Study of the Decay $K_L^0 \to \pi^+\pi^-\gamma$

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Using a proportional-chamber spectrometer and an array of lead-glass photon detectors, we have observed 1070 $K_L^0 \to \pi^+\pi^-\gamma$ events. We have extracted the branching ratios of the inner-bremsstrahlung component $b(K_L^0 \to \pi^+\pi^-\gamma,\ k>20\ \text{MeV})_{\text{IB}} = (1.52 \pm 0.16) \times 10^{-5}$, which agrees within errors with the theoretical prediction, and of the direct-emission component, $b(K_L^0 \to \pi^+\pi^-\gamma)_{\text{DE}} = (2.89 \pm 0.28) \times 10^{-5}$. The γ-energy spectrum for direct emission shows possible evidence for a deviation from the pure $M1$ shape.

The decay $K_L^0 \to \pi^+\pi^-\gamma$ is of interest as a proving ground for theories of weak radiative decay[1-5] and as a possible locus for CP nonconservation.[6-8] Contributions to this decay are expected from (1) inner bremsstrahlung (IB) by a pion from the decay $K_L^0 \to \pi^+\pi^-$, and (2) the physically more interesting direct-emission (DE) process. Should CP be nonconserved in the direct process, the two contributions could interfere. The CP suppression of $K_L^0 \to \pi^+\pi^-$ prevents inner bremsstrahlung from dominating direct emission as occurs in $K_S^0 \to \pi^+\pi^-\gamma$ (Ref. 9) and nearly occurs in $K^\pm \to \pi^\pm\pi^0\gamma$.[10] Thus, potentially, the direct term may be studied in detail. Heretofore, however, the study of $K_L^0 \to \pi^+\pi^-\gamma$ has been impeded by its low branching ratio: Only 24 events have been observed previously.[11] We have performed an experiment in which 1070 events have been observed.

The experiment was carried out in a neutral beam at the Brookhaven National Laboratory alternating-gradient synchrotron. The beam and apparatus are discussed in the preceding Letter.[12] The electronic triggering requirements for $\pi^+\pi^-\gamma$ were $(\overline{D}) \cdot (\gamma_{\text{anti}}) \cdot$(two tracks in each spectrometer plane)$\cdot$($\geq$three UV and LG clusters) $\cdot\, \overline{(\mu_H \cdot \mu_V)} \cdot \overline{C}$.

In addition to the topological, timing, and fiducial requirements demanded of all K_L^0-decay candidates,[12] the $\pi^+\pi^-\gamma$ candidates also had to satisfy (1) 0.2 GeV $< E_\gamma^{\text{lab}} <$ 4.0 GeV, (2) $\mathcal{P}_0^2 < -0.002$,[13] (3) $3 < P_{\pi^+\pi^-\gamma} < 15$ GeV/c, (4) no C_i fired, (5) $R < 0.9$ for both charged tracks,[13] and (6) neither charged track satisfied the μ conditions. Events passing these cuts were subjected to kinematic fitting under the hypotheses of $K_L^0 \to \pi^+\pi^-$, $\pi^+\pi^-\pi^0$, and $\pi^+\pi^-\gamma$. To be accepted as $\pi^+\pi^-\gamma$, an event had to satisfy (7) probability of $\pi^+\pi^-$ mode <0.01, (8) probability of $\pi^+\pi^-\pi^0$ mode <0.01, and (9) probability of $\pi^+\pi^-\gamma$ mode >0.10. A total of 1217 events passed all cuts.[14]

Figure 1 shows the mass spectrum for the $\pi^+\pi^-\gamma$ candidates which pass all the cuts except (9), and for which $\theta_{+-\gamma} < 1.73$ mrad.[15] The $K_L^0 \to \pi^+\pi^-\gamma$ peak is clearly visible with standard deviation $\sigma \approx 6$ MeV/c^2.

