Improved Experimental Limit on $K_L \to \pi^0 e^+ e^-$

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We report on results of a dedicated search for the *CP*-violating decay $K_L \to \pi^0 e^+ e^-$. We have found no evidence for this decay mode and obtain a 90%-confidence upper limit of 5.5×10^{-9} for its branching ratio.

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The decay $K_L \to \pi^0 e^+ e^-$ has recently received considerable attention because of its potential for shedding light on the mechanisms responsible for the violation of *CP* invariance. The lowest-order electroweak contribution to $K_L \to \pi^0 e^+ e^-$ (a one-loop-induced strangeness-changing neutral current coupled to the e^+e^- pair by a single γ or Z^0) is forbidden in the absence of CP violation. In the Kobayashi-Maskawa (KM) six-quark model of CP violation, $K_L \to \pi^0 e^+ e^-$ is expected to receive comparable CP-violating contributions from a *direct* K_2 decay amplitude and from an *indirect* amplitude arising from the CP impurity (ϵK_1) of the K_L state.

Calculations[1-4] within the standard (KM) model obtain very small values for the $K_L \to \pi^0 e^+ e^-$ branching ratio, typically in the range 10^{-11}-10^{-12}. The CP-conserving contribution to $K_L \to \pi^0 e^+ e^-$ through a $\pi^0\gamma\gamma$ intermediate state is also expected to be small, although there is theoretical uncertainty over its importance relative to the CP-violating contributions.[5-7] Recent measurements[8] provide a limit $B(K_L \to \pi^0 e^+ e^-) < 4\times 10^{-8}$ that is several orders of magnitude above any standard-model prediction. In this unexplored range the decay $K_L \to \pi^0 e^+ e^-$ provides an excellent means to search for light scalar particles that couple to e^+e^- or to detect effects expected in nonstandard models[4,9,10] of CP violation.

In the following we present first results from Brookhaven Alternating Gradient Synchrotron experiment 845, a dedicated search for $K_L \to \pi^0 e^+ e^-$. This search was conducted with a reconfigured detector, shown schematically in Fig. 1, employing many elements from a detector optimized[11] to search for $K_L \to \mu^\pm e^\mp$ (Ref. 12) and $K_L \to e^+ e^-$.[13]

The measurements were made on K_L decays occurring in a neutral beam produced by the interactions of 24-GeV/*c* protons with an 18-cm-long copper target. The production angle of the neutral beam was 2°, and its divergence (15 mrad vertically by 2.3 mrad horizontally) was defined by a series of brass collimators embedded in heavily shielded sweeping magnets. About 10 m of shielding and 6 T m of sweeping field separated the target from the beginning of the decay region. The final 1.5 m of shielding consisted of boron-loaded concrete. A 2.5-cm lead plug was placed in the neutral beam to remove high-energy γ rays originating in the target. The neutral beam was transported in vacuum (70 μm Hg) from the defining collimators to the end of the 6-m decay region. The evacuated decay region was terminated by a window consisting of 0.43 mm of Kevlar and 0.13 mm of Mylar.

Charged-particle trajectories were determined with four sets of chambers, two upstream (*A* and *B*) and two downstream (*C* and *D*) of a momentum-analysis magnet. The magnet had a 91-cm vertical gap and mean-field integral corresponding to a momentum transfer of 114 MeV/*c*. The chambers had 3.2-mm drift cells, and each set of chambers provided four measurements (*X*, *X'*, *Y*, and *Y'*) over a 1-m^2 region. Space points on charged-particle trajectories were determined with good resolu-

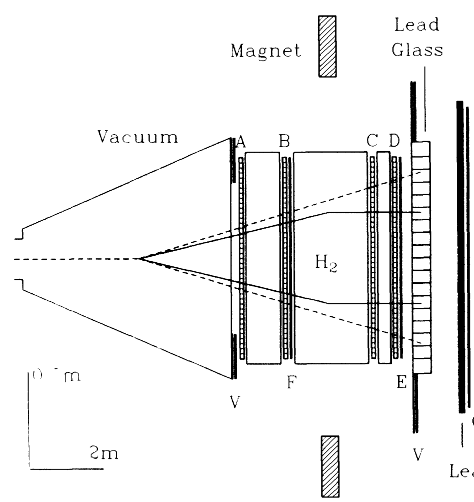

FIG. 1. Schematic plan view of the E845 detector. The neutral beam enters from the left. Note the different horizontal and vertical scales.

tion (250 μm) and high efficiency (99%). In order to maximize the acceptance, the neutral beam passed through the active regions of the chambers. Each chamber set presented less than 10^{-3} of an interaction length of material to the neutral beam.

