Measurement of the Branching Ratio of $\pi^0 \to e^+e^-$ from π^0's Produced by $K_L \to \pi^0\pi^0\pi^0$ Decays in Flight

K. S. McFarland, R. A. Briere, E. Cheu, D. A. Harris, G. Makoff, A. Roodman, B. Schwingenheuer, S. V. Somalwar,* Y. W. Wah, B. Winstein, and R. Winston
The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637

K. Arisaka, D. Roberts, W. Slater, and M. Weaver
University of California at Los Angeles, Los Angeles, California 90024

A. R. Barker
University of Colorado, Boulder, Colorado 80309

E. C. Swallow
Elmhurst College, Elmhurst, Illinois 60126
and The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637

G. J. Bock, R. Coleman, M. Crisler, J. Enagonio, R. Ford, Y. B. Hsiung, D. A. Jensen, E. Ramberg, and R. Tschirhart
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

E. M. Collins and G. D. Gollin
University of Illinois, Urbana, Illinois 61801

T. Nakaya and T. Yamanaka
Department of Physics, Osaka University, Toyonaka, Osaka, 560 Japan

P. Gu, P. Haas, W. P. Hogan, S. K. Kim,† J. N. Matthews, S. S. Myung,† S. Schnetzer, G. B. Thomson, and Y. Zou
Rutgers University, Piscataway, New Jersey 08855

(Received 22 February 1993)

The Fermilab E799 Collaboration has carried out a search for the rare decay $\pi^0 \to e^+e^-$ using π^0's produced from $K_L \to \pi^0\pi^0\pi^0$ decays in flight. We observe a signal of nine events with an e^+e^- mass close to the π^0 mass where only one event is predicted from other known processes. From this, we measure $B(\pi^0 \to e^+e^-, (m_{ee}/m_{\pi^0})^2 > 0.95) = [7.6^{+3.9}_{-2.8}\,(\text{stat}) \pm 0.5\,(\text{syst})] \times 10^{-8}$, over and above the contribution from π^0 Dalitz decays. Correcting for radiative effects, we find this result consistent with theoretical expectations from standard-model processes.

PACS numbers: 13.20.Cz, 13.40.Hq, 14.40.Aq

First calculated by Drell [1] in 1959, the rate for the rare decay $\pi^0 \to e^+e^-$ has been of considerable theoretical interest. In the standard model, this decay proceeds dominantly through the electromagnetic interaction, and is suppressed relative to $\pi^0 \to \gamma\gamma$ by two powers of α and by a factor of $(m_e/m_{\pi^0})^2$ from helicity suppression due to the vector nature of the interaction. The contribution to the rate proceeding through the intermediate state with two on-shell photons is easily calculated in QED and leads to a branching ratio prediction of 4.75×10^{-8}, not including radiative corrections. This contribution to $\pi^0 \to e^+e^-$ is a lower bound for the branching ratio, the so-called "unitarity limit." Model-dependent calculations that include contributions from off-shell photons predict branching ratios between 6×10^{-8} and 7×10^{-8} [2,3], again neglecting radiative effects. A significantly higher observed branching ratio could be a signature of non-standard-model processes such as interactions mediated by other pseudoscalar bosons like the axion [4], or leptoquark interactions [5].

Experimental studies of this decay have produced widely varying results. Fischer *et al.* [6] used π^0's from $K^+ \to \pi^+\pi^0$ decays in flight to search for $\pi^0 \to e^+e^-$ and measured the branching ratio to be $(2.23^{+2.4}_{-1.1}) \times 10^{-7}$ (90% confidence errors). Frank *et al.* [7] used a π^- beam to produce π^0's in a target through the reaction $\pi^- p \to n\pi^0$ and found a branching ratio consistent with that of the Fischer *et al.* measurement, $[1.7 \pm 0.6\,(\text{stat}) \pm 0.3\,(\text{syst})] \times 10^{-7}$. These two measurements suggest that the branching ratio is well above both the unitarity limit and standard-model predictions which could indicate contributions from non-standard-model effects. However, a recent experiment from the SINDRUM collaboration [8], using stopped π^-'s in a target to produce π^0's via charge-exchange and detecting the final state neutron, has placed an upper limit on the branching ratio of 1.3×10^{-7} at 90% confidence, which excludes the high central values of the earlier experiments.

