Measurement of the *CP*-Violation Parameter Re(ε'/ε)

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(Received 18 January 1993)

A measurement of the *CP*-violation parameter Re(ε'/ε) has been made using the full E731 data set. We find Re(ε'/ε) $=(7.4\pm5.2\pm2.9)\times10^{-4}$ where the first error is statistical and the second systematic.

PACS numbers: 13.25.+m, 11.30.Er, 14.40.Aq

Since the discovery [1] of *CP* violation in K_L decays in 1964, all manifestations of *CP* violation have been consistent with time-asymmetric oscillations (parametrized by ε) between particle and antiparticle, in this case the neutral kaon. The standard Cabbibo-Kobayashi-Maskawa (CKM) model [2] can naturally accommodate *CP* violation but it also predicts direct *CP* violation (DCPV), wherein a particle of one *CP* eigenstate can decay directly to a final state of opposite *CP*. There are alternative theories, such as the "superweak" [3] model, so it is important to refine searches for DCPV. While strong evidence [4] for DCPV in 2π decays of the neutral kaon was given in 1988, our collaboration gave a result [5] in 1990 based upon a 20% data set consistent with no DCPV. The result from the entire data set is presented in this paper [6], including a complete reanalysis of the earlier sample. This new result uses an enlarged fiducial region for the $K_L\to2\pi$ decays. Extensive improvements in the understanding of the detector allow a factor of 2 reduction in the systematic error.

The presence of DCPV, parametrized by ε', would shift the ratio of *CP*-violating to *CP*-conserving $\pi\pi$ decay amplitudes, η, of the charged relative to the neutral final state. Thus the following double ratio of rates would differ from unity:

$$\frac{|\eta_{+-}^2|}{|\eta_{00}^2|}=\frac{|\varepsilon+\varepsilon'|^2}{|\varepsilon-2\varepsilon'|^2}=\frac{\Gamma(K_L\to\pi^+\pi^-)/\Gamma(K_S\to\pi^+\pi^-)}{\Gamma(K_L\to\pi^0\pi^0)/\Gamma(K_S\to\pi^0\pi^0)}$$
$$\approx1+6\,\mathrm{Re}(\varepsilon'/\varepsilon)\,.$$

In the CKM model, the expected [7] level for Re(ε'/ε) is of order 0.001.

To minimize systematics, K_L and K_S decays to either the neutral or charged final state were collected simultaneously [8]. The experiment used two parallel kaon beams, one pure K_L and one with K_S produced by coherent regeneration. Producing K_S this way gives K_L and K_S beams with identical spatial and similar momentum distributions. Because the decays from the two beams are collected simultaneously, the ratio of rates in the two beams is largely insensitive to accidental activity and to changes in detector or accelerator performance on any time scale during the run. However, the difference in the K_S and K_L lifetimes requires that the detector acceptance as a function of decay vertex be well understood. Many K_L decays to the $\pi e\nu$ ($Ke3$) and $3\pi^0$ final states were collected to aid in the acceptance determination.

Detailed descriptions of the detector and of reconstruction techniques can be found in the preceding paper [9] and other publications [5,10–12]. We give the essentials here. To reconstruct the $\pi^+\pi^-$ decays, tracks measured with a drift chamber spectrometer were used to determine the $\pi^+\pi^-$ momenta, mass, and decay vertex. For $\pi^0\pi^0$ decays, the energies and positions of the four photons were measured with an 804 block lead glass calorimeter. The best pairing of photons into two pions gave the kaon decay position and the $\pi^0\pi^0$ mass. A trigger plane, including a 0.5 mm Pb sheet in the first 60% of the $\pi^0\pi^0$ data, was located near the center of our neutral fiducial volume. It is important that the event trigger, reconstruction, and selection criteria were *independent* of the beam from which the kaon decayed.

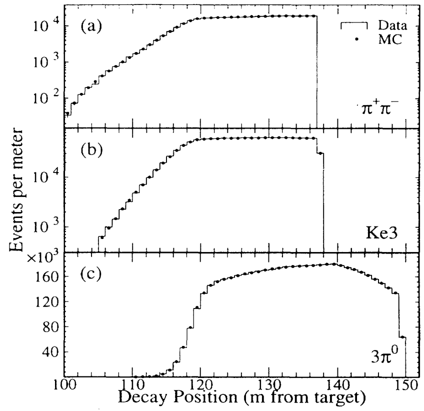

FIG. 1. Reconstructed K_L event vertex distributions for (a) $\pi^+\pi^-$ (full sample); (b) $Ke3$; and (c) $3\pi^0$. The $\pi^+\pi^-$ MC distribution is 25 times the data. The $\pi^0\pi^0\pi^0$ and $Ke3$ distributions have MC samples roughly equal to the data subsets of a few million events. The acceptance falloff for upstream decays is due to a precision photon veto counter at 122 m. The overlays all have acceptable χ^2.