The two significant background processes are (1) $K_L^0 \to \pi^+\pi^-\pi^0$ in which a charged π undergoes an undetected large-angle decay and in which one γ escapes both the lead-glass and the γ_{anti}, (2) $K_L^0 \to \pi^\pm\mu^\mp\nu\gamma$ in which the μ escapes detection in our μ counters. Process (1) tends to contaminate the DE region while (2) tends to populate the IB region.

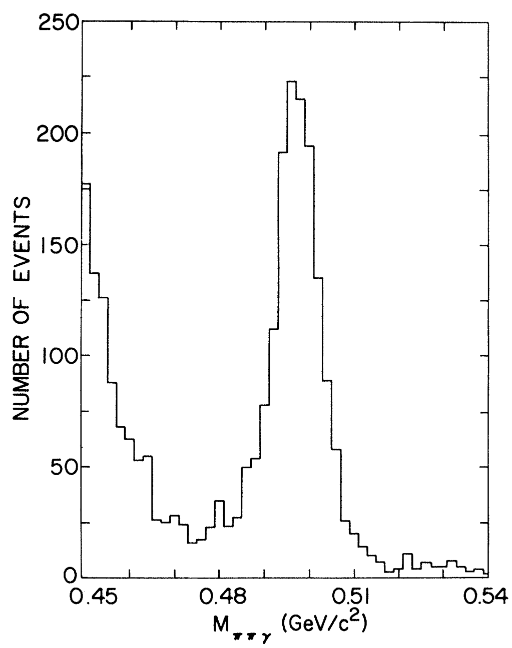

FIG. 1. $M_{\pi^+\pi^-}$ for events with $\theta_{+-\gamma} < 1.73$ mrad.

A Monte Carlo calculation indicates that 80 ± 30 $K_L^0 \to \pi^+\pi^-\pi^0$ decays can be accepted by the above $\pi^+\pi^-\gamma$ cuts. Since the decay $K_L^0 \to \pi^\pm \mu^\mp \nu\gamma$ has not been observed previously, its contribution was simulated according to the theoretical matrix element of Fearing *et al.*[16] Applying our measured μ-misidentification probability[17] we calculate a contamination of 92 ± 31 events. To develop more exact subtractions we determined the shape of the χ^2 distribution of background events from the Monte Carlo calculation and used the observed tails of the χ^2 distribution of the $\pi^+\pi^-\gamma$ candidates for normalization. This led to a total subtraction of 147 ± 43 events.

Figure 2(a) shows the spectrum of the center-of-mass γ energy, k, for $\pi^+\pi^-\gamma$ candidates. Also shown is the calculated background as discussed above. The simplest expectation for the k spectrum is an incoherent sum of IB with its characteristic $1/k$ falloff, and an $M1$ direct contribution which starts rising as k^3 until cut off by phase space. The precise shapes, corrected for detection efficiency, are indicated on the figure. Evidently, a roughly equal mixture of these components provides a good qualitative explanation for the observed spectrum. Fitting the spectrum by a sum of IB and $M1$ shapes yields 515.7 ± 31.4 IB and 546.0 ± 32.3 DE events ($\chi^2 = 16.8$ for 12 degrees of freedom). Normalizing via the $K_L^0 \to \pi^+\pi^-\pi^0$ sample as discussed in Ref. 12, we obtain $[b(K_L^0 \to \pi^+\pi^-\gamma,\ k > 20\text{ MeV})]_{\text{IB}} = (1.61 \pm 0.10) \times 10^{-5}$ and $[b(K_L^0 \to \pi^+\pi^-\gamma)]_{M1} = (2.88 \pm 0.17) \times 10^{-5}$. The theoretical expectation for the IB branching ratio is 1.45×10^{-5}.[4] This is in satisfactory agreement, particularly when our 7% normalization error is included.[12] However, we note indications that the spectrum in the direct-emission region is systematically shifted toward lower k relative to the $M1$ expectation. To get a quantitative measure of the effect we fit only the region $k = 20-60$ MeV where the effect of DE is small[18] and extract an IB branching ratio $= (1.43 \pm 0.13) \times 10^{-5}$. We subtract an IB contribution of this magnitude from the data and divide the result by the $M1$ expectation to obtain the points shown in Fig. 2(b). The variation in this ratio suggests the presence of a form factor in the direct-emission amplitude. Also shown in the figure is the k dependence of the square of the ρ propagator, which qualitatively matches the data. This type of energy dependence is not surprising since the $M1$ transition leaves the π^+ and π^- in a relative p wave; in fact, just such an effect is observed in the decay $\eta \to \pi^+\pi^-\gamma$.[19] The integral of the subtracted spectrum yields a DE branching ratio of $(3.11 \pm 0.28) \times 10^{-5}$. If we fit the spectrum with a sum of IB and an $M1$ matrix element modified by a form factor proportional to the ρ propagator, we find $(1.52 \pm 0.10) \times 10^{-5}$ and $(2.89 \pm 0.17) \times 10^{-5}$ for the IB and DE branching ratios, respectively. The $\chi^2 = 10.5$ for 12 degrees of freedom, an improvement of 6.3 (in χ^2) over that of the original

