Observation of CP Violation in $K_L \to \pi^+\pi^-e^+e^-$ Decays

A. Alavi-Harati,[12] I. F. Albuquerque,[10] T. Alexopoulos,[12] M. Arenton,[11] K. Arisaka,[2] S. Averitte,[10] A. R. Barker,[5] L. Bellantoni,[7] A. Bellavance,[9] J. Belz,[10] R. Ben-David,[7] D. R. Bergman,[10] E. Blucher,[4] G. J. Bock,[7] C. Bown,[4] S. Bright,[4] E. Cheu,[1] S. Childress,[7] R. Coleman,[7] M. D. Corcoran,[9] G. Corti,[11] B. Cox,[11,*] M. B. Crisler,[7] A. R. Erwin,[12] R. Ford,[7] A. Glazov,[4] A. Golossanov,[11] G. Graham,[4] J. Graham,[4] K. Hagan,[11] E. Halkiadakis,[10] K. Hanagaki,[8] M. Hazumi,[8] S. Hidaka,[8] Y. B. Hsiung,[7] V. Jejer,[11] J. Jennings,[2] D. A. Jensen,[7] R. Kessler,[4] H. G. E. Kobrak,[3] J. LaDue,[5] A. Lath,[10] A. Ledovskoy,[11] P. L. McBride,[7] A. P. McManus,[11] P. Mikelsons,[5] E. Monnier,[4,†] T. Nakaya,[7] U. Nauenberg,[5] K. S. Nelson,[11] H. Nguyen,[7] V. O'Dell,[7] M. Pang,[7] R. Pordes,[7] V. Prasad,[4] C. Qiao,[4] B. Quinn,[4] E. J. Ramberg,[7] R. E. Ray,[7] A. Roodman,[4] M. Sadamoto,[8] S. Schnetzer,[10] K. Senyo,[8] P. Shanahan,[7] P. S. Shawhan,[4] J. Shields,[11] W. Slater,[2] N. Solomey,[4] S. V. Somalwar,[10] R. L. Stone,[10] I. Suzuki,[8] E. C. Swallow,[4,6] R. A. Swanson,[3] S. A. Taegar,[1] R. J. Tesarek,[10] G. B. Thomson,[10] P. A. Toale,[5] A. Tripathi,[2] R. Tschirhart,[7] Y. W. Wah,[4] J. Wang,[1] H. B. White,[7] J. Whitmore,[7] B. Winstein,[4] R. Winston,[4] J.-Y. Wu,[5] T. Yamanaka,[8] and E. D. Zimmerman[4]

(KTeV Collaboration)

[1]*University of Arizona, Tucson, Arizona 85721*
[2]*University of California at Los Angeles, Los Angeles, California 90095*
[3]*University of California at San Diego, La Jolla, California 92093*
[4]*The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637*
[5]*University of Colorado, Boulder, Colorado 80309*
[6]*Elmhurst College, Elmhurst, Illinois 60126*
[7]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[8]*Osaka University, Toyonaka, Osaka 560 Japan*
[9]*Rice University, Houston, Texas 77005*
[10]*Rutgers University, Piscataway, New Jersey 08855*
[11]*The Department of Physics and Institute of Nuclear and Particle Physics, University of Virginia, Charlottesville, Virginia 22901*
[12]*University of Wisconsin, Madison, Wisconsin 53706*
(Received 2 August 1999)

We report the first observation of a manifestly CP violating effect in the $K_L \to \pi^+\pi^-e^+e^-$ decay mode. A large asymmetry was observed in the distribution of these decays in the CP-odd and T-odd angle ϕ between the decay planes of the e^+e^- and $\pi^+\pi^-$ pairs in the K_L center of mass system. After acceptance corrections, the overall asymmetry is found to be $[13.6 \pm 2.5(\text{stat}) \pm 1.2(\text{syst})]\%$. This is the largest CP-violating effect yet observed when integrating over the entire phase space of a mode and the first such effect observed in an angular variable.

PACS numbers: 11.30.Er, 13.20.Eb

The KTeV E799 experiment at Fermi National Accelerator Laboratory recently reported the first observation [1] of the four body decay mode $K_L \to \pi^+\pi^-e^+e^-$. Based on 2% of the data, a branching ratio of $3.2 \pm 0.6(\text{stat}) \pm 0.4(\text{syst}) \times 10^{-7}$ was measured. In this paper, we report an analysis of the entire KTeV E799 data from which the $K_L \to \pi^+\pi^-e^+e^-$ signal (shown in Fig. 1) of 1811 events above background was obtained after the analysis cuts described below. We observed in these $K_L \to \pi^+\pi^-e^+e^-$ data a CP-violating asymmetry in the CP- and T-odd variable $\sin\phi\cos\phi$,