Electrons and positrons were identified by a hydrogen-gas threshold Čerenkov counter ($\check{C}$) operating at atmospheric pressure, as well as by the pattern of energy deposited in a segmented lead-glass calorimeter. The Čerenkov counter has a nominal 2-m-long radiator volume and was divided into four cells, hereafter referred to as quadrants. Each quadrant was viewed by a 12.7-cm-diam EMI-9823B quartz-window photomultiplier tube by reflection from a front-surface spherical mirror. Cones of simple construction covered with aluminized Mylar were used to increase the light collection at the phototube. The efficiency of the Čerenkov counter was determined to be 92% using electrons (from K_{e3} events) in the data sample.

γ rays were also detected in the lead-glass array that consisted of 244 blocks of Schott F2 glass, each of dimension $6.4\times6.4\times46$ cm (length). The blocks were arranged in a square (1-m^2) array with a 12.7×38-cm^2 hole in the center to pass the neutral beam. In addition, 64 larger blocks defined a fiducial border around the periphery of the central array. The energy resolution of the lead-glass array for electrons was $\sigma_E/E = 7\%/E^{1/2} + 1.6\%$ (E in GeV), and the position resolution was 13 mm for 1-GeV electrons.

Accepted events were required to have two charged tracks consistent with electron identification, and at least 4 GeV of energy deposited in the lead-glass array. An electron was identified at the trigger level by the activation of one Čerenkov quadrant, and a downstream scintillation counter (E) in the same quadrant. In addition, the energy deposited in the corresponding quadrant of lead glass was required to be greater than 800 MeV, as determined by a fast-analog-summing network. One of the electrons was required to activate an upstream scintillation counter (F). Discrimination at the trigger level against penetrating pions and muons was obtained with a scintillation-counter veto array (G) placed downstream of a 15-cm-thick lead wall behind the lead-glass array. Scintillation counters (V) covered with three radiation lengths of material were used to veto events with γ rays outside the fiducial detector acceptance. The γ veto counters were located around the exit window (69 cm high by 76 cm wide) of the decay tank, and outside the fiducial face of the lead-glass array.

Unbiased triggers, without particle-identification, energy, or veto requirements, were collected concurrently, prescaled by a factor of 10000. From this sample $K_L \to \pi^+\pi^-\pi^0$ decays were identified and used to determine the resolution of the detector and the sensitivity of the experiment. The unbiased triggers also provided data that were used to monitor the performance of specific elements of the detector (e.g., the Čerenkov-counter efficiency).

In order to suppress potential backgrounds, time and pulse-height information was recorded for the trigger counters and calorimeter elements. Times for the Čerenkov counter were determined with a resolution of 860 psec with respect to the event time, as defined by the F and E scintillation counters. Digitization of the pulse heights from the lead glass required an integration time of 100 nsec. However, times for lead-glass pulses crossing an effective threshold of 300 MeV were determined with a resolution of 1.5 nsec. The timing resolution of the detector was essential for the rejection of backgrounds arising from the overlap of two K decays—for example, $K_L \to \pi e \nu$, with the pion misidentified as an electron, in coincidence with two γ rays from another K decay such as $K_L \to 3\pi^0$. The pulse heights of the F and $\check{C}$ counters were recorded to aid in the (off-line) rejection of $K_L \to 2\pi^0$ and $3\pi^0$ decays with two π^0's suffering highly asymmetric Dalitz decays. In these events, even if only two complete tracks through the analysis magnet were found, the Dalitz pairs might be revealed by pulse heights observed in the upstream detectors. Since no events consistent with the kinematics of $K_L \to \pi^0 e^+ e^-$ were found, the counter pulse-height information was used only to monitor the performance of the detector.

The data were collected with a Fastbus data-acquisition system[11,14] that rejected uninteresting events in several levels of on-line processing. Typically about 10^{12} protons per (1-sec) pulse were directed onto the target, resulting in a beam flux of 3×10^8 neutrons per pulse. At this intensity the counting rate was about 6 MHz/m^2 at the face of the lead-glass array. About 500 triggers per pulse were recorded and about 80 events were written to tape per pulse after passing on-line event-selection criteria. In particular, wire-address (but not drift-time) information was used from the X and Y chambers to search for at least two track candidates originating in the decay region.[15] The data-acquisition live time was typically 90%. In all, about 10^8 events were collected.