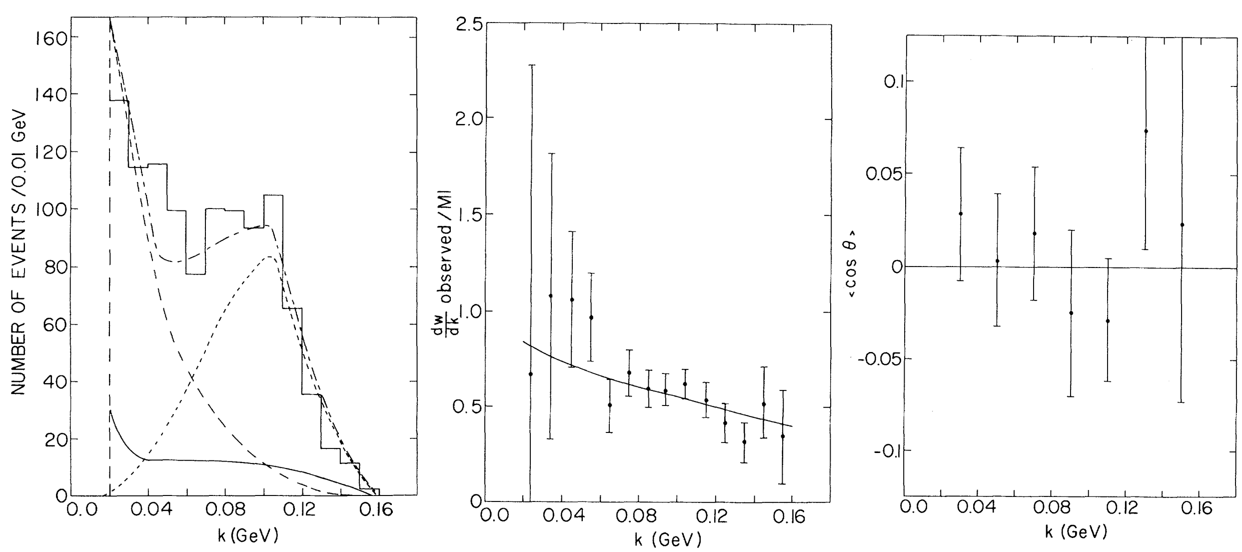

FIG. 2. (a) Histogram is k spectrum for 1070 $\pi^+\pi^-\gamma$ candidates. Dashed line is the fitted IB contribution, dotted line is the fitted $M1$ DE contribution, and the dash-dotted line is their sum. Solid line is the estimated background (already subtracted from the data). (b) $(dW^{\text{obs}}/dk)(dW^{M1}/dk)^{-1}$ for data with IB contribution subtracted. The solid line shows the shape of the square of the ρ propagator. (c) $\langle\cos\theta\rangle$ vs k.

