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Measurement of the branching ratio of the decay $K_L \to \pi^0\gamma\gamma$

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Using the complete Fermilab E731 data set, we find $\Gamma(K_L \to \pi^0\gamma\gamma,\ m_{\gamma\gamma} \geq 0.280\ \text{GeV})/\Gamma(K_L \to \text{all}) = (1.86 \pm 0.60 \pm 0.60) \times 10^{-6}$, in good agreement with a recent report of the first observation of this decay. For the low $\gamma\gamma$ mass region we find $\Gamma(K_L \to \pi^0\gamma\gamma,\ m_{\gamma\gamma} < 0.264\ \text{GeV})/\Gamma(K_L \to \text{all}) < 5.1 \times 10^{-6}$ (90% confidence).

The decay $K_L \to \pi^0\gamma\gamma$ is of current interest [1–6] within the context of both chiral perturbation theory and the vector-meson-dominance model, and also for its contribution to the decay $K_L \to \pi^0 e^+ e^-$ as a *CP*-conserving intermediate state. Predictions for its branching ratio vary from 6.3×10^{-7} to 6.2×10^{-6}, and predicted $\gamma\gamma$ mass distributions differ markedly. At the one-loop level in chiral perturbation theory [1], the branching ratio is estimated to be 6.8×10^{-7} with a characteristic $\gamma\gamma$ invariant-mass distribution ($m_{\gamma\gamma}$) peaking at about 0.325 GeV.

Earlier we reported [7] an upper limit for the branching ratio of this decay of 2.7×10^{-6} (90% confidence) assuming the $\gamma\gamma$ invariant-mass distribution expected by chiral perturbation theory. That result was based on a subset of our data; here we report results from the entire data sample which therefore supersede the earlier results. In the meantime, CERN experiment NA31 has recently reported [8] an observation of the decay: They have found a signal primarily at high $\gamma\gamma$ invariant mass and a branching ratio significantly greater than that predicted by chiral perturbation theory. They find

$$\frac{\Gamma(K_L \to \pi^0\gamma\gamma,\ m_{\gamma\gamma} \geq 0.280\ \text{GeV})}{\Gamma(K_L \to \text{all})} = (2.1 \pm 0.6) \times 10^{-6}\,.$$

The primary goal of experiment E731 is the determination of the *CP*-violation parameter ϵ'/ϵ [9]. The characteristics of the detector and the event reconstruction have been described in detail elsewhere [7,10]; here we summarize the essential features of the analysis and its differences from that used in our previous publication. Energies and positions of photons were measured with an 804-block lead-glass calorimeter. Candidates for the $K_L \rightarrow \pi^0\gamma\gamma$ decay were required to have exactly four electromagnetic showers (clusters) in the lead glass, each with an energy of at least 1 GeV, and total energy between 40 and 150 GeV. The decay vertex was determined from the measured cluster energies and positions by assuming that the invariant mass of the four photons was that of the neutral kaon. The two photons, labeled (12), with invariant mass closest to the nominal neutral-pion mass (m_{π^0}) were taken to be the decay products of the candidate π^0. The π^0 mass resolution was about 3 MeV and it was required that $|m_{12}-m_{\pi^0}| \leq 5$ MeV.

Background rejection is critical since the signal is poorly constrained. The rejection of the $K_L \rightarrow 2\pi^0$ background was done in two steps. First, it was required that the mass of the non-π^0 pair ($m_{\gamma\gamma}$ or m_{34}) differ from m_{π^0} by at least 14 MeV. Second, the candidate event was reconstructed as a $K_L \rightarrow 2\pi^0$ decay by constraining the invariant masses of each pair of photons to the nominal π^0 mass, and if it satisfied the criteria described in Refs. [7] and [10], it was rejected as a mispaired $2\pi^0$ decay. $K_L \rightarrow 3\pi^0$ decays, which are the dominant remaining background, can masquerade as four-cluster events either when photons escape the detector or when multiple photons fuse in the lead glass to form a single cluster. This background was considerably reduced (1) by using the many photon veto counters for the detection of escaping photons, (2) by requiring that the transverse center of energy of the four photons be in the K_L beam region, and (3) by considering only decays in the upstream part of the decay region, starting at 110 m and ending at 128 m from the target. The selection of the downstream edge of this decay region was made on the basis of a Monte Carlo study to maximize the sensitivity to a signal in the presence of known amounts of $3\pi^0$ and $2\pi^0$ backgrounds; the data themselves were not used. In fact, the sensitivity is relatively independent on the position of the downstream edge. The background with overlapping clusters was substantially reduced by rejecting events with cluster shapes inconsistent with that of a single photon. Additional suppression of the $3\pi^0$ background came from kinematically rejecting events with two superimposed π^0 (double fusion events) where each photon from one π^0 overlaps with a photon from the other π^0 so that $m_{\gamma\gamma} > 2m_{\pi^0}$. For this background, these fused clusters are the $\gamma\gamma$ pair about 70% of the time according to the Monte Carlo simulations; in addition, the energies of the photons which fuse tend to be high. By analyzing each candidate event as though these clusters are so fused, the individual photon energies could be kinematically determined. A cut on a combination of these energies reduced the background by about 28% while reducing the expected signal by about 6.5% (see Ref. [10]). The drift-chamber spectrometer and four scintillation hodoscopes were used to reject K_L decays with charged particles in the final state (e.g., $K_L \rightarrow \pi^+\pi^-\pi^0$) or events with photon conversions. The contribution from accidental clusters in our data sample is found to be negligible. Finally, we rejected events with photons projecting outside the holes of the lead-mask photon veto which is located at about 122 m from the target and is one of our defining apertures.

