

New Limits on $K_{L,S} \rightarrow \pi^0 e^+ e^-$

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Data taken in a Fermilab experiment designed to measure the CP -violation parameter ϵ'/ϵ from a study of $K \rightarrow 2\pi$ decays were used to look for the as yet unseen decay modes $K_{L,S} \rightarrow \pi^0 e^+ e^-$. The detector was optimized for the detection of kaon decays with four electromagnetic showers in the final state. The results (90% confidence) are branching ratios $< 4.2 \times 10^{-8}$ and $< 4.5 \times 10^{-5}$ for $K_L \rightarrow \pi^0 e^+ e^-$ and $K_S \rightarrow \pi^0 e^+ e^-$, respectively.

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The $\pi^0 e^+ e^-$ decay of the long-lived neutral kaon (K_L) is an attractive avenue for the observation of CP violation in a decay amplitude, particularly should detailed studies of the 2π decays of the neutral kaon (ϵ'/ϵ) prove inconclusive. The CP -violating amplitude is expected¹ to be comparable to or larger than the CP -conserving one. The leading CP -conserving amplitude proceeds through two-photon exchange while the CP -violating one may proceed via one-photon exchange. Within the framework of the standard model where CP violation comes from the phase δ in the Kobayashi-Maskawa matrix,² $K_L \rightarrow \pi^0 e^+ e^-$ may have a sizable $\Delta S = 1$ CP -violating effect. Theoretical estimates¹ of the branching ratio are in the 10^{-11} range, while the current experimental limit³ is $< 2.3 \times 10^{-6}$ at 90% confidence. There has been no $K_S \rightarrow \pi^0 e^+ e^-$ measurement, while predictions¹ range from 5×10^{-9} to 5×10^{-10} .

Fermilab experiment E-731, which was performed in the Meson Center beam line at the Tevatron, had as its primary goal the determination of the $K \rightarrow 2\pi$ CP -violation parameter ϵ'/ϵ . The present search is based upon the analysis of a special data set in which $K_{L,S} \rightarrow \pi^0 \pi^0$ and $K_{L,S} \rightarrow \pi^+ \pi^-$ were recorded simultaneously.

Two neutral K_L beams ($\frac{1}{2} \times \frac{1}{2}$ mrad²) were created at 4.8 mrad by 800-GeV protons striking a Be target. A regenerator which moved alternately between the beams every proton spill was used to provide K_S . The detector

was employed in an earlier test run and it is shown schematically in Fig. 1; it has been described elsewhere^{4,5} in detail. Charged particles were measured and momentum analyzed with a 2000-wire drift-chamber spectrometer which consisted of eight x planes and eight y planes with 0.635-cm maximum drift distance. These planes had a position resolution of about 110 μm and were 98% efficient. Energies and positions of photons and electrons were measured with an 804-block lead-glass array stacked circularly. Each block measured 5.82 cm (H) by 5.82 cm (W) by 60 cm (L), giving a depth of 20 radiation lengths. There were two holes (11.6 cm \times 11.6 cm) separated vertically by 11.6 cm at the center of the array for the beams to pass. A common pulsed light source illuminated every block once every second to provide short-term gain tracking. The pulse heights were digitized with effectively 15-bit analog-to-digital converters using a 150-ns gate.

Several improvements have been made to the detector since the previous data taking period. The most important one was the instrumentation of each of the lead-glass phototube outputs with a 60-MHz flash analog-to-digital converter. These were the front-end electronics for a two-dimensional cluster-finding trigger processor, and they also served to suppress out-of-time photons. A cluster was defined as a "neighbor-connected" island of lead-glass blocks each with more than 1 GeV. The trigger processor contributed less than 2% dead time and