fit. We note that the branching ratios agree to $\sim 1\sigma$ for the three methods of analysis. The results are not significantly altered by reasonable variations in the cuts or background subtractions. Varying these led us to assign additional systematic errors of $\sim 3\%$ to those discussed in Ref. 12. Including all systematic errors, our final result is $[b(K_L{}^0 \to \pi^+\pi^-\gamma,\ k > 20\text{ MeV})]_{\text{IB}} = (1.52 \pm 0.16)\times 10^{-5}$ and $[b(K_L{}^0 \to \pi^+\pi^-\gamma)]_{\text{DE}} = (2.89 \pm 0.28)\times 10^{-5}$. This corresponds to $[\Gamma(K_L{}^0 \to \pi^+\pi^-\gamma)]_{\text{DE}} = (558 \pm 54)/\text{sec}$, which is about a factor of 4 less than the corresponding charged-K rate.[20]

We next address the possibility of contributions from higher multipoles and from CP nonconservation in the DE amplitude. The presence of higher multipoles allows explicit CP nonconservation in the form of a charge asymmetry in the Dalitz plot. However, this asymmetry is not expected to exceed a few percent.[7] To check for such an effect, in Fig. 2(c) we plot the average value of $\cos\theta$ vs k (θ is the angle between the γ and the π^+ in the π-π rest system). $\cos\theta$ is proportional to the asymmetry in the π kinetic energies in the overall c.m. system. We find no evidence for a significant asymmetry. In the presence of CP-conserving quadrupole terms, the θ distribution of the direct decay would be $\sin\theta(1+\alpha\cos^2\theta)$, where α is proportional to the square of the quadrupole amplitude. Fitting the θ distribution of events in the DE region ($k > 80$ MeV) to this form, we find $\alpha = 0.00 \pm 0.15$, indicating no need for quadrupole terms.

If we consider only dipole terms, nonconservation in the direct amplitude would manifest itself via interference with IB. In this case we have[7,8]

$$\frac{d^2W}{dk\,d\cos\theta} = \frac{\alpha}{\pi}\,\Gamma(K_S \to \pi^+\pi^-)\frac{k^3\beta^3}{8\beta_0}\sin^2\theta\left\{\frac{16}{k^4}\frac{|\eta_{+-}|^2}{(1-\beta^2\cos^2\theta)^2} - \frac{8}{k^2}\frac{|\eta_{+-}|\sin(\varphi_{+-}-\delta_0-\delta_1{}^1)}{1-\beta^2\cos^2\theta}X_E + (X_E{}^2 + X_M{}^2)\right\},$$

where $\Gamma(K_S \to \pi^+\pi^-)$ is the $K_S \to \pi^+\pi^-$ decay rate, β is the $\pi^\pm$ velocity in the $\pi^+\pi^-$ rest frame, β_0 is $\beta(k=0)$, $|\eta_{+-}|$ and φ_{+-} are the magnitude and phase of $A(K_L{}^0 \to \pi^+\pi^-)/A(K_S{}^0 \to \pi^+\pi^-)$, X_M is the product between the strength and form factor of the CP-conserving $M1$ direct emission process, X_E is the product between the strength and form factor of the CP-nonconserving $E1$ direct emission process, and δ_0 and $\delta_1{}^1$ are the s- and p-wave $\pi\pi$ phase shifts.[21]

If we fit the spectrum to this form, holding X_E and X_M constant, we obtain the dashed χ^2 contours of Fig. 3 in which the best fit ($\chi^2 = 10.56$ for 12 degrees of freedom) is for a $\sim 13\%$ admixture of CP-nonconserving direct decay, lying $< 2\sigma$ from the no-interference fit. However, if we fit the spectrum using form factors varying like the ρ propagator, we find an equally good fit with no interference required (solid contours of Fig. 3). In principle a sufficiently precise experiment could distinguish between these hypotheses but at the present level of statistics it is not possible to do so. However, since a measurable CP nonconservation in the direct amplitude is now considered extremely unlikely,[22] we interpret our results as possible evidence for the presence of a form factor in this decay.

