Measurement of the branching ratio of $\pi^0 \to e^+e^-$ using $K_L \to 3\pi^0$ decays in flight

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The branching ratio of the rare decay $\pi^0 \to e^+e^-$ has been measured in E799-II, a rare kaon decay experiment using the KTeV detector at Fermilab. We observed 275 candidate $\pi^0 \to e^+e^-$ events, with an expected background of 21.4 ± 6.2 events which includes the contribution from Dalitz decays. We measured $\mathrm{BR}\left(\pi^0 \to e^+e^-, (m_{e^+e^-}/m_{\pi^0})^2 > 0.95\right) = (6.09 \pm 0.40 \pm 0.24) \times 10^{-8}$, where the first error is statistical and the second systematic. This result is the first significant observation of the excess rate for this decay above the unitarity lower bound.

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The decay $\pi^0 \to e^+e^-$ has received much experimental and theoretical attention since its branching ratio was first calculated by Drell in 1959 [1]. Within the Standard Model, this decay proceeds predominantly through a two-photon intermediate state, at a rate less than 10^{-7} that of $\pi^0 \to \gamma\gamma$. Relative to $\pi^0 \to \gamma\gamma$, $\pi^0 \to e^+e^-$ is suppressed by a helicity factor $(2m_e/m_{\pi^0})^2$ as well as by two orders of $\alpha_{\rm EM}$. The contribution to the decay from on-shell internal photons has been calculated exactly in QED [2], and forms the "unitarity bound," a lower limit on the branching ratio which is $\mathrm{BR}(\pi^0 \to e^+e^-) \geq 4.69 \times 10^{-8}$, ignoring final-state radiative effects. The contribution from off-shell photons depends on the $\pi^0\gamma^*\gamma^*$ form factor, and is model-dependent. Recent vector meson dominance [3] and chiral perturbation theory [4,5] calculations predict this contribution to be somewhat smaller than that from on-shell photons, giving a total branching ratio of $(6-9) \times 10^{-8}$, ignoring radiative corrections.

Earlier experiments have produced conflicting measurements of the branching ratio for this mode. The earliest measurements of $\pi^0 \to e^+e^-$ were performed by a Geneva-Saclay group in 1978 [6] using π^0's produced by the decay $K^+ \to \pi^+\pi^0$ in flight, and by a LAMPF group in 1983 [7] using the charge-exchange process $\pi^-p \to \pi^0 n$ from a 300 MeV/c pion beam. Both experiments favored a branching ratio of $\sim 2 \times 10^{-7}$, which would be hard to accomodate within the Standard Model. A 1989 search by the SINDRUM collaboration [8], using stopped $\pi^-p \to \pi^0 n$, produced a 90% confidence level upper limit of 1.3×10^{-7}, excluding the central values of both previous measurements. In 1993, BNL E851 [9] and FNAL E799-I [10] observed the decay at the $(5-10) \times 10^{-8}$ level, near the Standard Model expectation. The BNL measurement used $K^+ \to \pi^+\pi^0$ decays, while the FNAL experiment used $K_L \to 3\pi^0$ decays.

In this Letter we present a new, precision measurement of $\mathrm{BR}(\pi^0 \to e^+e^-)$ from E799-II, a rare K_L decay experiment which took data in 1997 at Fermilab. The π^0's were produced using $K_L \to 3\pi^0$ decays in flight, where the other two π^0's in the event decayed to $\gamma\gamma$. The $\pi^0 \to e^+e^-$ events were normalized to Dalitz decays ($\pi^0 \to e^+e^-\gamma$) with $m_{e^+e^-} >$ 65 MeV/c^2, which were collected and analyzed simultaneously. High-$m_{e^+e^-}$ events were used in order to keep the charged track kinematic variables as similar as possible for the signal and normalization modes, and thus cancel many detector-related systematic errors.

This technique, which was adapted from E799-I, has significant advantages over those used in other measurements. The π^0's were produced and decayed in vacuum, eliminating backgrounds and resolution smearing from decay products scattering or converting in charge-exchange targets. The continuum process $K_L \to \pi^0\pi^0e^+e^-$ has never been observed and does not pose a significant background. By contrast, the analogous processes in K^+ experiments ($K^+ \to \pi^+e^+e^-$) and charge-exchange experiments ($\pi^-p \to e^+e^-X$) both produce large backgrounds to $\pi^0 \to e^+e^-$. Reconstruction of the full kaon decay provides redundant kinematic constraints, eliminating all non-$K_L \to 3\pi^0$ backgrounds.

