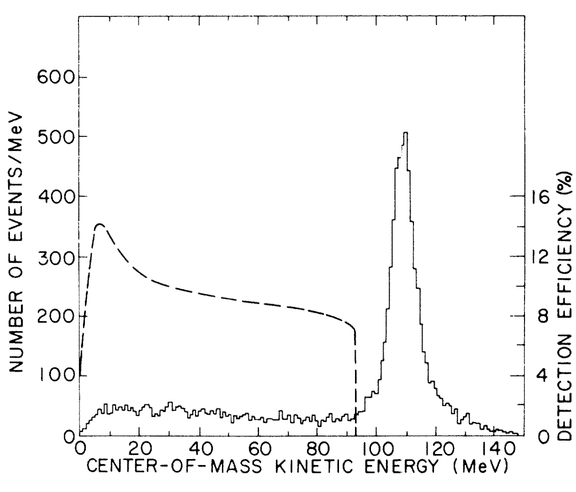

FIG. 3. Solid histrogram and left ordinate: center-of-mass kinetic energy spectrum of the charged secondary (assuming it to be a pion) obtained from the wire-chamber information for events where ≥2 γ's were required in the trigger. Dashed curve and right ordinate: detection efficiency as a function of center-of-mass kinetic energy of our experiment for $K^{\pm}\to\pi^{\pm}\gamma\gamma$ decay in the fiducial volume.

In Fig. 4(a) we show for our sample of $K^{\pm}\to\pi^{\pm}\pi^0$ decays this distribution in χ^2. There is reasonable agreement with the theoretical χ^2 distribution, indicating that the estimates for the measurement errors are correct; these were measured independently. The distribution in χ^2 for the events with

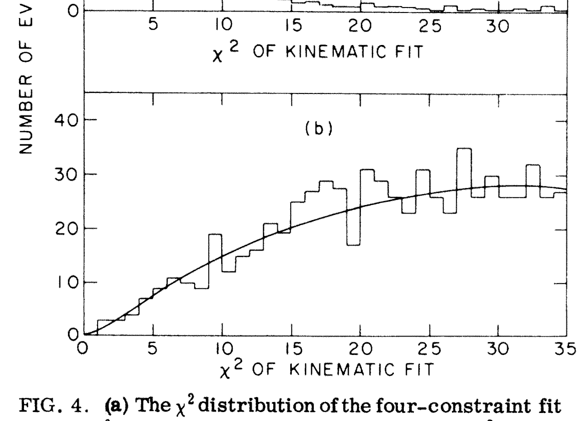

FIG. 4. (a) The χ^2 distribution of the four-constraint fit to $K^{\pm}\to\pi^{\pm}\pi^0$ events ($100 < T_{c.m.} < 117$ MeV). (b) χ^2 distribution for all the events with $T_{c.m.} < 92$ MeV. The solid curve is the sum of the fitted signal and background functions described in the text, over the range $0 < \chi^2 < 35$ and with $N = 2$.

TABLE I. Results of the fits to Fig. 4(b) described in the text.

Range of χ^2 used in fit	Value of N in background function $\sum_{n=1}^{N}\beta_n(\chi^2)^n$	Confidence level of fit	Number of signal events
$0\le\chi^2\le 10$	1	84%	-2.3 ± 6.1
$0\le\chi^2\le 15$	1	97%	-7.2 ± 5.4
$0\le\chi^2\le 20$	1	80%	-3.0 ± 5.2
$0\le\chi^2\le 25$	2	88%	-4.0 ± 6.0
$0\le\chi^2\le 30$	2	92%	-5.0 ± 5.7
$0\le\chi^2\le 35$	2	97%	-5.7 ± 5.5

$T_{\text{c.m.}} < 92$ MeV is given in Fig. 4(b). As can be seen from the figure, there is a background which falls approximately linearly as χ^2 approaches zero with no evidence for a signal of the expected form indicated by Fig. 4(a). A Monte Carlo calculation of the major backgrounds, $K_{\mu 3}$, K_{e3}, and τ', gave a χ^2 distribution qualitatively in agreement with that of Fig. 4(b).

A fit was made to the χ^2 distribution in Fig. 4(b) with a function of the form $\alpha s(\chi^2)+\sum_{n=1}^{N}\beta_n(\chi^2)^n$. $S(\chi^2)$ is a signal function of unit area given by the shape of the distribution in Fig. 4(a), and the coefficient α represents the number of signal events. The second term represents the background, and the fitting was done from $\chi^2=0$ to m, where m was varied in steps of 5 from 10 to 35. For each of the six values of m, N was increased until the goodness of fit ceased to improve. The six best fits are shown in Table I; they are all consistent, and each gives a negative number of signal events. The average of the six values gave a rate of $(-4.2 \pm 5.2)\times 10^{-5}$.