This paper gives the first result to be published from Fermilab E799, a rare K_L decay experiment. In E799, two parallel K_L beams were produced by interactions of 800 GeV protons from the Fermilab Tevatron in a Be tar-

0031-9007/93/71(1)/31(4)$06.00

get 120 m from the detector. The search for $\pi^0 \to e^+e^-$ uses π^0's from the decay $K_L \to \pi^0\pi^0\pi^0$ where both the parent K_L and π^0 decays are fully reconstructed. This new technique has considerable advantages over those of previous experiments. First, there is no significant background from the continuum e^+e^- production process, $K_L \to \pi^0\pi^0e^+e^-$, analogous to the backgrounds from $K^+ \to \pi^+e^+e^-$ and $\pi^-p \to ne^+e^-$ which are present in the K^+ decay and charge-exchange production experiments, respectively. Second, because the π^0's are produced in flight, there is minimal material in the path of the decay products. This results in low photon conversion probability $[(0.32\pm0.02)\%]$ and improved e^+e^- mass resolution, which further reduces potential backgrounds. Because of these two factors, E799 can make this measurement in a relatively low background environment.

The E799 detector, shown in Fig. 1, emphasized both charged particle momentum resolution and photon calorimetry, and has been used previously for high statistics studies of $K_L \to \pi^0\pi^0\pi^0$ decays [9]. Descriptions of the detector can be found elsewhere [10], so only the elements most important to the $\pi^0 \to e^+e^-$ analysis will be described here in detail. For charged particle reconstruction, a spectrometer consisting of four drift chambers and an analyzing magnet with a transverse momentum kick of 200 MeV/c was used. The single hit resolution in the drift chambers was approximately 100 μm, and the observed momentum resolution was $(\sigma_p/p)^2 = (5\times10^{-3})^2 + \{1.4\times10^{-4}(p\ [\mathrm{GeV}/c])\}^2$, where the first contribution was due to multiple scattering in material inside the spectrometer, and the second was from the chamber resolution. For $\pi^0 \to e^+e^-$ decays, the mean electron momentum was about 15 GeV, so the multiple-scattering term typically dominated the resolution. To detect photons and electromagnetic showers from charged particles, a calorimeter made of 804 lead-glass blocks, $(5.8\ \mathrm{cm})^2 \times 18.7$ radiation-lengths deep, was employed. In the experiment, calorimeter resolution was somewhat degraded because of the high-rate environment and substantial radiation damage. The average electron energy resolution, σ_E/E, was 4.4%.

E799 took a variety of triggers designed to accept many different K_L decays. For this analysis, candidate events were selected on-line using a trigger which accepted events with two electrons and at least two photons. In order to satisfy the fast trigger, events were required to leave at least 55 GeV in the calorimeter and have two hits in each of two scintillator banks directly upstream of the lead glass. In addition, there were counters in veto to reject events with charged particles escaping the detector fiducial region, events with photons or electrons pointing down the beam holes of the lead glass, and events with hadron showers in the calorimeter. Hardware processors required at least four clusters of energy above 2.5 GeV in the lead glass and sufficient hits in the drift chambers to be consistent with two tracks.

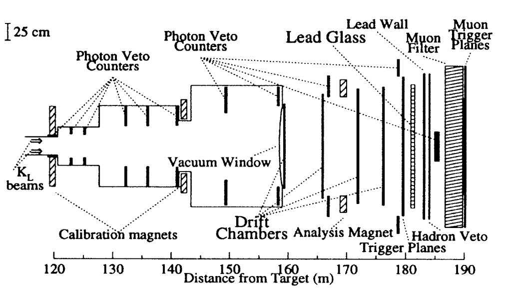

FIG. 1. The E799 detector.

Off-line, events were selected by first locating tracks in the drift chambers. If these tracks pointed to clusters of energy in the calorimeter, and the track momentum and calorimeter energy matched to within 15%, these tracks were identified as electron candidates. For the $\pi^0 \to e^+e^-$ signal, two electron candidates and four photon candidates in the calorimeter were required in order to reconstruct the parent $K_L \to \pi^0\pi^0\pi^0$ decay. Using the charged tracks to locate the decay vertex, various kinematic quantities could then be calculated. A Monte Carlo simulation of the detector was then used to choose cuts applied to these quantities. The total observed mass was required to be within 41 MeV/c^2 (2.9σ) of the K_L mass, and the total observed momentum transverse to the parent kaon direction was restricted to be less than 32 MeV/c (2.3σ). The four photons in the calorimeter were also required to be consistent above the 1% confidence level with being the decay products of two π^0's. Most important for background rejection was the cut placed on the e^+e^- mass which was required to be within 4.5 MeV/c^2 of the π^0 mass, a 2.5σ cut. In addition, events with signals in the photon veto counters, which indicate a photon escaping the lead glass fiducial region, were removed from the event sample, as were events found to have extra clusters of energy in the calorimeter above a threshold of approximately 500 MeV. All clusters in the lead glass were required to have a shape consistent with a single electromagnetic shower. Finally, a cut of 2.5 GeV was placed on electromagnetic energy in a lead-Lucite veto counter behind the lead glass beam holes in order to veto events with photons pointing down the beam holes.