A highly detailed Monte Carlo (MC) simulation was used for the acceptance determination as well as for simulation of the backgrounds. The transverse positions of the few apertures determining the acceptance were measured with the $Ke3$ sample to better than 50 μm; in the worst case a 1 mm uncertainty leads to less than a 0.5% change in the K_L/K_S ratio. The full nonlinear response of the calorimeter was modeled. Figure 1 displays the agreement between the data and MC K_L vertex distributions for the modes with very small backgrounds: $\pi^+\pi^-$, $Ke3$, and $3\pi^0$.

For $\pi^+\pi^-$ candidates, semileptonic decays were rejected using the ratio of shower energy to track momentum ($Ke3s$) and a hodoscope following a 3.2 m steel μ filter ($K\mu3s$). Demanding that the kaon transverse momentum satisfy $p_t^2 < 250$ MeV$^2/c^2$ limited the background in the vacuum beam to $0.316\% \pm 0.014\%$. In the regenerator beam, the background from noncoherent kaon scattering in the B_4C regenerator was $0.155\% \pm 0.011\%$ after the same p_t^2 cut. These backgrounds were determined from the shapes of the p_t^2 distributions. The errors include the systematic uncertainty.

In the $\pi^0\pi^0$ sample, the MC simulation of the $3\pi^0$ background agrees with the data in both the decay vertex and mass distributions (Fig. 2). The $3\pi^0$ fractions were 1.78% (0.049%) in the vacuum (regenerator) beam. A background from beam interactions in the trigger plane was $0.21\% \pm 0.027\%$. Studies using different subtraction schemes and mass cuts limited the systematic uncertainty in K_L/K_S from $3\pi^0$ and beam interaction backgrounds to 0.036%.

To subtract the neutral background resulting from noncoherent scattering at the regenerator, we used the distribution of the event center of energy in concentric square "rings" centered on each beam. The vacuum

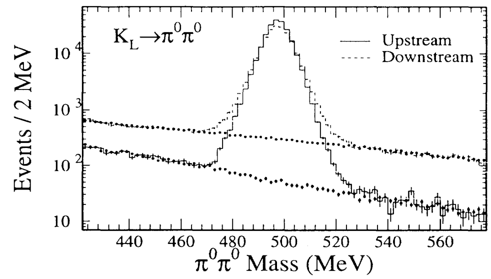

FIG. 2. Distribution in $\pi^0\pi^0$ mass for $K_L \to 2\pi^0$ events upstream and downstream of the trigger plane. The histogram is the data; the dots are the $3\pi^0$ background MC simulation together with the small contribution from beam interactions.

beam was affected as well as the regenerator beam because of kaons that scattered through very large angles. The "ring number" shape was predicted with our MC using the p_t^2 spectrum measured directly in the $\pi^+\pi^-$ sample. The background levels were 2.53% and 2.26% in the regenerator and vacuum beams, respectively. The predicted shapes agreed with the data in 1 m bins over the entire fiducial region. The overall agreement (Fig. 3) limits the uncertainty in the background level to less than 1.4% of itself. Although this background nearly cancels in the single ratio, we treat the two beams independently, resulting in a 0.05% uncertainty in the ratio.

Incoherent scattering at the trigger plane also had to be subtracted. Diffractive scatters were easily simulated and subtracted as the amplitudes and p_t^2 spectra are well known [13–15]; this background was 0.78% (0.027%) in the vacuum (regenerator) beam. Inelastic scatters were largely vetoed, but left a residual of 0.13% (0.027%). These contributions are also shown in Fig. 3. From the $\pi^0\pi^0\pi^0$ sample, we determined the four photon transmission probability, nominally 75%, to within 0.16%. The total systematic error from this plane is 0.07%, dominated by uncertainty in the conversion probability.

Figure 4 shows the vertex distribution in the vacuum beam for the two neutral data subsets with all of the

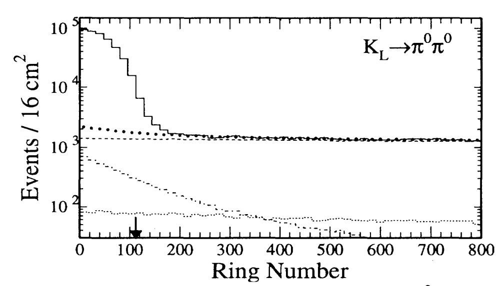

FIG. 3. Distribution in ring number for $3\pi^0$ background-subtracted $K_L \to 2\pi^0$ events. The histogram is the data; the large dots are the MC simulation for incoherent processes. Contributions from regenerator incoherent scattering (dashed line), diffractive (dash-dotted line), and inelastic (small dots) scattering at the trigger plane are shown separately. The arrow shows the position of the cut.