$$A = \frac{N_{\sin\phi\cos\phi>0.0} - N_{\sin\phi\cos\phi<0.0}}{N_{\sin\phi\cos\phi>0.0} + N_{\sin\phi\cos\phi<0.0}}, \qquad (1)$$

where ϕ is the angle between the e^+e^- and $\pi^+\pi^-$ planes in the K_L center of mass system (cms). This asymmetry implies, with the mild assumption of unitarity to avoid exotic CPT violation [2], time reversal symmetry violation. The quantity $\sin\phi\cos\phi$ is given by $(\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \cdot \hat{z}(\hat{n}_{ee} \cdot \hat{n}_{\pi\pi})$, where the $\hat{n}'$s are the unit normals and $\hat{z}$ is the unit vector in the direction of the $\pi\pi$ in the K_L cms.

The observed asymmetry $\sin\phi\cos\phi$ shown in Fig. 2 was $[23.3 \pm 2.3(\text{stat})]\%$ before corrections. Inspection of Fig. 2 shows that the asymmetry between the bins near $\sin\phi\cos\phi = \pm 0.5$ is considerably larger. As discussed below, this cannot be explained by asymmetries due to either the spectrometer acceptance or detector elements. Using the model of Refs. [3–5] to correct for regions of $K_L \to \pi^+\pi^-e^+e^-$ phase space outside the acceptance of the KTeV spectrometer (which have small asymmetry), an asymmetry integrated over the entire phase space of the $K_L \to \pi^+\pi^-e^+e^-$ mode of $[13.6 \pm 2.5(\text{stat})]\%$ was obtained, the largest such CP- (and T-) violating effect yet observed. In comparison, CPLEAR recently reported a $[0.66 \pm 0.13(\text{stat})]\%$ T-violating asymmetry [6] between $K^0 \to \overline{K}^0$ and $\overline{K}^0 \to K^0$ transition rates.

The $K_L \to \pi^+\pi^-e^+e^-$ data were accumulated during the ten weeks of E799 operation. A proton beam with intensity in the range $(3.0–3.5) \times 10^{12}$ protons per 23 sec spill incident at an angle of 4.8 mr on a BeO target was employed to produce two nearly parallel

 0031-9007/00/84(3)/408(4)$15.00

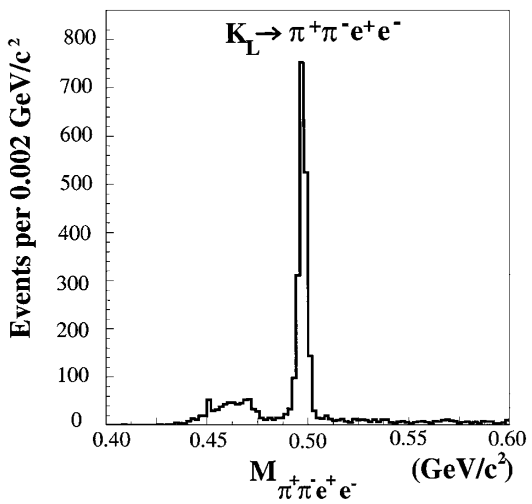

FIG. 1. $M_{\pi^+\pi^-e^+e^-}$ invariant mass for events passing cuts.

K_L beams for E799. The KTeV E799 spectrometer configuration consisted of a vacuum decay region, a magnetic spectrometer with four drift chambers, photon vetoes, eight transition radiation chambers, a CsI electromagnetic calorimeter, and a muon detector. A total of 2.7×10^{11} K_L decays were accumulated during the E799 run. Details of the KTeV detector are given in Ref. [1].

The KTeV four track trigger [1] selected 1.3×10^8 events. Candidate $K_L \to \pi^+\pi^-e^+e^-$ events were extracted from these triggers by requiring events with four tracks that passed track quality cuts and had a common vertex with a good vertex χ^2. To be designated as $e^\pm$, two of the tracks were required to have opposite charges and $0.95 \le E/p \le 1.05$ where E was the energy deposited by the track in the CsI and p was the momentum obtained from magnetic deflection. To be consistent with a $\pi^\pm$ pair, the other two tracks were required to have $E/p \le 0.90$ and opposite charges.

To reduce backgrounds arising from other types of K_L decays in which decay products have been missed, the candidates $\pi^+\pi^-e^+e^-$ were required to have transverse momentum P_t^2 of the four tracks relative to the direction of the K_L be less than 0.6×10^{-4} GeV$^2/c^2$. This cut was 91.8% efficient for retaining $K_L \to \pi^+\pi^-e^+e^-$.

