Improved Sensitivity in a Search for the Rare Decay $K_L^0 \longrightarrow e^+e^-$

K. Arisaka,[1] L. B. Auerbach,[2] S. Axelrod,[3,a] J. Belz,[2,b] K. A. Biery,[3,c] P. Buchholz,[2,d] M. D. Chapman,[4,e] R. D. Cousins,[1] M. V. Diwan,[3,f] M. Eckhause,[4] J. F. Ginkel,[4,g] C. Guss,[2,h] A. D. Hancock,[4] A. P. Heinson,[5,i] V. L. Highland,[2] G. W. Hoffmann,[6] J. Horvath,[5] G. M. Irwin,[3] D. Joyce,[4,j] T. Kaarsberg,[1,k] J. R. Kane,[4] C. J. Kenney,[4,l] S. H. Kettell,[2,m] W. W. Kinnison,[7] P. Knibbe,[5,n] J. Konigsberg,[1,o] Y. Kuang,[4] K. Lang,[3,p] D. M. Lee,[7] J. Margulies,[3,q] C. Mathiazhagan,[5] W. K. McFarlane,[2,f] R. J. McKee,[7] P. Melese,[1,r] E. C. Milner,[7,f] W. R. Molzon,[5] D. A. Ouimette,[3,j] P. J. Riley,[6] J. L. Ritchie,[6] P. Rubin,[1,s] G. H. Sanders,[7] A. J. Schwartz,[3,t] M. Sivertz,[2,u] W. E. Slater,[1] J. Urheim,[5,v] W. F. Vulcan,[4,j] D. L. Wagner,[1,w] R. E. Welsh,[4] R. J. Whyley,[4,x] R. G. Winter,[4,y] M. T. Witkowski,[4] S. G. Wojcicki,[3] A. Yamashita,[6,m] and H. J. Ziock[7]

(BNL E791 Collaboration)

[1]*University of California, Los Angeles, California 90024*
[2]*Temple University, Philadelphia, Pennsylvania 19122*
[3]*Stanford University, Stanford, California 94309*
[4]*College of William and Mary, Williamsburg, Virginia 23187*
[5]*University of California, Irvine, California 92717*
[6]*University of Texas, Austin, Texas 78712*
[7]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
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In a search for the decay $K_L^0 \to e^+e^-$, no candidates have been observed. We determine the sensitivity from the detected number of CP-violating $K_L^0 \to \pi^+\pi^-$ decays and place a 90% confidence level upper limit on the branching ratio of $B(K_L^0 \to e^+e^-, |M_K - M_{ee}| < 6\ \mathrm{MeV}/c^2) \leq 4.1 \times 10^{-11}$. This result is a significant improvement over previous measurements, although still above the standard model prediction of 3×10^{-12}.

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The decay $K_L^0 \to e^+e^-$ is the helicity-suppressed counterpart of the effective flavor-changing neutral current process $K_L^0 \to \mu^+\mu^-$ which has played an important role in the development of the standard model. Recent measurements of the $K_L^0 \to \mu^+\mu^-$ branching ratio [1–3], near the QED lower limit obtained from the contribution of the on-shell part of the two-photon intermediate state [4] (often called the unitarity bound), imply that this decay is dominated by standard model processes. A search for the decay $K_L^0 \to e^+e^-$ at a sensitivity approaching the standard model level of 3×10^{-12} is then sensitive to new contributions which may not be suppressed by the $V - A$ structure of the weak interaction. This Letter describes a search for the decay $K_L^0 \to e^+e^-$ and reports a significantly improved upper limit on the branching ratio to this process [5,6]. The limit is still roughly an order of magnitude above the standard model prediction.

The data presented here were taken as part of Brookhaven National Laboratory experiment 791 (BNL E791), concurrent with a search for $K_L^0 \to \mu^\pm e^\mp$ and a study of $K_L^0 \to \mu^+\mu^-$ at sensitivities better than previously achieved. The data were collected in periods of 15 and 12 weeks during the 1989 and 1990 runs of the Alternating Gradient Synchrotron (AGS). The kaon beam line, the typical running conditions, and the E791 detector have recently been described elsewhere [7]. Here we restrict our description to a summary of those elements critical to the $K_L^0 \to e^+e^-$ search.

