Search for $K_L \to \pi^0\gamma\gamma$

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A search for the rare decay mode $K_L \to \pi^0\gamma\gamma$ was performed using a data set from Fermilab experiment E-731. The decay is of interest in the context of chiral perturbation theory and for its contribution to the decay $K_L \to \pi^0 e^+e^-$. The result is $B(K_L \to \pi^0\gamma\gamma) < 2.7\times10^{-6}$ (90% confidence level) which is nearly a two-order-of-magnitude improvement over the previous best limit.

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The as yet unobserved decay $K_L \to \pi^0\gamma\gamma$ is of current interest for at least three reasons. First, it provides an opportunity to test the standard model in the context of chiral symmetry: At the one-loop level in chiral perturbation theory,[1] the decay has a branching ratio of 6.8×10^{-7} with a characteristic $\gamma\gamma$ invariant-mass ($m_{\gamma\gamma}$) distribution having a peak at about 325 MeV.[2] Second, this decay provides a *CP*-conserving intermediate state for the $K_L \to \pi^0 e^+e^-$ decay which has been the subject of recent experimental[3-5] and theoretical[6] attention as a possible avenue for the observation of direct *CP* nonconservation; its magnitude will greatly affect the interpretation of the results of such experimental efforts. Third, this mode could be a background to the $K_L \to 2\pi^0$ decay for precision experiments[7,8] measuring ϵ'/ϵ, especially if its branching ratio were at the level of the current limit,[9,10] 2.4×10^{-4}.

The principal background for this mode is the $K_L \to 3\pi^0$ decay occurring 3×10^5 times more frequently than the signal. The challenge in observing such a signal at the predicted level is the effective rejection of the $3\pi^0$ decays; in addition, the understanding of the residual background after the necessarily stringent analysis cuts allows better sensitivity.[11]

This experiment, E-731 at Fermilab, collected data with the primary goal of determining ϵ'/ϵ. The search reported here is based upon an analysis of a subset of the data that was particularly suited for this analysis. Some characteristics of the detector have been described previously;[3,7] here, we summarize the essential features relevant to the decay mode in question. Energies and positions of photons were measured with an 804-block lead-glass array having transverse block dimensions of 5.82×5.82 cm^2. The energy resolution for photons was given approximately by $\sigma_E/E = (2.5+5.0/\sqrt{E})\%$ (E in GeV) and the corresponding π^0 mass resolution was about 3 MeV. Events with the desired number of electromagnetic showers were selected on line by a trigger processor[12] which counted clusters in the lead-glass array. Eleven planes of photon-veto counters situated between 75 m upstream and 2 m downstream of the lead glass were employed to reject the background arising from $K_L \to 3\pi^0$ decays where one or two photons miss the lead-glass calorimeter. A drift-chamber system was used to reject K_L decays with charged particles in the final state.

Candidates for the $K_L \to \pi^0\gamma\gamma$ decay were required to have exactly four clusters in the lead-glass array and total energy between 40 and 150 GeV. The decay vertex was determined with the measured cluster energies and positions by assuming that the invariant mass of the four photons was that of the neutral kaon. To determine the pairing of the photons, the pair with invariant mass closest to that of the neutral pion (m_{π^0}) was chosen as the candidate π^0; this pair is labeled (12) and it was required that $|m_{12} - m_{\pi^0}| < 5$ MeV. Up to this point the cuts were also satisfied by $2\pi^0$ decays which would usually have both pair masses, m_{12} and m_{34}, consistent with m_{π^0}. The rejection of the $2\pi^0$ decays was done in two steps. First, it was required that $|m_{34}-m_{\pi^0}|>12$ MeV; this resulted in a suppression of a factor of about 25. Second, some $2\pi^0$ events with their photons paired as (13)(24) or (14)(23) would still remain; if either of these alternative pairings was consistent with the $2\pi^0$ hypothesis,[7] the event was also discarded. This latter requirement provided an additional rejection factor of about 40.

$K_L \rightarrow 3\pi^0$ decays can become background four-cluster events either when photons are undetected or when they overlap in the lead glass so that they are unresolvable as separate clusters. The veto counters were effective in detecting photons escaping from the fiducial volume of the detector and events with substantial energy deposit in these counters were rejected from the sample. In addition, the transverse center of energy of the four photons was required to be in the K_L beam region (11.2×11.2 cm^2).[13] The number of events with unresolved overlapping clusters was substantially reduced by rejecting those with cluster shapes inconsistent with that of a single photon. The $3\pi^0$ background was further reduced by considering only decays in the upstream 14-m region of the decay volume ending 57 m upstream of the glass array: The reconstructed decay vertex in events with missing photons is artificially shifted downstream; also, photons are more likely to overlap when the decay occurs near the lead-glass array. The selection of this region of the decay region was made on the basis of a Monte Carlo study to optimize the experimental sensitivity in the presence of this background. These criteria provide a rejection factor for $3\pi^0$ decays relative to $\pi^0\gamma\gamma$ decays of about 10^4.