The elements of the E799-II spectrometer (Fig. 1) relevant to this measurement are described below. Two nearly-parallel neutral kaon beams were produced by 800 GeV protons striking a 30 cm BeO target at a targeting angle of 4.8 mrad. Two neutral beams, each one up to 0.35 μsr, were defined by collimators. A Pb absorber converted photons in the beam, and charged particles were removed by a series of sweeping magnets. A 65 m evacuated decay region ended at a Mylar-Kevlar vacuum window 159 m from the target. The beams in the decay region were composed mostly of neutrons and K_L, with small numbers of K_S, Λ^0, $\bar{\Lambda}^0$, Ξ^0, $\bar{\Xi}^0$. These short-lived particles tended to decay upstream. The K_L momentum ranged from ~ 20 to ~ 200 GeV/c.

Charged particles were tracked using four drift chambers with two orthogonal views; a dipole magnet downstream of the second chamber provided a transverse momentum kick of 205 MeV/c. Helium bags were placed between the chambers to reduce multiple scattering and photon conversions.

Photon energy measurement and electron identification were performed using a 3100-block pure CsI electromagnetic calorimeter. The photon energy resolution was $\sim$ 1%, averaged over the energy range typical of $\pi^0 \to e^+e^-$ events (2$-$60 GeV). Immediately upstream of the CsI, two overlapping banks of scintillation counters (the "trigger hodoscopes") provided fast signals for triggering on charged particles. Downstream of the calorimeter, a 10 cm lead wall followed by a scintillator plane formed a hadron veto which rejected at trigger level events with charged pions in the final state. An eleven-plane photon veto system, consisting of lead-scintillator counters throughout the decay region and spectrometer, detected particles which left the fiducial volume.

The trigger required at least 24 GeV of in-time energy in the CsI, and hits in the drift chambers and trigger hodoscopes consistent with at least two tracks. Events were rejected when more than 0.5 GeV was deposited in any photon veto counter, or more than the equivalent of 2.5 minimum ionizing particles were detected in the hadron veto. A hardware processor [11] required at least four energy clusters in the CsI, where a "cluster" was a set of contiguous blocks with at least 1 GeV deposited in each block.

Offline, events with exactly two reconstructed tracks were selected and the tracks were required to form a common vertex inside the decay region. They also had to be electron candidates, defined as tracks which pointed to a CsI cluster whose energy E was within $\pm$8% of the track momentum p. The reconstructed kaon energy was required to be at least 40 GeV, and each cluster in the CsI at least 1.5 GeV. These cuts reduced the dependence of the result on CsI trigger thresholds. Clusters without tracks pointing to them were assumed to be photons. $\pi^0 \to e^+e^-$ candidates were required to have four photons; $\pi^0 \to e^+e^-\gamma$ candidates were required to have five.

Photons were reconstructed assuming that each pair of photons came from a $\pi^0 \to \gamma\gamma$ decay. We calculated the distance $Z_{12} \equiv (r_{12}/m_{\pi^0})\sqrt{E_1E_2}$ of the decay from the CsI, where E_i is the energy of photon i and r_{ij} is the transverse separation of photons i and j at the CsI. For $\pi^0 \to e^+e^-$ candidates,

there were three possible pairings of the photons into two π^0's. The pairing was chosen which minimized the χ^2 for the hypothesis that the two π^0 decays occurred at the same position. For $\pi^0 \to e^+e^-\gamma$ candidates, there were fifteen pairings; the best was selected and the unpaired photon was assumed to have come from the $\pi^0 \to e^+e^-\gamma$ decay.

The photon four-momenta were calculated assuming the photons originated at the weighted average of the Z positions of the two π^0's and the transverse position of the reconstructed two-electron vertex. This reconstruction method allowed kinematic quantities to be calculated in nearly the same way for the signal and normalization modes, thereby canceling certain systematic errors.