The two important backgrounds to this measurement of $\pi^0 \to e^+e^-$ are the π^0 Dalitz decay ($\pi^0 \to e^+e^-\gamma$) and processes producing four electrons in the final state. In the case of the Dalitz background, the e^+e^- mass spectrum of these decays strongly favors low e^+e^- mass, and only one in 1.4×10^6 decays will satisfy our e^+e^- mass cut. The e^+e^- mass spectrum for Dalitz decays is checked by looking at a sample of fully reconstructed $K_L \to \pi^0\pi^0\pi^0$, $\pi^0 \to e^+e^-\gamma$ (Fig. 2), and is well modeled by the detector simulation. The prediction of the Monte Carlo simulation was used to subtract 0.85 ± 0.08(stat) events background from Dalitz decays where the photon is not observed. The four-electron backgrounds result

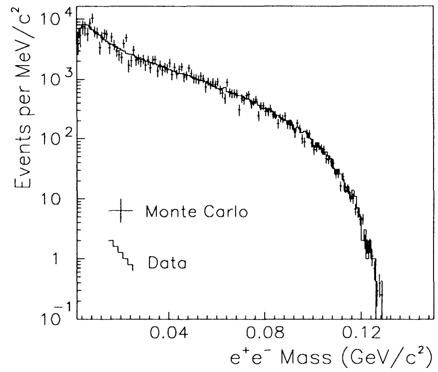

FIG. 2. The e^+e^- invariant mass of fully reconstructed $K_L \to \pi^0\pi^0\pi^0$, $\pi^0 \to e^+e^-\gamma$ events in the data and Monte Carlo simulation.

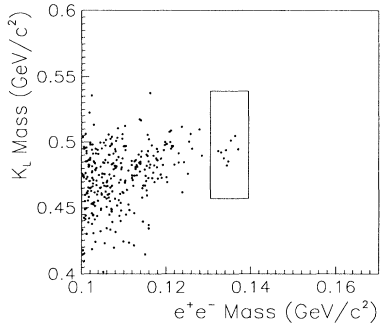

FIG. 3. The total $\pi^0\pi^0e^+e^-$ invariant mass versus the e^+e^- mass of $\pi^0 \to e^+e^-$ candidates. The box indicates the signal region chosen in the analysis. Events outside the signal region are from $\pi^0 \to e^+e^-\gamma$ decays, where the photon is missed.

from processes involving two distinct internal or external photon conversions in which one electron from each of the low-mass e^+e^- conversion pairs is lost, leaving a potentially high-mass "pair." Because such processes can produce e^+e^- pairs with masses at or above the π^0 mass, these backgrounds are potentially problematic. However, four-electron events were effectively rejected by searching for the extra hits from the lost electrons in the drift chamber just upstream of the analysis magnet. Before such a cut, these backgrounds contribute approximately 50 events to the signal region; after the cut, a Monte Carlo sample with 8 times the data statistics has a single event in the signal region. Thus, a total of $0.97^{+0.28}_{-0.12}$ events background are predicted in the Monte Carlo simulation. The possibility of additional nonsimulated backgrounds, such as those from hadronic final states, was studied by looking in the data at sidebands of high transverse momentum and high e^+e^- mass. No events were observed in these sidebands, so an upper limit on these backgrounds of 0.26 events at the 90% confidence level was included in the systematic error. After all cuts, nine events were observed in the data (Fig. 3), well above the number predicted from background processes. A comparison of the data and background Monte Carlo simulation is shown in Fig. 4.