Figure 1(a) shows the $\gamma\gamma$ effective mass for the "non π^0" photon pair. A characteristic feature in this distribution is a prominent "double fusion" peak appearing at about $m_{\gamma\gamma}=270$ MeV which arises when two π^0's in $K_L \rightarrow 3\pi^0$ decays are superimposed: Each photon from one π^0 overlaps with a photon from the other π^0 with an invariant-mass threshold of twice the π^0 mass. The solid curve indicates the $K_L \rightarrow \pi^0\gamma\gamma$ signal shape predicted by chiral perturbation theory;[1] $(60.0\pm 1.2)\%$ of the $\pi^0\gamma\gamma$ events have $m_{\gamma\gamma}$ greater than 300 MeV and we have chosen this region for our search to have good discrim-

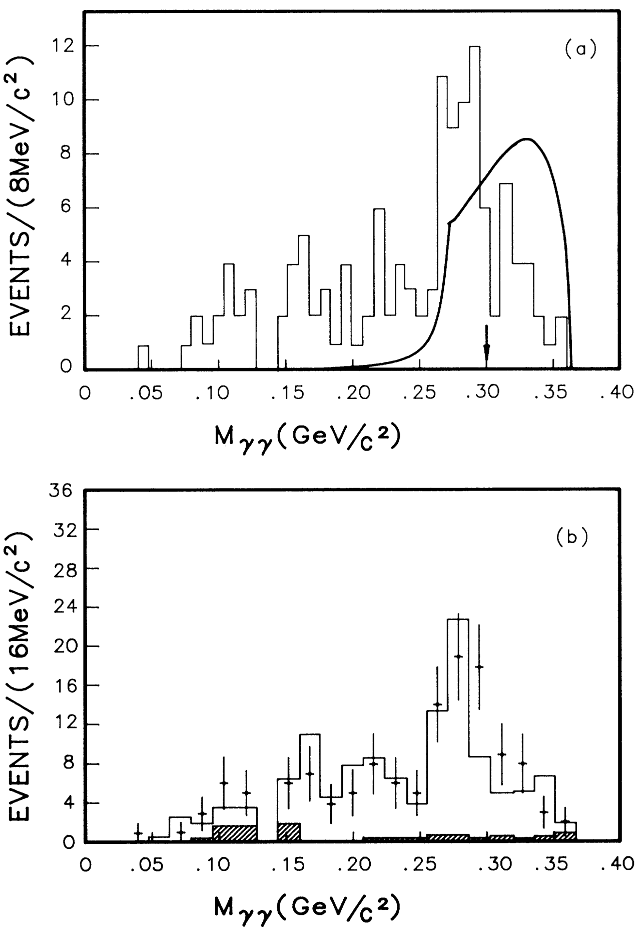

FIG. 1. (a) $\gamma\gamma$ invariant mass for $K_L \rightarrow \pi^0\gamma\gamma$ decay events. The histograms are the candidate events and the solid curve represents the distribution predicted by chiral perturbation theory for a branching ratio of 10^{-5}. The arrow indicates the position of the cut (300 MeV). (b) $\gamma\gamma$ invariant mass for data and background Monte Carlo simulation. The dots correspond to the data [the same as in (a) with coarser binning]; the shaded histogram corresponds to the $K_L \rightarrow 2\pi^0$ contribution to the background; the unshaded histogram corresponds to the sum of the backgrounds from $K_L \rightarrow 2\pi^0$ and from $K_L \rightarrow 3\pi^0$ decays. The background Monte Carlo simulation (twice the statistics as the data) is absolutely normalized.

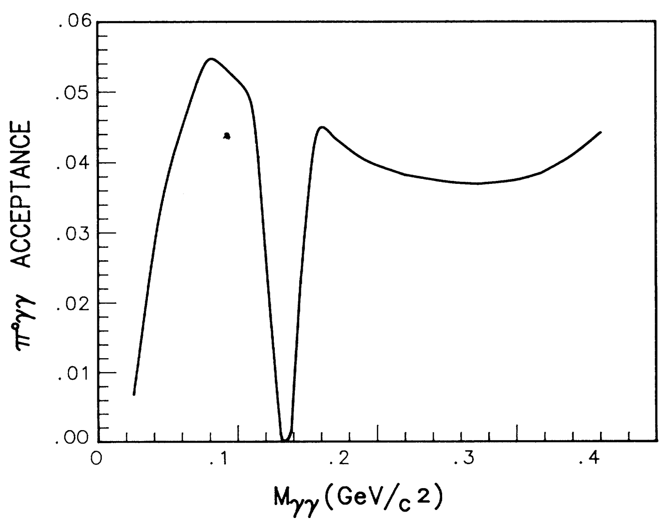

FIG. 2. Acceptance vs the $\gamma\gamma$ invariant mass for $K_L \rightarrow \pi^0\gamma\gamma$ decays. The dip around 135 MeV is due to the cut that excludes $\gamma\gamma$ masses near the π^0 mass.