The spectrometer consisted of five pairs of drift chambers and two analyzing magnets with transverse momentum impulses of 300 MeV/c and 318 MeV/c of opposite sign. For the 1990 run the two most upstream chambers were replaced with larger modules placed closer to the neutral beam, resulting in a 43% increase in acceptance for $K_L^0 \to e^+e^-$ events. Downstream of the drift chambers were two pairs of vertical and horizontal trigger scintillation counter hodoscopes (TSC's) and particle identification (PID) detectors. Electrons were identified with time information from a threshold gas Cherenkov counter (CER) and pulse height information from a lead-glass array (PBG). The PBG array was composed of two layers, a converter array (3.3 radiation lengths) and an absorber array (10.5 radiation lengths).

Trigger decisions were made at multiple levels. The first two levels (referred to as $L0$ and $L1$) were made in hardware. The third level ($L3$) was based on a software algorithm running in a farm of 3081/E computers [8]. (A level 2 trigger was designed but never used in either running period.) The $L0$ trigger was defined as an overlap coincidence of the four TSC's in which the hits in the vertical and horizontal views were required to be consistent in position and time. A "minimum bias" signal was formed from a coincidence of the $L0$ trigger signal with signals from the three most upstream drift cham-

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bers on each side of the spectrometer. The $L1$ trigger selected ee candidate events, defined by a coincidence of the minimum bias signal with a CER signal on each side of the apparatus. It also included minimum bias events prescaled by 2000, from which the sample of $K_L^0 \to \pi^+\pi^-$ events used to calculate the sensitivity of the experiment was selected.

The $L3$ trigger decision was based on the two-body mass (M_{ee}) and the collinearity angle (θ_K), defined as the difference between the kaon direction obtained from the target and vertex positions and the reconstructed two-body momentum direction. Electron pair triggers were required to have $\theta_K^2 < 100$ mrad^2, $M_{ee} > 460$ MeV/c^2 and, in 1989 only, $M_{ee} < 550$ MeV/c^2. The efficiency of this algorithm was measured, using minimum bias events passing the event quality and kinematic cuts described below, to be 66% (1989) and 91% (1990). The improved efficiency in 1990 was achieved with modifications to the code to find events with missing hits and events contaminated with extra hits in the chambers more effectively. Also, an inherent bias against like-charge events in the 1989 $L3$ algorithm was removed from the 1990 $L3$ algorithm. These events were important in understanding backgrounds to the $K_L^0 \to e^+e^-$ search.

Events with at least two tracks traversing the full spectrometer and originating from a common vertex were reconstructed and further analyzed off line. The invariant mass and collinearity were recalculated and the transverse momentum (p_T), defined to be the product of the two-body momentum with the collinearity angle, was calculated. Events with $M_{ee} > 470$ MeV/c^2 and either $\theta_K^2 <$ 10 mrad^2 or $p_T^2 < 800$ (MeV/c)^2 were selected. In the analysis of the 1989 data it was also required that $M_{ee} <$ 530 MeV/c^2. Events satisfying these criteria were then fit using a full magnetic field map to determine their kinematics more accurately. The minimum bias sample was further prescaled off line by a factor of 3 (2) in 1989 (1990). Thus the overall prescale of the $K_L^0 \to \pi^+\pi^-$ normalization sample was 6000 (4000).

As in the search for the decay $K_L^0 \to \mu^\pm e^\mp$, selection criteria were devised without studying events in the kinematic region in which signal events are expected [7]. Specifically, events in the region defined by $|M_{ee} - M_K| <$ 10 MeV/c^2 and $\theta_K^2 < 2$ mrad^2 were excluded from analysis until the selection criteria had been chosen. All selection criteria except PID were applied to both the $K_L^0 \to e^+e^-$ and the normalization data samples.

Candidate events were required to have a vertex at least 9.75 m from the target and within a region defined by the beam divergence. Events with charged particle trajectories which projected to the vacuum flanges or other thick materials were eliminated. The charged particles were required to have momenta above 1.5 GeV/c and below 12.0 GeV/c. The reconstructed kaon momentum was required to be below 20 GeV/c. (The mean kaon momentum of detected $K_L^0 \to \pi^+\pi^-$ events was 8.0 GeV/c.) Track and vertex quality were assured by

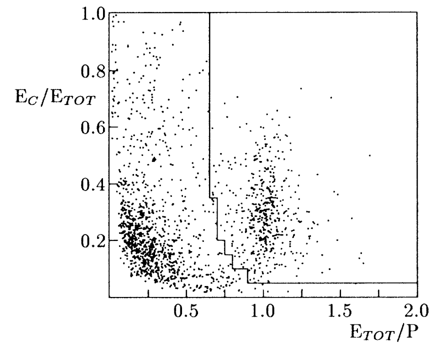

FIG. 1. A scatter plot of the fraction of energy deposited in the convertor layer of the PBG ($E_C/E_{\rm tot}$) versus the ratio of the deposited energy to measured momentum ($E_{\rm tot}/P$), for particles from minimum bias data. Particles in the region above and to the right of the indicated contour are identified as electrons in the PBG.