The basic reconstruction cuts described below were applied, and the samples obtained were used to study acceptance and backgrounds. The total invariant mass $m_{\pi^0\pi^0e^+e^-}$ was required to be within 50 MeV/c^2 of the K_L mass. The total momentum transverse to the kaon direction was required to be less than 30 MeV/c. For the normalization sample, the Dalitz decay mass $m_{e^+e^-\gamma}$ was required to be within 30 MeV/c^2 of the π^0 mass, and the reconstructed electron pair mass $m_{e^+e^-} > 70$ MeV/c^2 in order to avoid systematic errors from mass resolution smearing near the 65 MeV/c^2 cutoff.

A detailed Monte Carlo (MC) simulation was used to estimate acceptance for the signal and normalization modes, as well as the level of backgrounds in the samples. Both the signal and normalization MC were implemented with radiative corrections.The $\pi^0 \to e^+e^-$ MC used the $\mathcal{O}(\alpha_{\rm EM})$ radiation model of Bergström [12] , and the $\pi^0 \to e^+e^-\gamma$ MC used an $\mathcal{O}(\alpha_{\rm EM}^2)$ calculation based on the work of Mikaelian and Smith [13].

At this stage, the sample in the $\pi^0 \to e^+e^-$ signal region ($0.132 < m_{e^+e^-} < 0.138$ GeV/c^2) was background-dominated. Fig. 2 shows the distribution of $m_{e^+e^-}$ for data and for the MC background predictions. The backgrounds, which all came from $K_L \to 3\pi^0$ decays, were as follows. Very high-$m_{e^+e^-}$ Dalitz decays ($\pi^0 \to e^+e^-\gamma$) could be misreconstructed as $\pi^0 \to e^+e^-$ if the photon was not detected and $m_{e^+e^-}$ was reconstructed slightly high (by 1-10 MeV). Another type of background came from decays with four electrons in the final state. When one electron of each sign was soft, the spectrometer magnet could sweep them out of the fiducial volume, leaving only two reconstructible tracks. The four electrons could come from $K_L \to 3\pi^0$ with multiple $\pi^0 \to e^+e^-\gamma$ decays, from a $\pi^0 \to e^+e^-e^+e^-$ decay, or from photon conversions in the $(3.55 \pm 0.17) \times 10^{-3}$ radiation length vacuum window assembly [14].

The four-electron backgrounds fell into two categories. 1) "Correctly paired" four-track backgrounds, where all four electrons came from the same π^0: these included i) $\pi^0 \to e^+e^-e^+e^-$ decays, ii) $\pi^0 \to e^+e^-\gamma$ where the photon from the Dalitz decay converted, iii) $3\pi^0 \to 6\gamma$ where two photons from the same π^0 converted. In correctly paired four-track events, the reconstructed $m_{e^+e^-}$ was generally below m_{π^0}, and $m_{\pi^0\pi^0e^+e^-}$ was slightly below m_{K_L}. 2) "Mispaired" four-track backgrounds, where the four electrons came from *different* π^0's: These included i) events where two π^0's decayed to $e^+e^-\gamma$, ii) $\pi^0 \to e^+e^-\gamma$ events where a photon from a different π^0 converted, iii) $3\pi^0 \to 6\gamma$ events where two photons from different π^0 decays converted. In these cases, because the two observed electrons did not come from the same π^0, the $m_{e^+e^-}$ distribution was nearly flat. Because the four photons were not from two $\pi^0 \to \gamma\gamma$ decays, the Z position and the photon four-momenta were misreconstructed, giving a flat $m_{\pi^0\pi^0e^+e^-}$ distribution as well.

Requiring the pairing χ^2 to be below 4.5 removed 88% of the mispaired four-track background at the cost of 10% of the signal. Tightening the total mass cut to $|m_{\pi^0\pi^0e^+e^-} - m_{K_L}| < 10$ MeV/c^2 removed a further 80% of the mispaired four-track background with negligible signal loss.

The correctly paired four-track background could not be reduced significantly with pairing or kinematic cuts. About 99% of these events, as well as 98% of the remaining mispaired four-track background and 8% of signal, were removed by cutting events with evidence of extra in-time tracks in the second drift chamber. The last three cuts were applied to both the signal and normalization samples.