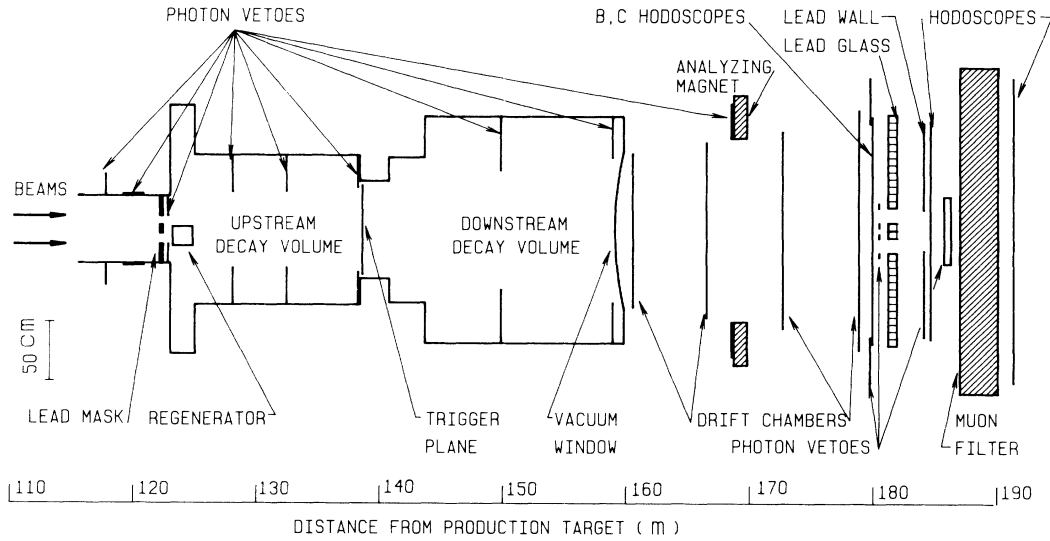


FIG. 1. Detector schematic, elevation view.

a FASTBUS-based data-acquisition system was implemented to increase the data taking capability as well.

There were two triggers relevant to the data set used in this search. The first (“four cluster”) required exactly four clusters, 30 GeV or more energy deposited in the lead-glass, and no hit in the trigger plane (see Fig. 1). Hence this trigger recorded $\pi^0 e^+ e^-$ candidates in the downstream decay region as well as $\pi^0 \pi^0$ candidates from both upstream and downstream decay regions. The second trigger (“two track”) required one or more hits at the trigger plane and