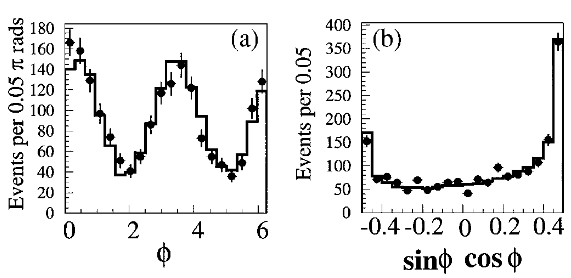

FIG. 2. (a) Observed ϕ and (b) $\sin\phi\cos\phi$ angular distributions: The data are shown as dots. The histogram is a Monte Carlo simulation based on the model of Ref. [3].

The major background to the $K_L \to \pi^+\pi^-e^+e^-$ mode was $K_L \to \pi^+\pi^-\pi^0_D$ where π^0_D was a Dalitz decay, $\pi^0 \to \gamma e^+e^-$, in which the photon was not observed in the CsI calorimeter or the photon vetoes. To reduce this background, all $K_L \to \pi^+\pi^-e^+e^-$ candidate events were interpreted as $K_L \to \pi^+\pi^-\pi^0_D$ decays. Under this assumption, the momentum squared $P^2_{\pi^0}$ of the assumed π^0 can be calculated in the frame in which the momentum of $\pi^+\pi^-$ is transverse to the K_L direction. $P^2_{\pi^0}$ was mostly greater than zero for $K_L \to \pi^+\pi^-\pi^0_D$ decays except for cases where finite detector resolution produces a $P^2_{\pi^0} \le 0$. In contrast, most of the $K_L \to \pi^+\pi^-e^+e^-$ decays had $P^2_{\pi^0} \le 0$. The requirement that all $\pi^+\pi^-e^+e^-$ had $(P_{\pi^0})^2 \le -0.006\,25$ GeV$^2/c^2$ minimized $K_L \to \pi^+\pi^-\pi^0_D$ while retaining 94.8% of the signal.

Other backgrounds were relatively minor. The largest of these was due to $K_L \to \pi^+\pi^-\gamma$ decays in which the photon converted in the material of the spectrometer. These events, which reconstructed to the K_L mass and survived the P_t^2 and $P^2_{\pi^0}$ cuts, were eliminated by requiring $M_{e^+e^-} \ge 2.0$ MeV$/c^2$. The $M_{e^+e^-}$ cut retained 95.3% of the $K_L \to \pi^+\pi^-e^+e^-$ events. A third background due to accidental coincidence of two $K_L \to \pi^\pm e^\mp \nu$ decays (K_{e_3}) whose decay vertices overlap was minimized by track and vertex χ^2 cuts. A fourth background due to $\Xi^0 \to \Lambda\pi^0_D$ where the proton from the Λ decay was misidentified as a π^+ was made negligible by K^0 momentum and vertex χ^2 cuts. A fifth background due to $K_S \to \pi^+\pi^-e^+e^-$ decays was eliminated by requiring the energy of the $\pi\pi ee$ be $\le$200 GeV.

The final requirement of the $K_L \to \pi^+\pi^-e^+e^-$ events was 492 MeV$/c^2 \le M_{\pi\pi ee} \le 504$ MeV$/c^2$. The magnitude of the background under the K_L peak was determined by a fit to the $\pi^+\pi^-e^+e^-$ mass distribution outside the signal region. From this fit, a $K_L \to \pi^+\pi^-e^+e^-$ signal of 1811 ± 43(stat) events above a background of 45 ± 11 events was obtained in the signal region. The 45 event background was composed of residual $K_L \to \pi^+\pi^-\pi^0_D$ (36 events), $K_L \to \pi^+\pi^-\gamma$ (4.0 events), overlapping K_{e_3} (3.5 events), cascade decays (1.3 events), and $K_S \to \pi^+\pi^-e^+e^-$ (0.2 events).

Possible sources of false asymmetries were considered, including those due to backgrounds and asymmetries in the detector. To check for detector asymmetries, the copious $K_L \to \pi^+\pi^-\pi^0_D$ decay mode, which has a similar topology to $K_L \to \pi^+\pi^-e^+e^-$ except for the presence of an extra photon in the CsI, was used. This mode is expected to have no asymmetry in the ϕ distribution formed using the $\pi^+\pi^-e^+e^-$. In a sample of approximately 5×10^6 Dalitz decays, an asymmetry of $(-0.02 \pm 0.05)\%$ was observed. The small background under the K_L was determined not to contribute significantly to the asymmetry in the K_L mass region since the asymmetry of the sideband regions below and above the K_L mass was measured to be $(3.1 \pm 5.1)\%$ and $(-2.3 \pm 9.2)\%$, respectively.