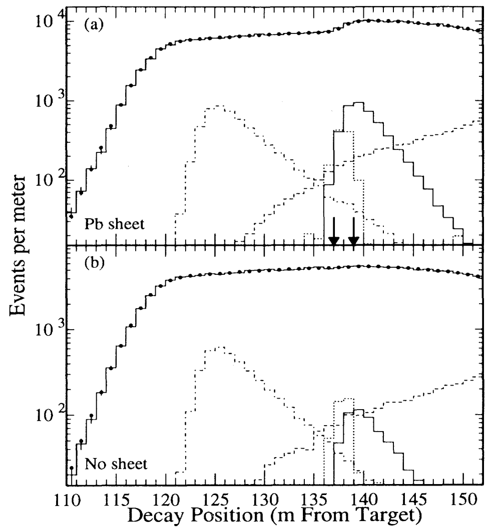

FIG. 4. Reconstructed $K_L \rightarrow 2\pi^0$ vertex distributions with and without Pb converter. The histogram is the background subtracted data; the large dots are the MC simulation (25 times the data). The overlays have acceptable χ^2. The region between the arrows in the Pb data set is excluded from the fits. Also shown are the (subtracted) contributions from regenerator noncoherent scattering (dot-dashed line), trigger plane noncoherent scattering (solid line), beam interactions (dotted line), and $3\pi^0$ decays (dashed line).

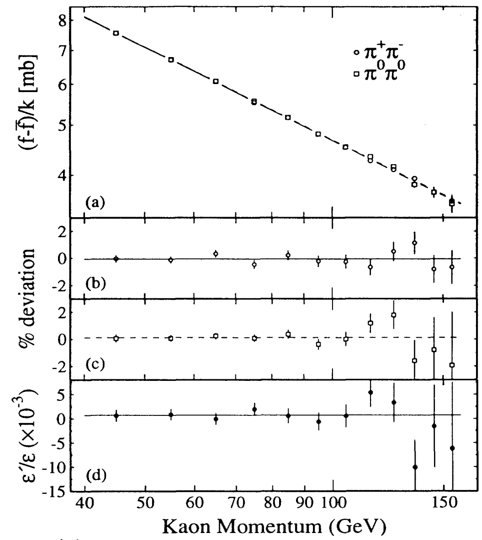

FIG. 5. (a) Regeneration amplitudes vs momentum. The best power-law fits are shown. The residuals, from the combined fit, are for (b) $\pi^+\pi^-$ data and (c) $2\pi^0$ data. (d) $\mathrm{Re}(\varepsilon'/\varepsilon)$ vs momentum.

above background contributions. As in the other decay modes shown in Fig. 1, the agreement with the MC simulation is very good.

After background subtraction, the event totals in the vacuum beams were 327 006 $\pi^+\pi^-$ and 410 043 $2\pi^0$. In the regenerator beams there were 1 060 687 $\pi^+\pi^-$ and 800 037 $2\pi^0$.

To fit for $\mathrm{Re}(\varepsilon'/\varepsilon)$, the data were divided into fourteen 10 GeV/c by 27 m (42 m) bins in the charged (neutral) mode, starting at 40 GeV/c in momentum and 110 m from the target. The ratio of vacuum to regenerator events was fitted in each momentum bin, the functional incorporating all interference effects (see preceding paper), including regeneration at the trigger plane. Neutral subsets with and without the lead sheet were treated separately.

The regeneration amplitude, proportional to the difference in the forward scattering amplitudes, f/k and $\bar{f}/k$, of the K^0 and $\bar{K}^0$, is expected to fall with kaon momentum as p^α. Assuming this form, we fitted for α, the regeneration amplitude at 70 GeV/c, and $\mathrm{Re}(\varepsilon'/\varepsilon)$. The combined fit to the charged and neutral data yielded $\mathrm{Re}(\varepsilon'/\varepsilon) = (7.4 \pm 5.2) \times 10^{-4}$. A separate fit to the charged (neutral) mode sample gave $\alpha = -0.6052 \pm 0.0065$ (-0.6025 ± 0.0072) with a χ^2 of 8.9 (16.8) for 9 (21) degrees of freedom. The fits, shown in Fig. 5, agree with previous measurements [11,14,15]. Fitting without the power-law assumption gives a nearly identical result. A fit including only those neutral events upstream of the trigger plane gave consistent results. Fitting the subset used for our previous result [5] after reanalysis yielded a value within 1.6×10^{-4} of that published.