The off-line event analysis required that two oppositely charged tracks meet, with a distance of closest approach < 1.25 cm, at a point in the neutral beam between 46 and 608 cm upstream of the first chamber (A). The tracks were required to satisfy electron-identification criteria. Each track had to be uniquely associated with a Čerenkov-counter pulse occurring within ± 2.5 nsec of the event time. The momentum (p) of each track was required to be less than the Čerenkov-counter threshold for charged pions (8 GeV/c). The energy (E) of an electron as measured in the lead glass had to be consistent with its momentum: $0.75 < E/p < 1.25$. In addition, the transverse profile of the shower in the lead glass was required to have a second (energy-weighted) moment of less than 32 cm^2. The π/e rejection ratio was about 5×10^{-5}, and electrons were identified with an overall efficiency of 90%.

The momentum asymmetry of the charged tracks,

$A=|(p_+-p_-)/(p_++p_-)|$, was limited to 0.8. This resulted in a further suppression of backgrounds involving K_{e3} decays, but a negligible loss of acceptance for the $\pi^0e^+e^-$ and $\pi^+\pi^-\pi^0$ decay modes. For the $\pi^0e^+e^-$ decay mode the electron-positron pair mass was restricted to be greater than 145 MeV/c^2 to exclude backgrounds arising from π^0 Dalitz decays.

Clusters of energy in the lead-glass array not associated with charged particles were identified as γ rays. γ rays with energies above 500 MeV occurring within ± 5 nsec of the event time were included in the analysis. In order to suppress backgrounds from neutral-beam interactions, the minimum energy was 700 MeV for γ rays striking within 6 cm of the neutral-beam hole in the lead-glass array. Each cluster was also required to have a narrow transverse shower profile. The reconstruction of a π^0 from two γ clusters assumed the decay vertex established by the charged-particle trajectories.

Additional constraints were imposed in order to reject events arising from coincident K decays. The analysis required that the reconstructed kaon momentum be less than 20 GeV/c. Events were rejected if they exhibited track segments in the A and B chambers originating at the vertex, or if charged-particle tracks were found passing through the neutral-beam hole in the lead-glass array. Finally, $\pi^0e^+e^-$ events were required to have no additional clusters in the lead glass with $E>500$ MeV and within ± 5 nsec of the event time. Altogether these requirements were found to result in a loss of about 5% of otherwise good events.

The resolution of the detector for the $K_L\to\pi^0e^+e^-$ search was determined from the study of $K_L\to\pi^+\pi^-\pi^0$ decays. Figure 2 shows the relevant kinematic distributions: (a) the $\gamma\gamma$ effective mass; (b) the $\pi^+\pi^-\pi^0$ effective mass; and (c) θ_K^2, the square of the angle between the line from the target to the decay vertex and the reconstructed kaon momentum vector. Events were required to have a $\gamma\gamma$ pair with an invariant mass within 34 MeV/c^2 of the π^0 mass. With the $\gamma\gamma$ mass constrained to the π^0 mass, events were selected if the $\pi^+\pi^-\pi^0$ effective mass was within 13 MeV/c^2 of the K^0 mass, and if $\theta_K^2<12$ mrad^2. The kinematic constraints constitute cuts for values 3 standard deviations away from the mean.

Using the $\pi^+\pi^-\pi^0$ mass resolution of 4.3 MeV/c^2 as a normalization, the uncertainty in mass for the $\pi^0e^+e^-$ final state was calculated by Monte Carlo methods to be 10.7 MeV/c^2. The results of the analysis for the $\pi^0e^+e^-$ final state are presented as a scatter plot (Fig. 3) of the $\pi^0e^+e^-$ effective mass and θ_K^2 for events passing the criteria described above. Events from $K_L\to\pi^0e^+e^-$ decays are expected to be concentrated in the (3σ) bounded region shown, corresponding to a $\pi^0e^+e^-$ effective mass within 32 MeV/c^2 of the K^0 mass and $\theta_K^2<12$ mrad^2. There were no event candidates consistent with the decay $K_L\to\pi^0e^+e^-$. Background is expected from the decay modes $K_L\to\pi^0\pi^0$ and $K_L\to\pi^0\pi^0\pi^0$ with two π^0 Dalitz decays, from K_{e3} decays with pion misidentification and accidental coincidence with γ's from another decay, and the Dalitz decay $K_L\to e^+e^-\gamma$ with internal radiation. The latter process is ultimately the most serious and will be discussed in detail elsewhere.[16]

The limit on the branching ratio is obtained from the following expression:

$$B(K_L\to\pi^0e^+e^-)=B(K_L\to\pi^+\pi^-\pi^0)\frac{N(\pi ee)}{N(\pi\pi\pi)}\frac{A(\pi\pi\pi)}{A(\pi ee)}\frac{1}{C},$$

where $N(\pi ee)=2.3$ for a 90%-confidence limit since no $\pi^0e^+e^-$ candidates were observed. The number of $K_L\to\pi^+\pi^-\pi^0$ events observed including the prescale fac-