In summary, we have observed for the first time both the inner bremsstrahlung and direct-emission components of $K_L{}^0 \to \pi^+\pi^-\gamma$. The inner-bremsstrahlung rate agrees with theoretical expectation. The direct branching ratio $(2.89 \pm 0.28)\times 10^{-5}$ is about a factor of 2 smaller than that of the previous low-statistics experiment[23] and lies at the lower end of the range of theoretical calculations.[1-5] However, it is ~ 40 times higher

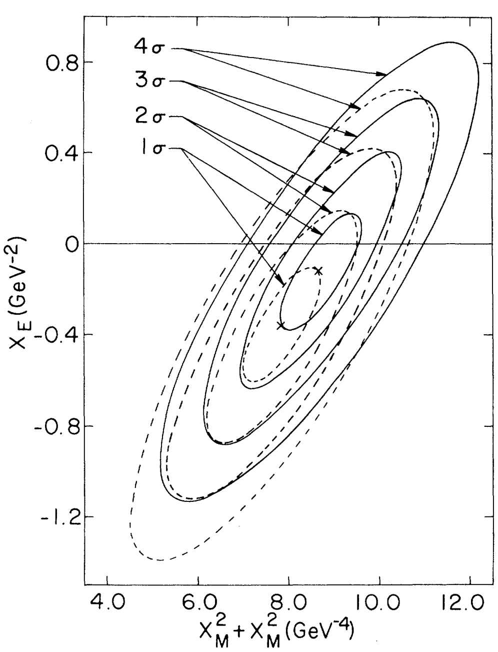

FIG. 3. χ^2 contours for fits including interference. X_E is a measure of the strength of the CP-nonconserving $E1$ direct amplitude. $X_E{}^2 + X_M{}^2$ is proportional to the decay rate for direct emission. Solid (dashed) lines are contours given by a fit with (without) ρ propagator in the direct amplitude. X_E and X_M are evaluated at $k = 0.1$ GeV.

than the gauge-theory "short-distance" contribution calculated by Malakian.[5] At the 2.5σ level, a form-factor dependence on k is observed, although the possibility that this effect is due to $\sim 13\%$ CP nonconservation in the direct amplitude cannot be ruled out.

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[13]For a definition of this quantity, see Ref. 12.

[14]These cuts retain 70% of $\pi\pi\gamma$ events passing the electronic triggering requirements.

[15]$\theta_{+-\gamma}$ is the angle between the incident K_L^0 and the sum of the final-state momenta.

[16]H. W. Fearing *et al.*, Phys. Rev. D 2, 542 (1970).

[17]The probability of identifying a μ as a π was calculated via our sample of kinematically identified $K_L^0 \to \pi^\pm \mu^\mp \nu$ decays.

[18]An $M1$ shape was assumed for the DE component. In fitting over this range of k the extracted IB branching ratio is very insensitive to the precise DE shape used as input.

[19]J. G. Layter *et al.*, Phys. Rev. D 7, 2565 (1973), and references therein.

[20]The rate of Ref. 10 corrected for their Dalitz-plot acceptance is $\Gamma(K^\pm \to \pi^\pm\pi^0\gamma)_{\rm DE} = 2480/{\rm sec}$.

[21]We have used the $\delta_0 - \delta_1^1$ as measured by L. Rosselet *et al.*, Phys. Rev. D 15, 574 (1977).

[22]See, e.g., W. C. Carithers, Jr., in *Particles and Fields–1974*, edited by C. E. Carlson, AIP Conference Proceedings No. 23 (American Institute of Physics, New York, 1975), p. 75.

[23]Our result is $<2\sigma$ lower than that of Ref. 11. However, since no correction was made in Ref. 11 for the IB component presumably present in their data, the results are not strictly comparable.