This experiment has been normalized to the number of reconstructed $K^\pm \to \pi^\pm\pi^0$ events (branching ratios = 0.21) so that γ scanning efficiencies are taken into account. In the experiment the equivalent of 25436 $K_{\pi 2}$'s were observed. A Monte Carlo calculation gave a 6.0% acceptance for $K_{\pi 2}$ decay averaged over our running conditions.

The upper limit to the branching ratio depends on the model for the $\pi^\pm\gamma\gamma$ decay used, since the predicted distributions (see Fig. 1 for examples) must be folded in with the acceptance function shown in Fig. 3.

Using our measured rate we derive the branching ratios indicated in Table II. The quoted results from three previous experiments are also given, and where appropriate we have combined the results to provide an improved upper limit.

All of the models listed in Table II, except for that of Moshe and Singer, are ruled out by this measurement when combined with the earlier re-

TABLE II. Results of searches for $K^\pm \to \pi^\pm\gamma\gamma$ compared to those models for this decay that predict branching ratios $\gtrsim 10^{-5}$; ξ and ϵ_2 are parameters in two of the models. Column 6 gives the detection efficiency of this experiment for $K^\pm \to \pi^\pm\gamma\gamma$ decay in the fiducial volume weighted by the predicted model distribution. Key: (a) Ref. 2; (b) Ref. 3; (c) Ref. 1; (d) Ref. 5 (note that the η pole model of Ref. 4 predicts a branching ratio of $\sim 2\times 10^{-6}$); (e) Ref. 6; (f) Ref. 7; (g) Ref. 10; (h) Ref. 11; (i) Ref. 12; (j) for consistency, all results are given for $T_{\text{c.m.}} < 102$ MeV; (k) for consistency, all results are given for $T_{\text{c.m.}} < 70$ MeV.

Model	Predicted $\frac{K^\pm\to\pi^\pm\gamma\gamma}{K^\pm\to\text{all}}$	Previous experiments: Chen *et al.* (g)	Previous experiments: Klems *et al.* (h) (90% (C.L.)	Previous experiments: Ljung & Cline (i) (90% C.L.)	This experiment: Detection efficiency	This experiment: Branching ratio	Combined results (90% C.L.)
π^0 pole	(a) 7×10^{-5} $\lvert\xi\rvert\approx 20$	$\lvert\xi\rvert<30$		$<2.2\times 10^{-5}$ $\lvert\xi\rvert<11$	9.6%	$-2.4\pm 2.9\times 10^{-5}$ $\lvert\xi\rvert<9$	$<0.9\times 10^{-5}$ $\lvert\xi\rvert<8$ (j)
	(b) 2×10^{-5} $\lvert\xi\rvert\approx 10$						
σ pole	(c) 4×10^{-3} for $m_\sigma=400$ MeV $\Gamma_\sigma=100$ MeV	$<3.3\times 10^{-4}$			10.4%	$-2.2\pm 2.7\times 10^{-5}$	
η pole	(d) 3×10^{-4}			$<2.1\times 10^{-5}$	10.3%	$-2.2\pm 2.7\times 10^{-5}$	$<0.8\times 10^{-5}$ (k)
Axial-vector meson dominance	(e) 1.5×10^{-5}–2.1×10^{-4}				5.2%	$-4.4\pm 5.4\times 10^{-5}$	
Moshe and Singer	(f) 0.6×10^{-5}–2×10^{-5} for $-10<\epsilon_2<-4.5$			$<2.9\times 10^{-5}$	7.0%	$-3.2\pm 4.0\times 10^{-5}$	$<1.1\times 10^{-5}$
Phase space		$<1.1\times 10^{-4}$	$<4.5\times 10^{-5}$	$<3.5\times 10^{-5}$	5.4%	$-4.2\pm 5.2\times 10^{-5}$	$<1.0\times 10^{-5}$

sults. If the model of Moshe and Singer is adjusted to the direct emission seen in our $K^{\pm} \to \pi^{+}\pi^{0}\gamma$ decay experiment,[13] then a branching ratio of 2.5 $\times 10^{-6}$ is expected for the $\pi^{\pm}\gamma\gamma$ decay.[16]

In future experiments on $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay, a goal should be to measure the branching ratio to at least $\sim 10^{-6}$, in order to test some of the other models[4,8,16,17] proposed for this decay.

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†Work performed under the auspices of the U. S. Atomic Energy Commission.

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