To extract the branching ratio, a 10 039 event sample of fully reconstructed $K_L \to \pi^0\pi^0\pi^0$, $\pi^0 \to e^+e^-\gamma$ decays with an e^+e^- invariant mass greater than 70 MeV/c^2 was examined in parallel with the signal events using similar analysis cuts. This e^+e^- mass cut in the normalization sample not only rejects background from external photon conversions, but also produces a sample kinematically similar to the $\pi^0 \to e^+e^-$ decays and with a comparable detector illumination. However, the high e^+e^- mass portion of the Dalitz decay spectrum is sensitive to radiative corrections and the π^0 form factor. To treat the radiative corrections to Dalitz decay, both the normalization and background Monte Carlo simulation included the PHOTOS Monte Carlo package [11] which uses an approximation of $O(\alpha)$ radiative effects to simulate bremsstrahlung. The results of this simulation were tested by comparing to an analytic calculation [12], and the small residual disagreements did not contribute significantly to the systematic error. This radiative correction resulted in a $(5.5 \pm 1.8)\%$ decrease in the acceptance for the normalization sample. To treat the π^0 form-factor slope, a result from the CELLO collaboration [13] of a (0.0326 ± 0.0026) slope extracted from a fit to data from the two-photon process $e^+e^- \to \pi^0e^+e^-$ was used. However, this measurement was made in a kinematic region different from that probed by Dalitz decays, and the results from Dalitz decay spectra are controversial [14]. To account for this uncertainty, shifts of ± 0.1 were added to the form-factor slope to evaluate systematic effects in the normalization and background. Finally, from the acceptance determined in Monte Carlo simulation, the number of $K_L \to \pi^0\pi^0\pi^0$ decays with a K_L energy between 35 and 220 GeV and with a decay vertex between 90 and 160 m from our target was determined to

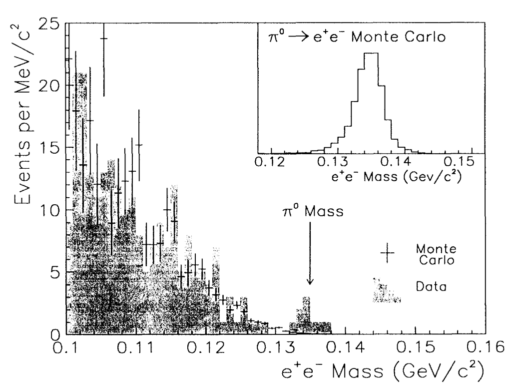

FIG. 4. The e^+e^- mass of $\pi^0 \to e^+e^-$ candidates and the background Monte Carlo prediction. There are no events in the data with an e^+e^- mass above 140 MeV/c^2. The inlaid plot shows the Monte Carlo prediction for $\pi^0 \to e^+e^-$, including radiative effects.

be $[4.95 \pm 0.08(\text{stat})] \times 10^9$.

It is important in this analysis to consider the radiative corrections to $\pi^0 \to e^+e^-$. While the correction to the total rate has been shown to be only a few percent [15], emission of a bremsstrahlung photon lowers the e^+e^- invariant mass, giving rise to a nontrivial e^+e^- mass spectrum. Because of the presence of Dalitz decays, we quote the branching ratio for $\pi^0 \to e^+e^-$ where $(m_{ee}/m_{\pi^0})^2 > 0.95$, over and above the small contribution from Dalitz decays. In our $\pi^0 \to e^+e^-$ Monte Carlo simulation, the $O(\alpha)$ radiative corrections are based on the work of Bergström [15], which assumes a pointlike $\pi^0 e^+e^-$ coupling independent of m_{ee}. Interference between π^0 Dalitz decay and e^+e^- decay with bremsstrahlung is small in the m_{ee} region considered here, and is ignored. The acceptance for fully reconstructing $K_L \to \pi^0\pi^0\pi^0$, $\pi^0 \to e^+e^-$, $(m_{ee}/m_{\pi^0})^2 > 0.95$, is $(0.71 \pm 0.01)\%$. Combining this with the number of $K_L \to \pi^0\pi^0\pi^0$ decays given above, the single-event sensitivity is $[0.95 \pm 0.02\,(\text{stat})] \times 10^{-8}$.

We also use our simulation to extract the rate for $\pi^0 \to e^+e^-$ in the absence of radiative corrections. This rate, Γ^0_{ee}, when normalized by the total π^0 decay rate, Γ_{all}, is effectively the branching ratio in the absence of radiative effects. $\Gamma^0_{ee}/\Gamma_{\text{all}}$ is 16.1% larger [15] than the above branching ratio and should be used in comparisons to theoretical predictions that do not include radiative corrections.