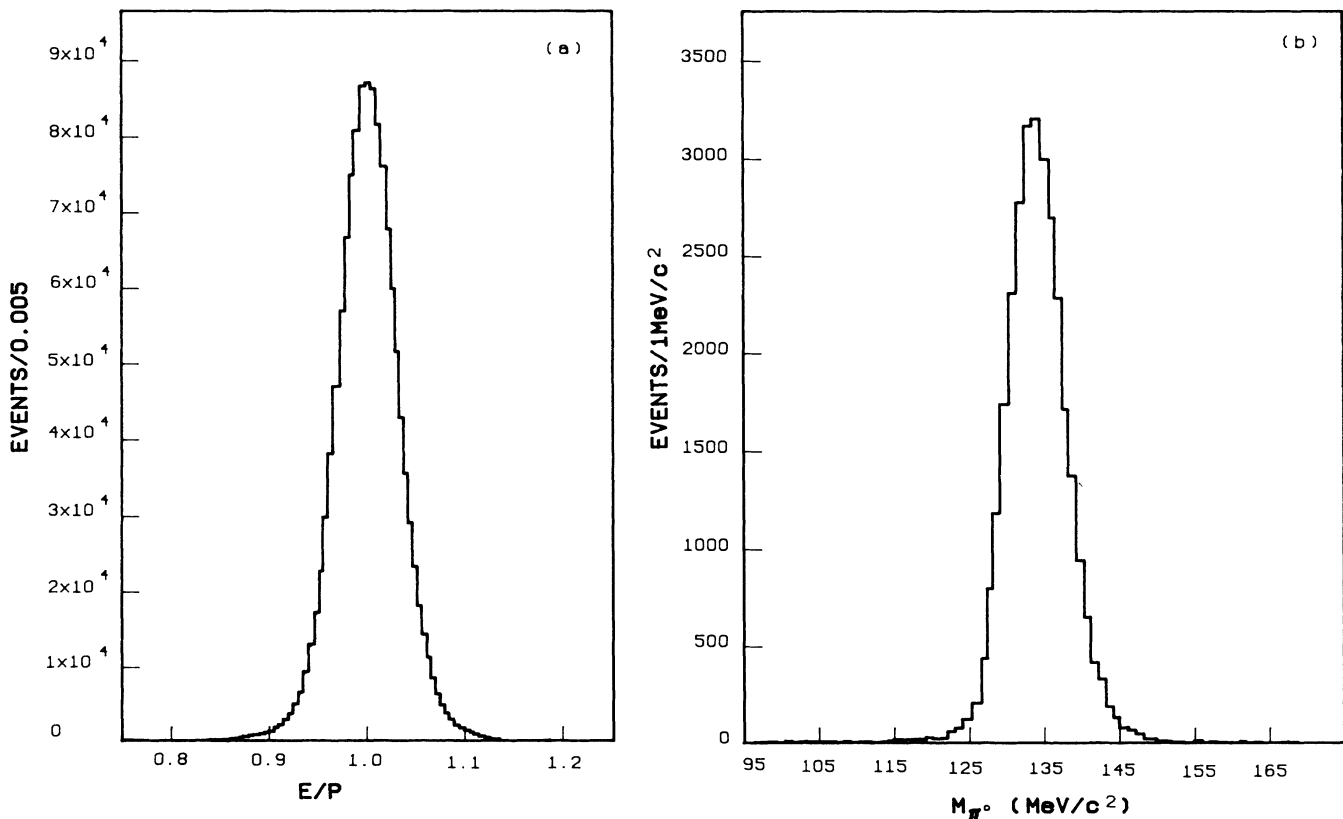


FIG. 2. (a) Distribution of E/P in the lead-glass from the electron calibration data. The resolution is about 4% rms; (b) distribution of the π^0 mass reconstructed from $K_L \rightarrow \pi^+ \pi^- \pi^0$ decays.

two tracks in the spectrometer, and hence was sensitive to $\pi^0 e^+ e^-$ decays from the upstream decay region; however, this trigger was prescaled by a factor of 8.

Because the trigger processor used signals from the lead-glass directly, the relative gains of all lead-glass blocks were monitored and adjusted to within 5% over the entire data taking period. Calibration data with $e^+ e^-$ pairs produced in a thin upstream foil were taken periodically to provide high-statistics calibration for the lead-glass; the resolution was $\sigma/E \approx 1.5\% + 5\%/\sqrt{E}$ (E in GeV). Chamber-alignment data were also recorded daily.

The momenta of the e^+ and e^- and the decay vertex of $K_L \rightarrow \pi^0 e^+ e^-$ candidates were determined by the drift-chamber spectrometer. The e^+ and e^- were identified by matching the tracks with the clusters, and requiring $0.85 < E/P < 1.15$, where E is the cluster energy and P is the momentum. Figure 2(a) shows the E/P distribution for electrons from the calibration data (which is essentially identical to the same distribution of electrons from K_{e3} decays taken during the main data run). From a study of $K_L \rightarrow \pi^+ \pi^- \pi^0$ decays, the π^0

mass resolution was determined to be about $4 \text{ MeV}/c^2$ [see Fig. 2(b)]. The $\gamma\gamma$ mass was required to be within $10 \text{ MeV}/c^2$ of the nominal π^0 value. By then constraining the $\gamma\gamma$ mass to the nominal value, the reconstructed kaon mass ($M_{\pi ee}$) would have a resolution of about $4.5 \text{ MeV}/c^2$. The square of the transverse momentum (P_T^2) of the $\pi^0 e^+ e^-$ system with respect to the line connecting the decay vertex and the production target had a resolution of about $50 \text{ MeV}^2/c^2$. The candidates are displayed in a two-dimensional $M_{\pi ee}$ vs P_T^2 plot as shown in Fig. 3(b). A candidate is defined to have $P_T^2 < 200 \text{ MeV}^2/c^2$ and $489 < m_K < 507 \text{ MeV}/c^2$; these cuts would include about 95% of the signal. No candidate is found in the signal region. Figure 3(a) shows the equivalent region for $K_L \rightarrow \pi^+ \pi^- \pi^0$ decays. Given the timing and energy resolution of the detector, the background of $K \rightarrow 2\pi^0$ with Dalitz decays is insignificant; the very few remaining events are consistent with radiative K_{e3} with an accidental photon.