cutting on χ^2's calculated during the fitting procedure. The asymmetry in the two charged particle momenta, $|\mathbf{p}_1 - \mathbf{p}_2|/|\mathbf{p}_1 + \mathbf{p}_2|$, was required to be less than 0.67 in order to remove $\Lambda^0 \to p^+\pi^-$ events from the $K_L^0 \to \pi^+\pi^-$ normalization sample.

The signals in those elements of the CER and PBG detectors to which fitted tracks projected were compared to those expected for different particle types. To be identified as electrons, particles were required to have an associated CER hit within 4 ns of the event time, where the rms timing resolution was measured to be 0.95 ns for electrons from $K_L^0 \to \pi^\pm e^\mp \nu$ decays. In addition, these tracks were required to have an appropriate signal in the PBG array. Specifically, particles identified as electrons had to lie above and to the right of the contour indicated in Fig. 1. That contour was determined empirically from the study of $K_L^0 \to \pi^\pm e^\mp \nu$ events so as to obtain optimum pion rejection consistent with high electron identification efficiency.

Events with M_{ee} above 470 MeV/c^2 still remained after applying the above criteria. Potential sources of high mass e^+e^- pairs are K_L^0 decays into $e^+e^-e^+e^-$, $e^+e^-\gamma$, or $\gamma\gamma$, the latter two with photon conversions in the vacuum window or upstream drift chambers. The background from these sources was studied by Monte Carlo techniques and by looking in the data for events either with extra tracks in the two upstream drift chamber planes or with like-charge ee pairs. Background from $K_L^0 \to \pi^\pm e^\mp \nu$ decays is highly suppressed since it requires a pion to be misidentified as an electron and is kinematically restricted to values of M_{ee} below 478 MeV/c^2 in the absence of measurement errors.

In order to test our understanding of the sources of high-mass ee pairs of both like and unlike charge, we focused our attention on the 1990 data, since the 1989 $L3$ code had an unmeasureable bias against like-charge events. Figure 2 is a scatter plot of θ_K^2 vs M_{ee}, for the 1990 data. Events with one particle momentum above

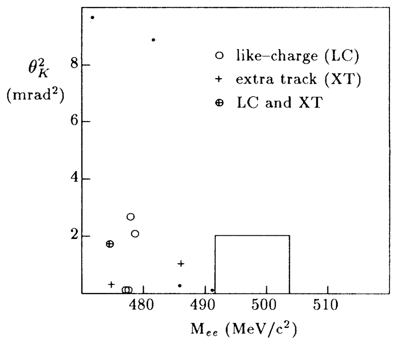

FIG. 2. Scatter plot of θ_K^2 vs M_{ee} for events from the 1990 data set which satisfy all selection criteria except those on θ_K^2 and M_{ee}. Events identified as originating from $K_L^0 \to \pi^{\pm}e^{\mp}\nu$ have been removed. Like-charge events (identified with o's), and events with one or more extra tracks detected in the upstream two drift chamber planes (identified with +'s) have been restored to the plot.

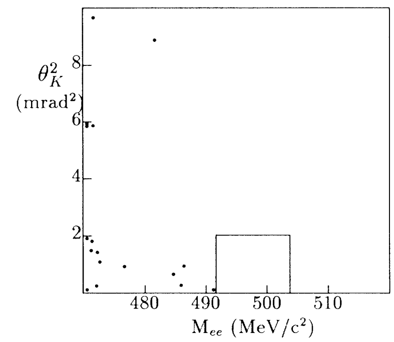

FIG. 3. Scatter plot of θ_K^2 vs M_{ee} for events from the combined 1989 and 1990 data sets which satisfy all selection criteria except those on θ_K^2 and M_{ee}. Events identified as originating from $K_L^0 \to \pi^{\pm}e^{\mp}\nu$ are included in this plot.

pion CER threshold and $M_{ee} < 478$ MeV/c^2 have been eliminated for clarity; these events are K_{e3} in which the pion is misidentified as an electron in the PBG. Real $K_L^0 \to e^+e^-$ events would be concentrated on the plot around $\theta_K = 0$ and $M_{ee} = M_K = 497.67$ MeV/c^2.