The dominant systematic errors were from the previously discussed Dalitz decay form-factor slope uncertainty (4.9%) and limits on unsubtracted backgrounds (0.26 events). An additional important error is from uncertainty in the Dalitz decay branching ratio, $(1.198 \pm 0.032)\%$ [16]. Also considered were the effects of systematic uncertainties in the understanding of the calorimeter, such as the effect of varying the energy scales, lead-glass gains and pedestals, and the effects of momentum scale and resolution uncertainties in the charged spectrometer; the total systematic error from these sources is 2.1%. Finally, the change in the extracted flux from varying the e^+e^- mass cut in the normalization sample contributes a 1.9% systematic error. All sources of error were added in quadrature to obtain the final systematic error.

Our final result for the branching ratio of $\pi^0 \to e^+e^-$, $(m_{ee}/m_{\pi^0})^2 > 0.95$ is $[7.6^{+3.9}_{-2.8}\,(\text{stat}) \pm 0.5\,(\text{syst})] \times 10^{-8}$, based on eight signal events and one background event. For comparison with theoretical predictions which do not include radiative corrections, we extract the $\pi^0 \to e^+e^-$ rate in the absence of radiative effects, $\Gamma^0_{ee}/\Gamma_{\text{all}} = [8.8^{+4.5}_{-3.2}\,(\text{stat}) \pm 0.6\,(\text{syst})] \times 10^{-8}$. This result is consistent with standard-model predictions and helps limit possible exotic contributions to this decay. Given that this result is limited by statistics rather than systematics, future runs of planned high-intensity K_L decay experiments at Fermilab (E799, phase II) should be able to make significant improvements on this measurement.

Support was provided for this experiment by NSF and DOE. We would like to acknowledge contributions to this research from Gene Beck, John Krider, John Quackenbush, Harold Sanders, Peter Shawhan, Amy Wilson, the Fermilab computing department, and the Fermilab accelerator division. One of us (K.S.M.) wishes to acknowledge a graduate fellowship from NSF, and another of us (Y.W.W.) would like to acknowledge support from an O.J.I. grant from DOE. A.R.B. and E.C. would like to acknowledge support from McCormick Fellowships while at The University of Chicago. Finally, another of us (B.S.) receives support from the Daimler-Benz Stiftung.

* Present address: Rutgers University, Piscataway, New Jersey 08855.

† Present address: Seoul National University, Seoul 151-742, Korea.

[1] S.D. Drell, Nuovo Cimento **11**, 693 (1959).
[2] L.G. Landsberg, Phys. Rep. **128**, 301 (1985).
[3] L. Bergström *et al.*, Phys. Lett. **126B**, 117 (1983).
[4] E. Massó, Phys. Lett. B **181**, 388 (1986).
[5] J. Pati and A. Salam, Phys. Rev. D **11**, 1137 (1975).
[6] J. Fischer *et al.*, Phys. Lett. **73B**, 364 (1978).
[7] J.S. Frank *et al.*, Phys. Rev. D **28**, 423 (1983).
[8] C. Niebuhr *et al.*, Phys. Rev. D **40**, 2797 (1989).
[9] S. Somalwar *et al.*, Phys. Rev. Lett. **68**, 2580 (1992).
[10] K.S. McFarland, Ph.D. thesis, University of Chicago, 1993 (unpublished). The E799 detector was originally used in experiment E731. Descriptions of the E731 detector can be found in L. Gibbons *et al.*, Phys. Rev. Lett. **70**, 1199 (1993); J.R. Patterson, Ph.D. thesis, University of Chicago, 1990 (unpublished).
[11] E. Barberio *et al.*, Comput. Phys. Commun. **66**, 115 (1991).
[12] K.O. Mikaelian and J. Smith, Phys. Rev. D **5**, 1763 (1972).
[13] H.J. Behrend *et al.*, Z. Phys. C **49**, 401 (1991).
[14] The four most significant measurements of the π^0 form-factor slope from Dalitz decay [J. Fischer *et al.*, Phys. Lett. **73B**, 359 (1978); H. Fonvieille *et al.*, Phys. Lett. B **233**, 65 (1989); R.M. Drees *et al.*, Phys. Rev. D **45**, 1439 (1992); F. Farzanpay *et al.*, Phys. Lett. B **278**, 413 (1992).] have central values ranging from -0.10 to $+0.11$. However, the weighted average of these measurements, dominated by Drees *et al.* is in agreement with the CELLO result.
[15] L. Bergström, Z. Phys. C **20**, 135 (1983).
[16] Particle Data Group, K. Hikasa *et al.*, Phys. Rev. D **45**, S1 (1992).