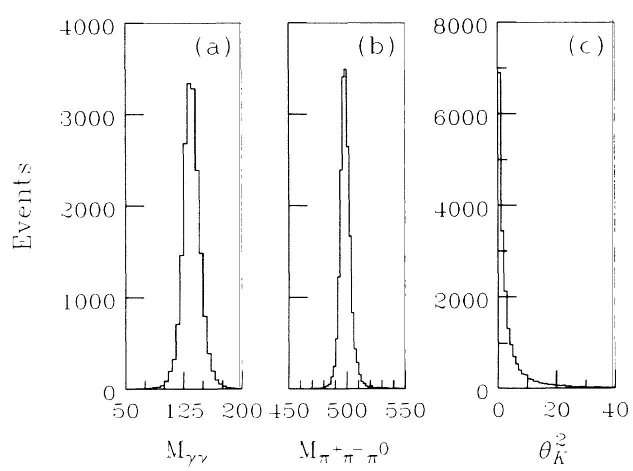

FIG. 2. For a sample of $K_L\to\pi^+\pi^-\pi^0$ decays the distributions of (a) the $\gamma\gamma$ effective mass (MeV/c^2); (b) the $\pi^+\pi^-\pi^0$ effective mass (MeV/c^2); and (c) θ_K^2, the square of the target reconstruction angle (mrad^2).

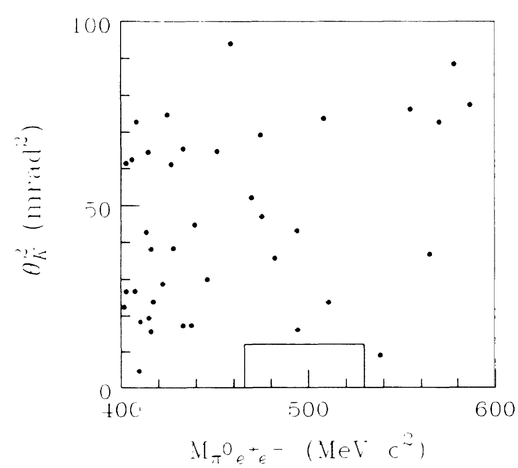

FIG. 3. Event scatter plot of the square of the target reconstruction angle vs the $\pi^0e^+e^-$ effective mass.

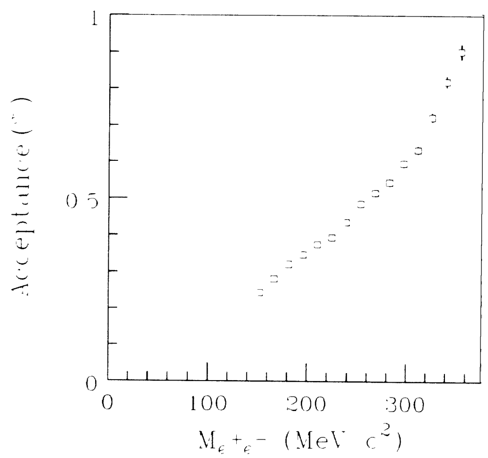

FIG. 4. Acceptance vs e^+e^- effective mass for $K_L \to \pi^0 e^+ e^-$ decays assuming a uniform Dalitz-plot population.

tor was $N(\pi\pi\pi) = 22\,082 \times 10\,000$. The known branching ratio for this mode is $B(K_L \to \pi^+\pi^-\pi^0) = 0.1237$. The acceptances, $A(\pi ee) = 0.37\%$ and $A(\pi\pi\pi) = 1.35\%$, were determined by Monte Carlo methods for kaon momenta greater than 4 GeV/c. The $\pi^0 e^+ e^-$ final state was generated by assuming a uniform Dalitz-plot population. The dependence of the $\pi^0 e^+ e^-$ acceptance on the electron-positron pair mass is shown in Fig. 4. The acceptance calculation included the measured temporal and spatial variations of the Čerenkov-counter efficiency. The correction factor $C = 0.86$ accounts for additional inefficiencies that affected only the $\pi^0 e^+ e^-$ mode. These inefficiencies were primarily due to the dead time introduced by veto requirements (G, V, and additional lead-glass clusters). The final result obtained is $B(K_L \to \pi^0 e^+ e^-) < 5.5 \times 10^{-9}$ (90% C.L.) which places further constraints on nonstandard-model contributions to this process. We have recently learned[17] of a new limit from Fermilab experiment 731, $B(K_L \to \pi^0 e^+ e^-) < 7.5 \times 10^{-9}$, in agreement with our result.

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