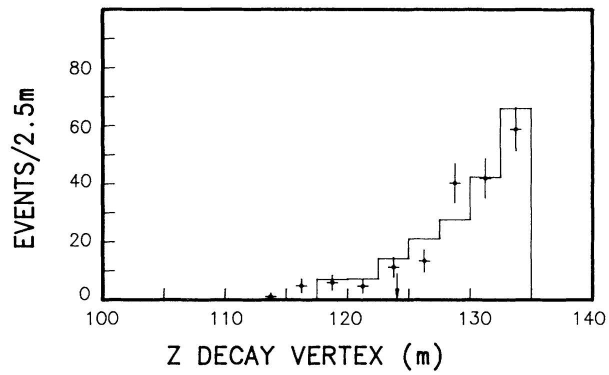

FIG. 3. The decay-vertex distribution, in meters from the K_L production target, for $K_L \to \pi^0\gamma\gamma$ candidates and background Monte Carlo events with $m_{\gamma\gamma} > 300$ MeV. The dots correspond to the data, while the histogram corresponds to the sum of the backgrounds from $K_L \to 2\pi^0$ and from $K_L \to 3\pi^0$ decays. The background Monte Carlo simulation is absolutely normalized. The arrow indicates the position of the cut (124 m).

ination against background. The acceptance is relatively flat for $m_{\gamma\gamma}$ above 160 MeV, as shown in Fig. 2. Figure 1(b) shows the Monte Carlo predictions of the backgrounds to $\pi^0\gamma\gamma$ decay coming from the $3\pi^0$ and $2\pi^0$ modes. The Monte Carlo distributions are normalized by means of a sample of fully reconstructed $K_L \to 2\pi^0$ decays observed simultaneously. The contribution from accidental clusters is found to be negligible. Figure 3 shows agreement in the reconstructed vertex distributions for the signal and expected background events with $m_{\gamma\gamma} > 300$ MeV, including the region downstream of the fiducial cut.

For the high-mass sample ($m_{\gamma\gamma} > 300$ MeV), we have 24 candidate events with a predicted background of 20.8 events (18.2 from $3\pi^0$'s and 2.6 from $2\pi^0$'s). From studies of the $3\pi^0$ background in this mode and in the $K_L \to 2\pi^0$ mode, we assign a 20% error to the estimate of the background in the high-mass region which is a combination of the statistical error in the Monte Carlo simulation (15%) and our estimate of the systematic error (12%). The systematic uncertainty comes largely from lack of precise knowledge of the efficiencies of the photon-veto planes. The 90%-confidence-allowed signal is 13.9 events, calculated with the maximum-likelihood method. The $\pi^0\gamma\gamma$ acceptance is 2.4% and the normalization is provided by 11.1×10^3 $K_L \to 2\pi^0$ decays observed simultaneously and selected with similar criteria as the $\pi^0\gamma\gamma$ candidates where appropriate, including photon-veto, cluster-shape, decay-region, and total-energy cuts. The corresponding acceptance for $K_L \to 2\pi^0$ is 5.8%. Using world average values[10] for the $K_L \to 2\pi^0$ and for $K_L \to 3\pi^0$ branching ratios we conclude that $B(K_L \to \pi^0\gamma\gamma) < 2.7\times10^{-6}$ (90% confidence level). We have assumed that the $m_{\gamma\gamma}$ spectrum follows that predicted in chiral perturbation theory; if instead a uniform phase space for the decay is assumed, the limit becomes 4.4×10^{-6} (90% confidence level) where the whole mass range except the region of the double fusion peak (264–292 MeV) is used.

Our result is nearly a factor of 90 improvement over the current experimental limit[9,10] which was also calculated using a distribution in $m_{\gamma\gamma}$ similarly peaked at high values. It is consistent with the predictions of chiral perturbation theory although another factor of about 4 in sensitivity would be required to confirm the prediction. The CP-conserving contribution to $K_L \to \pi^0 e^+ e^-$ has now been better constrained and we have shown that this decay should not be a serious background to the $K_L \to 2\pi^0$ mode.

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