Figure 1 shows the comparison of data and background Monte Carlo simulation for the $\gamma\gamma$ effective mass. A characteristic feature in this distribution is the prominent double fusion peak appearing at about $m_{\gamma\gamma}=0.270$ GeV. The background coming from the $3\pi^0$ and $2\pi^0$ modes is absolutely normalized to the data by means of a sample of fully reconstructed $K_L \rightarrow 2\pi^0$ decays observed simultaneously and selected with criteria similar to those used for the $\pi^0\gamma\gamma$ candidates. Although for low $\gamma\gamma$ mass the data–Monte Carlo agreement is good within statistics, at high masses there is a significant excess of data. The background in the high-mass region consists predominantly of events where both γ's are fused clusters. The Monte Carlo simulation correctly reproduces the prominent double fusion peak, which is important in establishing that the excess at higher values is indeed a signal. Figure 2 shows the comparison of data and background Monte Carlo simulation for the reconstructed z decay vertex distributions with $m_{\gamma\gamma} \gtrsim 0.280$ GeV, including the region downstream of the fiducial cut. The data excess is uniformly distributed over the decay region as is expected for a signal.

In Fig. 3 we show the data–Monte Carlo comparison for the m_{12} distribution for $m_{\gamma\gamma} \gtrsim 0.280$ GeV. The excess

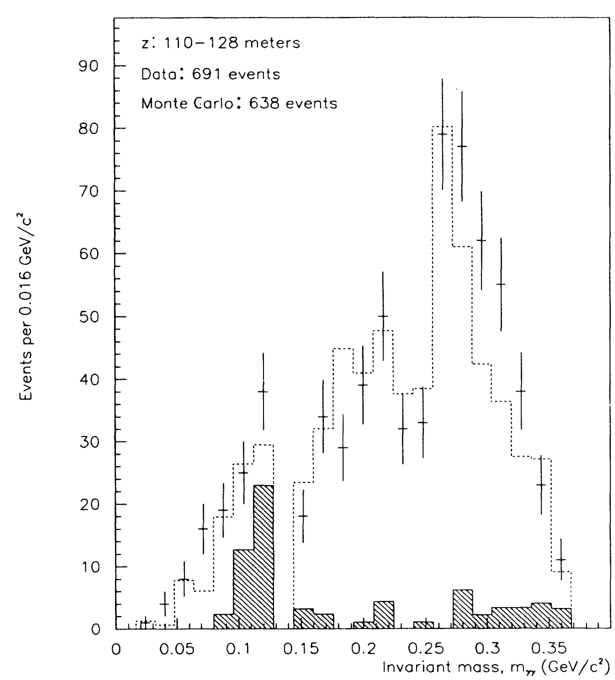

FIG. 1. Data–Monte Carlo comparison of the $\gamma\gamma$ mass distribution for $\pi^0\gamma\gamma$ candidates and background events based on the full data set. The normalization is absolute. The error bars correspond to the data, the shaded histogram to the $2\pi^0$ background Monte Carlo simulation, and the dashed histogram to the sum of the $3\pi^0$ and $2\pi^0$ background Monte Carlo simulations.

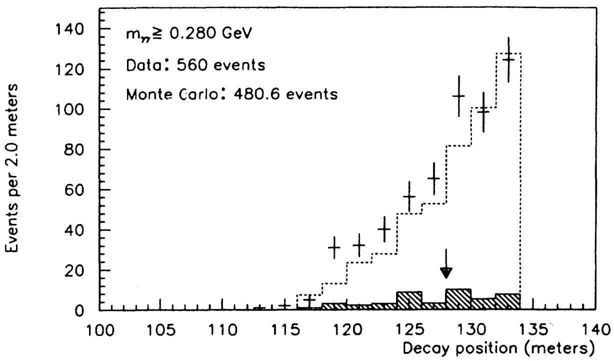

FIG. 2. Data–Monte Carlo comparison for the z decay vertex distribution for $\pi^0\gamma\gamma$ candidates and background events with $m_{\gamma\gamma} \geq 0.280$ GeV. The normalization is absolute. The error bars correspond to the data, the shaded histogram to the $2\pi^0$ background Monte Carlo simulation, and the dashed histogram to the sum of the $3\pi^0$ and $2\pi^0$ background Monte Carlo simulations. The arrow indicates the position of the cut.