The major sources of systematic uncertainty are associated with the acceptance calculation, the calibration of the lead-glass detector, accidental activity, and backgrounds. The background uncertainty estimates have been given above. Here we give the remaining uncertainties in $\mathrm{Re}(\varepsilon'/\varepsilon)$ and describe the systematic checks.

The agreement between data and MC simulation as a function of decay vertex is excellent (Figs. 1 and 4) in the 2π as well as the $Ke3$ and $3\pi^0$ modes. Introducing the maximum allowable distortions into the acceptance based upon many such data-MC overlays showed that the shifts in $\mathrm{Re}(\varepsilon'/\varepsilon)$ due to acceptance uncertainties in the charged (neutral) mode were limited to 0.5×10^{-4} (1.0×10^{-4}).

In neutral reconstruction, a bias in the reconstructed photon energy shifts cluster energy, vertex, and total energy distributions. This results in different fractions of events surviving fiducial cuts in the two beams. The overall energy scale is adjusted so that the data and MC upstream edges in the regenerator beam match. This limits the residual uncertainty to 0.03%. Using a variety of nonlinear energy biases, we estimate our uncertainty from cluster energy reconstruction on $\mathrm{Re}(\varepsilon'/\varepsilon)$ to be 1.60×10^{-4}.

Effects due to accidental activity in the detector cancel to first order with this technique. To estimate higher-order effects, we determined the change in the K_S/K_L acceptance ratio when detector activity from randomly triggered events was overlaid on $\pi\pi$ MC events. These events were collected along with the data, and thus were subject to the same beam intensity profile. The ratio in the

TABLE I. Summary of systematic uncertainties on ε'/ε.

Systematic effect	Uncertainty (10^{-4})
Acceptance	1.19
Energy calibration	1.60
Accidentals	1.07
$3\pi^0$ background	0.60
Regenerator scattering	0.84
Regenerator anticounter Position	0.51
Trigger plane effects	1.22
Charged background	0.29
Beam scattering	0.30
Total	2.85

charged data, taken at low intensity, needed no correction. The correction to the higher intensity neutral data shifted $\text{Re}(\varepsilon'/\varepsilon)$ by $+2.5\times10^{-4}$. The accidental uncertainty on $\text{Re}(\varepsilon'/\varepsilon)$ is 0.84×10^{-4} (0.67×10^{-4}) from the neutral (charged) mode.

To check time and intensity dependences, we look at the regeneration amplitude in nine different data collection periods, which alternated between neutral and charged running (except the last, when all modes were collected simultaneously). Within both the charged and neutral subsets, the intensity varied by a factor of 3. Three of the five neutral subsets had the lead sheet present. All subsets yielded consistent results.

Table I lists all of these systematic uncertainties, as well as smaller ones associated with the charged background, beam scattering, and the position of the regenerator anticounter. The total systematic uncertainty is 2.9×10^{-4}.

In the fits we used our own values [9] of Δm and τ_S, comparable in precision to current world averages. We used $\tan^{-1}[2\Delta m/(\Gamma_S-\Gamma_L)]$ for $\arg(\varepsilon)$, while for $|\varepsilon|$ we used the world average of $|\eta_{+-}|$ [16]. The $\pi\pi$ phase shift analysis of Ochs [17] gives $\phi\varepsilon'=43°\pm6°$. As in the preceding paper, we used the analyticity constraint for the regeneration phase [9,15]. The result is insensitive to the values of these parameters within their quoted errors.

Our final result is

$$\text{Re}(\varepsilon'/\varepsilon)=[7.4\pm5.2(\text{stat})\pm2.9(\text{syst})]\times10^{-4}.$$

The combined uncertainty is 5.9×10^{-4}. Compared to our previous publication [5], the statistical (systematic) error is a factor of 2.7 (2.1) smaller. Our value is not significantly different from zero. It implies $\text{Re}(\varepsilon'/\varepsilon) < 17\times10^{-4}$ (95% confidence), which does not support earlier evidence [4] for a large $\text{Re}(\varepsilon'/\varepsilon)$.

More precise experiments are required to establish a nonzero effect. Our error is principally statistical; the systematic uncertainty comes largely from the photon detector, so the technique of two simultaneous beams with more precise calorimetry and higher intensity can give improved accuracy.

This work was supported in part by the Department of Energy, the National Science Foundation, and the French Atomic Energy Commission. One of us (B.S.) receives support from the Daimler-Benz Stiftung.

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