Figure 4 shows the relative acceptance for Monte Carlo-generated $K_L \rightarrow \pi^0 e^+ e^-$ decays as a function of the $e^+ e^-$ effective mass. Because of the loose cuts, the

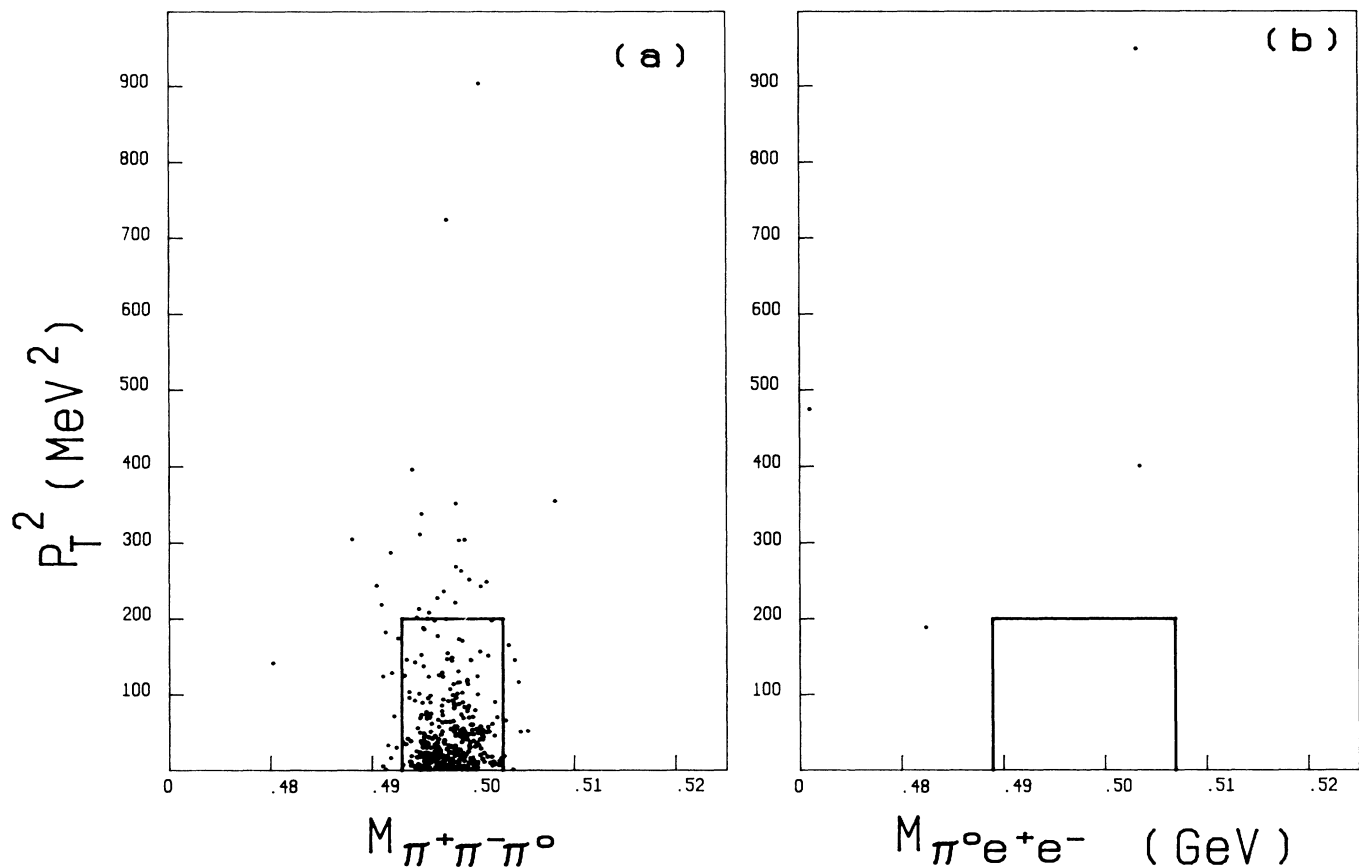


FIG. 3. Reconstructed kaon mass vs the square of the transverse momentum for (a) $K_L \rightarrow \pi^+ \pi^- \pi^0$ and (b) $K_L \rightarrow \pi^0 e^+ e^-$. There are 24 events above the top of the plot in (b). The events in the plots were selected with a π^0 mass cut of 2.5σ and the boxes represent the signal region. There are no background events for the K_S decay.

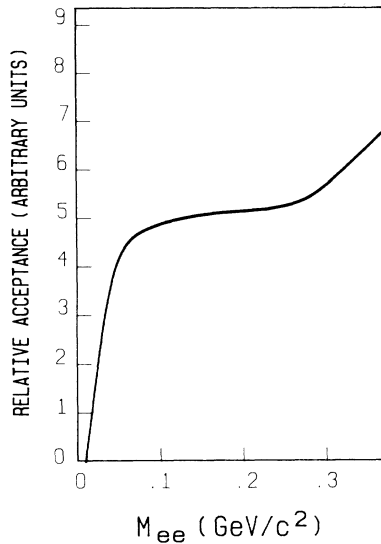


FIG. 4. The relative acceptance vs the e^+e^- invariant mass of the $K_L \rightarrow \pi^0 e^+ e^-$ decay for the four-cluster trigger.

effect of internal radiation is expected to be small; external radiation is properly treated. For the four-cluster trigger, the acceptance is 9.5% for a fiducial downstream decay volume of 22.2 m and for the two-track trigger, the acceptance is about 10% for an upstream decay volume of 14 m for kaon energy between 30 and 150 GeV, assuming a uniform three-body phase space distribution.

The upper limit $B(K_L \rightarrow \pi^0 e^+ e^-) < 4.7 \times 10^{-8}$ (90% confidence) is obtained by normalizing to a sample of 58.8×10^3 $K_L \rightarrow 2\pi^0$ decays observed simultaneously in the four-cluster trigger. The normalization