After all cuts, the total background was dominated by high-mass Dalitz decays (18.1 $\pm$ 4.7 events). Smaller backgrounds came from correctly paired (2.8 $\pm$ 1.1 events) and mispaired (0.5 $\pm$ 0.5 events) four-track modes. The errors on the four-track backgrounds are from MC statistics; the error on the Dalitz background reflects MC statistics and a 20% systematic uncertainty in the MC prediction of the misreconstructed $m_{e^+e^-}$ tail. An (18 $\pm$ 5)% discrepancy was seen between the data and the MC prediction in the level of the low-$m_{e^+e^-}$ Dalitz background between $0.110 < m_{e^+e^-} < 0.125$ GeV/c^2 (Fig. 3). Perfect agreement in this region was not expected, as these events typically had an extra low-energy photon near the cluster energy threshold. Although the Dalitz decays which entered the signal sample had a much lower-energy photon and were therefore less sensitive to the modeling of the threshold in the MC, we have treated this discrepancy conservatively as an additional systematic error on the background. The final background estimate was therefore 21.4 $\pm$ 6.2 events.

Radiative corrections to $\pi^0 \to e^+e^-$ had a significant effect on the acceptance. Internal bremsstrahlung can produce a $e^+e^-\gamma$ final state with $m_{e^+e^-} < m_{\pi^0}$, indistinguishable from the tree-level Dalitz decay. Following the convention of Ref. [10], we imposed a cutoff $(m_{e^+e^-}/m_{\pi^0})^2 > 0.95$. We thus quote the branching ratio for this range only, after subtracting the small contribution from the Dalitz diagram. In this kinematic region, interference between the two processes is negligible [12].

The normalization data set contained 650 264 events, with negligible backgrounds. The acceptance for Dalitz decays with $m_{e^+e^-} > 65$ MeV/c^2 was 1.03%, for kaons which decayed between 90 and 160 m from the target and had momentum between 20 and 200 GeV. The acceptance for the signal mode was 2.52%.

In the data, 275 $\pi^0 \to e^+e^-$ candidate events were observed (Fig. 3). Subtracting the estimated background yielded

the total sample size of 253.6 ± 16.6 events (the error is statistical only).

The largest source of systematic error was the 2.7% uncertainty in the $\pi^0 \to e^+e^-\gamma$ branching ratio $(1.198 \pm 0.032) \times 10^{-2}$ [15]. In addition, the $m_{e^+e^-}$ cutoff in the normalization Dalitz decays introduced a dependence of the acceptance on the Dalitz decay form factor. The MC used the form factor slope of 0.033 ± 0.003 measured by the CELLO collaboration [16], which gives the result that the $m_{e^+e^-} > 65$ MeV/c^2 region contains 3.19% of all Dalitz decays. The CELLO measurement used the reaction $e^+e^- \to \pi^0 e^+e^-$ in a region of spacelike momentum transfer, extrapolating the slope to the kinematic region of the Dalitz decay assuming vector meson dominance. The most recent direct measurement from the Dalitz decay is consistent but less precise [17]. Using the CELLO form factor, the observed $m_{e^+e^-}$ distribution (Fig. 4) was consistent with the MC. The statistical precision of our fit was 0.007, which we have taken to be the uncertainty in the form factor; this translates into a 0.5% systematic error on our measurement of $\pi^0 \to e^+e^-$.

The Dalitz decay branching ratio and the background uncertainty dominated the systematic error. Smaller acceptance uncertainties included a 1.0% uncertainty in the efficiency of the pairing χ^2 cut and a 1.2% systematic error assigned to the efficiency of the $m_{e^+e^-\gamma}$ cut in the normalization sample. These errors were determined from resolution studies using fully-reconstructed Dalitz decays. Adding all the systematic errors in quadrature, we obtained a total systematic error of 4.0%. Our result for the branching ratio is $\mathrm{BR}\left(\pi^0 \to e^+e^-, (m_{e^+e^-}/m_{\pi^0})^2 > 0.95\right) = (6.09 \pm 0.40 \pm 0.24) \times 10^{-8}$, where the first error is statistical and the second systematic.