We have estimated the number of events expected in Fig. 2 from $K_L^0 \to e^+e^-\gamma$ and $K_L^0 \to e^+e^-e^+e^-$ by the Monte Carlo technique [9]. The $K_L^0 \to e^+e^-\gamma$ Monte Carlo simulation used the Kroll-Wada differential decay spectrum [10], modified by inclusion of a vector-vector term in the $K_L^0 \to \gamma\gamma^*$ form factor [11–13]. If the real photon in the $K_L^0 \to e^+e^-\gamma$ process is sufficiently soft, the event can take on an e^+e^- invariant mass arbitrarily close to M_K. Assuming a $K_L^0 \to e^+e^-\gamma$ branching ratio of 9.1×10^{-6} [12,13], we predict 2 ± 1 events from $K_L^0 \to e^+e^-\gamma$ within the phase space of Fig. 2. The uncertainty in this prediction is dominated by the uncertainty in the $K_L^0 \to \gamma\gamma^*$ form factor.

The Monte Carlo calculation of the $K_L^0 \to e^+e^-e^+e^-$ events in Fig. 2 was based on the differential decay spectrum of Miyazaki and Takasugi [14] for double internal conversions. A flat $K_L^0 \to \gamma^*\gamma^*$ form factor was assumed. This is a reasonably accurate approximation since the largest contribution to the events in Fig. 2 arises when two low-mass intermediate photons convert asymmetrically. (The effect of the form factor is small when the intermediate photons have low mass.)

Using a branching ratio for this decay of 4×10^{-8} [15–17] we predict 7 ± 1 events in the full region of Fig. 2. The uncertainty in this prediction is primarily statistical. Half of the 7 events are expected to be like charge (5 are observed) and 2 of these 7 will contain one or two extra tracks in the upstream drift chambers (3 are seen).

Finally, approximately 1 event is expected in Fig. 2 from the photons from $K_L^0 \to e^+e^-\gamma$ and $K_L^0 \to \gamma\gamma$ decays converting in the vacuum window or first drift chamber. Thus the total predicted level of events in Fig. 2 from the decays $K_L^0 \to \gamma\gamma$, $K_L^0 \to e^+e^-\gamma$, and $K_L^0 \to e^+e^-e^+e^-$ (10 ± 2 events) agrees well with that observed (11 are seen).

Approximately half of the events in Fig. 2 are eliminated by requiring the events to have oppositely charged particles and requiring that no extra track project to within 1 cm of the event vertex. The minimum criterion for an extra track is that it have hits in both views of the first two drift chamber planes. The loss of real events due to the extra track cut was estimated to be 0.8% for both $K_L^0 \to e^+e^-$ and $K_L^0 \to \pi^+\pi^-$ events, based on measurements using $K_L^0 \to \pi^{\pm}e^{\mp}\nu$ events.

Figure 3 is a scatter plot of θ_K^2 vs M_{ee} for events from both data sets which pass all selection criteria described above. Events in this plot are classified as $K_L^0 \to e^+e^-$ if they have $\theta_K^2 < 2.0$ mrad^2 and a mass within 6.0 MeV/c^2 of the K_L^0 mass. The values of the cuts on θ_K^2 and M_{ee} were chosen to minimize the probability of including background events in the signal region while maintaining good acceptance. The value chosen for the mass cut corresponds to approximately 3σ in the resolution. The collinearity cut was left at 2 mrad^2, as tightening this cut was expected to have little effect on backgrounds. Monte Carlo calculations of the background sources described above predict that we should see fewer than 0.15 event in the signal region of Fig. 3. No events satisfy these criteria.

In the decay $K_L^0 \to e^+e^-$, the invariant mass of the e^+e^- pair can be reduced if a photon is radiated via the inner bremsstrahlung (IB) process. Therefore, the signal region is restricted to events in which the energy of the radiated photon is less than 6 MeV. Events with radiated photons of greater energy account for 17% of the total IB-corrected $K_L^0 \to e^+e^-$ rate [18]. We do not apply a correction to account for this effective loss in acceptance. A negligible fraction of the IB-corrected rate fails the collinearity cut exclusively.

Based on our observation of no signal events, we determine a 90% C.L. upper limit on the $K_L^0 \to e^+e^-$ branch-

TABLE I. Factors entering into the calculation of the $K_L^0 \to e^+e^-$ limit for the 1989 and 1990 data sets.