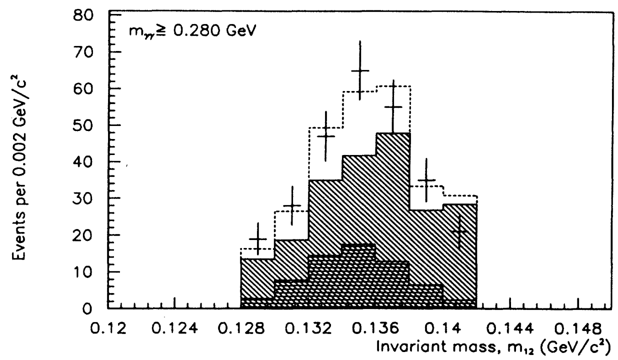

FIG. 3. Data–Monte Carlo comparison for the m_{12} (π^0 candidate) distribution for $\pi^0\gamma\gamma$ candidates and background events including $\pi^0\gamma\gamma$ signal Monte Carlo simulation, for $m_{\gamma\gamma} \geq 0.280$ GeV. The error bars correspond to the data; the diagonally shaded histogram to the sum of the $3\pi^0$ and $2\pi^0$ background Monte Carlo simulations; the horizontally shaded histogram to the $\pi^0\gamma\gamma$ signal normalized with the branching ratio of 1.86×10^{-6}, and the dashed histogram to the sum of the background and the signal. The normalization is absolute.

over the background Monte Carlo simulation is peaked at the nominal π^0 mass with a width consistent with the prediction of a $\pi^0\gamma\gamma$ Monte Carlo simulation. (It should be noted that the background also peaks near, but not at, the nominal neutral-pion mass. This happens because the background often has a true π^0 but, because of the overlaps of the other two clusters, its mass is somewhat shifted and broadened due to the nonlinearity in the lead-glass response.) The $\pi^0\gamma\gamma$ signal is normalized at a branching ratio 1.86×10^{-6} (see below). The agreement is good and gives additional confidence that the excess of data at high $m_{\gamma\gamma}$ is $\pi^0\gamma\gamma$ signal.

For the high-mass sample ($m_{\gamma\gamma} \geq 0.280$ GeV) we have 232 candidate events from which 104 come from a data set with a 0.09-radiation-length lead sheet inserted in the beams 137.8 m from the target. The effect of the lead sheet is that it will sometimes convert one (or more) of the photons causing both signal and background events to be lost. The Monte Carlo simulation properly accounts for this and the total predicted background is (171.9 ± 11.5) events (150.7 from $3\pi^0$'s and 21.2 from $2\pi^0$'s). Based on background studies and many comparisons of data with Monte Carlo distributions, we assign an 11% systematic error to the estimate of the background in the high mass region. There are three sources to this systematic uncertainty which are added in quadrature. The first is due to imperfect knowledge of the efficiencies of the photon vetoes (exclusive of the lead mask, itself a photon veto discussed later) and this is estimated to result in 5% uncertainty. The second arises from possible errors in the understanding of the photon energy resolution and this is estimated to result in a 3% uncertainty. The third, which is the largest, is associated with the discarding of a few remaining events with photons projecting outside the aperture of the lead mask. These events are not well simulated and this is estimated to result in a 9% uncertainty. The $\pi^0\gamma\gamma$ acceptance is 3.4% (4.4%) for data with (without) the lead sheet inserted and the normalization is provided by 45000 $K_L \to 2\pi^0$ decays taken simultaneously. Using the world average value [11] for the $K_L \to 2\pi^0$ branching ratio we conclude that

$$\frac{\Gamma(K_L \to \pi^0\gamma\gamma,\ m_{\gamma\gamma} \geq 0.280\ \text{GeV})}{\Gamma(K_L \to \text{all})} = (1.86\pm0.60\pm0.60)\times10^{-6},$$

where the first error is statistical and the second is systematic. If we assume the $m_{\gamma\gamma}$ distribution predicted by chiral perturbation theory we then have

$$\frac{\Gamma(K_L \to \pi^0\gamma\gamma)}{\Gamma(K_L \to \text{all})} = (2.2\pm0.7\pm0.7)\times10^{-6}.$$

We have also looked for a signal at lower $\gamma\gamma$ masses. Our acceptance for masses below the double fusion peak is smooth and averages [7,10] about 5%, except for the narrow region excluded around the nominal π^0 mass. For the region $m_{\gamma\gamma} < 0.264$ GeV we have 367 ± 19.2 data events and 377.5 ± 18.4 expected background events. This gives

$$\frac{\Gamma(K_L \to \pi^0\gamma\gamma,\ m_{\gamma\gamma} < 0.264\ \text{GeV})}{\Gamma(K_L \to \text{all})} < 5.1\times10^{-6}$$

(90% confidence)

where we have used a phase-space distribution for $m_{\gamma\gamma}$ and have included a 15% systematic error on the background prediction.

We thus confirm both the substantial branching ratio and the peaking at high mass first reported by the NA31 group. Our analysis uses less stringent kinematic cuts so that our acceptance is smooth and substantial over the entire mass region, leading to a limit at lower mass values. The central value for the branching ratio is a factor of three higher than the chiral perturbation theory prediction. More statistics and better background rejection will be necessary for additional studies of this decay mode.

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