data do not require track reconstruction; however, the relative branching ratios of $\pi^+\pi^-$ to $\pi^0\pi^0$ from both K_L and K_S were also determined from the same data set and they agree with the published values to within 5%. With the use of 71.3×10^3 $K_L \rightarrow \pi^+\pi^-$ and 2.24×10^5 K_S

$\rightarrow \pi^+\pi^-$ decays from the two-track trigger as normalization, the 90%-confidence limits from that trigger are $< 4.1 \times 10^{-7}$ and $< 4.5 \times 10^{-5}$, respectively.

By the combination of the above, the results are $B(K_L \rightarrow \pi^0 e^+ e^-) < 4.2 \times 10^{-8}$ and $B(K_S \rightarrow \pi^0 e^+ e^-) < 4.5 \times 10^{-5}$ (90% confidence). This is the first limit of any significance for the K_S decay. The K_L limit is an improvement of more than a factor of 50 over the previous limit³; while still far from the level predicted by the standard model, it serves to constrain the parameters of light scalar particles coupling to e^+e^- . The result is consistent with $B(K_L \rightarrow \pi^0 e^+ e^-) < 3.2 \times 10^{-7}$, recently obtained by Jastrzembski *et al.*⁶

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⁵For a complete description of the detector see P. Jarry, Ph.D. thesis, Université de Paris-Sud, 1987 (unpublished); M. Woods, Ph.D. thesis, University of Chicago, 1988 (unpublished).

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