Variable	1989	1990
$N_{\pi\pi}$	$15\,118 \pm 151$	$31\,354 \pm 217$
R	6000	4000
$A_{\pi\pi}/A_{ee}$	1.78 ± 0.01	1.69 ± 0.01
$\epsilon_{\pi\pi}$	0.954 ± 0.004	0.954 ± 0.004
ϵ_{ee}	0.733 ± 0.009	0.775 ± 0.007
$\epsilon_{\pi\pi}^{L3}/\epsilon_{ee}^{L3}$	1.00 ± 0.01	1.01 ± 0.01

ing ratio by evaluation of the following expression:

$$B(K_L^0 \to e^+e^-) \leq 2.3 \frac{B(K_L^0 \to \pi^+\pi^-)}{RN_{\pi\pi}} \frac{A_{\pi\pi}}{A_{ee}} \frac{\epsilon_{\pi\pi}}{\epsilon_{ee}} \frac{\epsilon_{\pi\pi}^{L3}}{\epsilon_{ee}^{L3}}.$$

$N_{\pi\pi}$ is the number of detected $K_L^0 \to \pi^+\pi^-$ events, after the prescale factor R. The branching ratio $B(K_L^0 \to \pi^+\pi^-) = (2.03 \pm 0.04) \times 10^{-3}$ [19]. The ratio of $K_L^0 \to \pi^+\pi^-$ to $K_L^0 \to e^+e^-$ acceptances $A_{\pi\pi}/A_{ee}$ was determined from a Monte Carlo simulation of the detector. The correction for pion loss due to interactions in the spectrometer and TSC is $\epsilon_{\pi\pi}$; this was obtained by analysis of specially triggered data. The efficiency for identifying electrons has been measured using K_{e3} decays in our minimum bias sample. From this the $K_L^0 \to e^+e^-$ particle identification efficiency ϵ_{ee} was derived. Finally, $\epsilon_{\pi\pi}^{L3}/\epsilon_{ee}^{L3}$ is the ratio of efficiencies of the $L3$ trigger for the $\pi^+\pi^-$ and e^+e^- modes. The values of these parameters are given in Table I for the two data sets. The uncertainty in the relative acceptance and efficiencies for the $K_L^0 \to \pi^+\pi^-$ and $K_L^0 \to e^+e^-$ decay modes is less than 5%; this has a negligible effect on the limit quoted [7,20].

We place 90% C.L. upper limits on the branching ratio for the process $K_L^0 \to e^+e^-$ of $B(K_L^0 \to e^+e^-) < 11.9 \times 10^{-11}$ (1989) and $B(K_L^0 \to e^+e^-) < 7.8 \times 10^{-11}$ (1990). These limits include events with less than 6 MeV of radiated energy. These new results, combined with our previous limit [5], give $B(K_L^0 \to e^+e^-, |M_K - M_{ee}| < 6\ \mathrm{MeV}/c^2) < 4.1 \times 10^{-11}$ at 90% C.L. This is consistent with the predictions of the standard model.

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[a] Present address: Measurex Corp., Cupertino, CA 95014.
[b] Present address: Rutgers University, Piscataway, NJ 08855.
[c] Present address: McGill University, Montreal, Canada.
[d] Present address: CERN CH-1211 Geneva 23, Switzerland.
[e] Present address: University of New Mexico, Albuquerque, NM 87444.
[f] Present address: SSCL, Dallas, Texas 75237.
[g] Present address: Colorado University, Boulder, CO 80309.
[h] Present address: Cornell University, Ithaca, NY 14853.
[i] Present address: University of California, Riverside, CA 92521.
[j] Present address: CEBAF, Newport News, VA 23606.
[k] Present address: Office of Sen. Domenici, Washington, DC 20510.
[l] Present address: SLAC, Stanford, CA 94309.
[m] Present address: BNL, Upton, NY 11973.
[n] Present address: Intermetrics, Warminster, PA 18974.
[o] Present address: Harvard University, Cambridge, MA 02138.
[p] Present address: University of Texas, Austin, TX 78712.
[q] Present address: LANL, Los Alamos, NM 87545.
[r] Present address: Rockefeller University, New York, NY 10021.
[s] Present address: College of William and Mary, Williamsburg, VA 23187.
[t] Present address: Princeton University, Princeton, NJ 08544.
[u] Present address: University of California at San Diego, La Jolla, CA 92093.
[v] Present address: CalTech, Pasadena, CA 91125.
[w] Present address: University of Chicago, Chicago, IL 60637.
[x] Present address: MCI Comm. Corp., McLean, VA 22102.
[y] Deceased.

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