For comparison with the unitarity bound and with theoretical models which neglect final-state radiation, we can invert the radiative corrections and extrapolate our result to the "lowest-order" rate (what the branching ratio would be in the absence of final-state radiation). This yields $\frac{\Gamma^{\text{lowest order}}_{e^+e^-}}{\Gamma_{\text{all}}} = (7.04 \pm 0.46(\text{stat}) \pm 0.28(\text{syst})) \times 10^{-8}$, which is over four standard deviations above the unitarity bound. This result, which is in agreement with recent Standard Model predictions, represents the first statistically signficant observation of an excess above unitarity.

E799-II expects to accumulate 2 to 4 times more data in a 1999 run, which will allow a further refinement of this measurement. This result should provide constraints for predictions of related decay modes such as $\eta \to \mu^+\mu^-$ and $K_L \to \mu^+\mu^-$ [3–5,18], and we hope that future experiments will be able to test these predictions.

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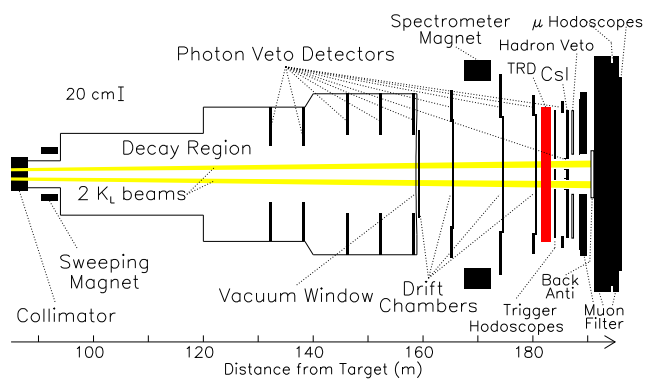

FIG. 1. Plan view of the KTeV spectrometer as configured for E799-II. The horizontal scale is compressed.

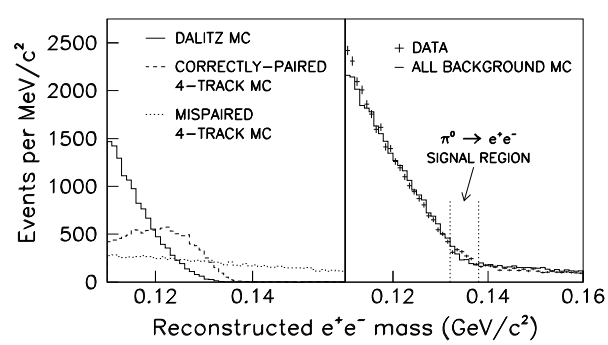

FIG. 2. Reconstructed $m_{e^+e^-}$ after basic reconstruction cuts. Left: background MC predictions. Right: E799-II data overlaid on sum of background predictions. (Backgrounds are normalized to the observed number of fully-reconstructed $\pi^0 \to e^+e^-\gamma$ decays.)

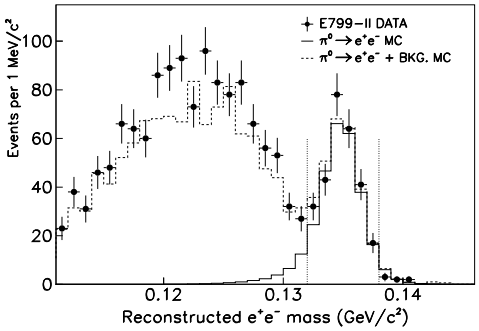

FIG. 3. Reconstructed $m_{e^+e^-}$ for data, background MC, and signal MC after all cuts. The vertical dotted lines indicate the defined signal region ($0.132 < m_{e^+e^-} < 0.138$ GeV/c^2).

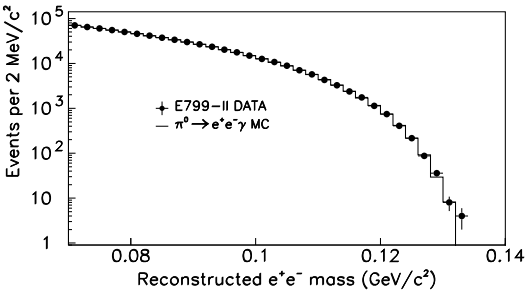

FIG. 4. Reconstructed $m_{e^+e^-}$ for normalization Dalitz decays.