To perform an acceptance correction for loss of events due to spectrometer geometry, trigger, reconstruction efficiency, and analysis cuts, we modeled the $K_L \to \pi^+\pi^-e^+e^-$ decays and simulated the response of the KTeV detector elements. The $K_L \to \pi^+\pi^-e^+e^-$ decay mode is expected [3–5] to proceed via both CP-violating and conserving amplitudes and exhibit both direct and indirect CP violation. The dominant CP-violating amplitude is indirect and proceeds via an initial decay of the K_L into $\pi^+\pi^-$ followed by one of the pions undergoing inner bremsstrahlung with the resulting photon internally converting to an e^+e^- pair. The dominant CP-conserving amplitude is the emission of an $M1$ photon at the $\pi^+\pi^-$ decay vertex followed by internal conversion. The interference between two amplitudes shown in Figs. 3a and 3b, respectively, generates the ϕ asymmetry.

Using this model, the angular distribution in ϕ is

$$\frac{d\Gamma}{d\phi} = \Gamma_1 \cos^2\phi + \Gamma_2 \sin^2\phi + \Gamma_3 \sin\phi \cos\phi\,, \qquad (2)$$

where the T-odd $\Gamma_3 \sin\phi \cos\phi$ term contains the interference between the $M1$ and bremsstrahlung amplitudes.

Two other processes that contribute small amounts to the $K_L \to \pi^+\pi^-e^+e^-$ decay were taken into account: the indirect CP-violating $E1$ photon emission (Fig. 3c) and the CP-conserving K^0 charge radius process (Fig. 3d) in which the $K_L \to K_S$ via emission of a photon.

The Monte Carlo simulation incorporated the amplitudes shown in Figs. 3a–3d. To obtain agreement with the virtual photon energy spectrum $E^*_\gamma = E_{e^+} + E_{e^-}$ of the data (Fig. 4a), a form factor was required in the $M1$ virtual photon emission amplitude of Fig. 3b. We turn now to a detailed discussion of this form factor.

Such a form factor has been required [7] to explain the energy spectrum of the $M1$ photon emitted in the $K_L \to \pi^+\pi^-\gamma$ decay. In order to incorporate a similar form factor, we have modified the coupling g_{M1} of the $M1$ amplitude, including a form factor

$$F = \tilde{g}_{M1}\left[1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K(E_{e^+} + E_{e^-})}\right] \qquad (3)$$

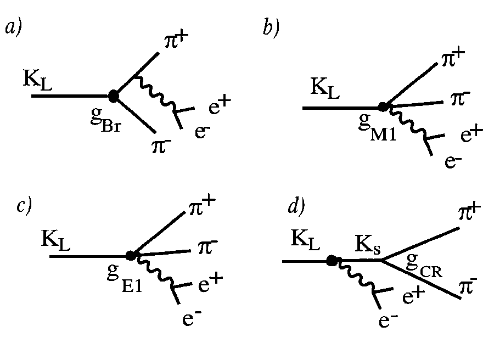

FIG. 3. $K_L \to \pi^+\pi^-e^+e^-$ processes: (a) CP-violating bremsstrahlung; (b) CP-conserving $M1$ γ emission; (c) CP-violating $E1$ γ emission; (d) charge radius process.

similar to that used to describe $K_L \to \pi^+\pi^-\gamma$ where M_ρ is the mass of the ρ meson (770 MeV$/c^2$) and the photon energy has been replaced by $E_{e^+} + E_{e^-}$. The ratio a_1/a_2 and $|\tilde{g}_{M1}|$ were determined by fitting the $K_L \to \pi^+\pi^-e^+e^-$ data using the likelihood function

$$L(a_1/a_2, \tilde{g}_{M1}) = \frac{\Pi_{k=1}^{N} P_M^k(a_1/a_2, \tilde{g}_{M1}) P_a^k}{[\int_{ps} P_M(a_1/a_2, \tilde{g}_{M1}) P_a(a_1/a_2, \tilde{g}_{M1})]^N}. \qquad (4)$$

The probability P_M^k of a given event is based on the $K_L \to \pi^+\pi^-e^+e^-$ matrix element and is a function of the five independent variables: ϕ, θ_{e^+} (the angle between the e^+ and the $\pi^+\pi^-$ direction in the e^+e^- cms), θ_{π^+} (the angle between the π^+ and the e^+e^- direction in the $\pi^+\pi^-$ cms), $M_{\pi^+\pi^-}$, and $M_{e^+e^-}$. It is calculated using the particular values of the parameters a_1/a_2 and $|\tilde{g}_{M1}|$ and nominal values from Refs. [8] or [3] for the other model parameters. The likelihood of an event is the product of P_M^k and P_a^k, the acceptance times efficiency of the event, normalized by the product of P_M and P_a integrated over the entire phase space (ps).

The result of the likelihood calculation is shown in Fig. 4b. The maximum of the likelihood occurs at $a_1/a_2 = -0.720 \pm 0.028$ GeV$^2/c^2$ and $|\tilde{g}_{M1}| = 1.35^{+0.20}_{-0.17}$ where the errors represent the excursions of

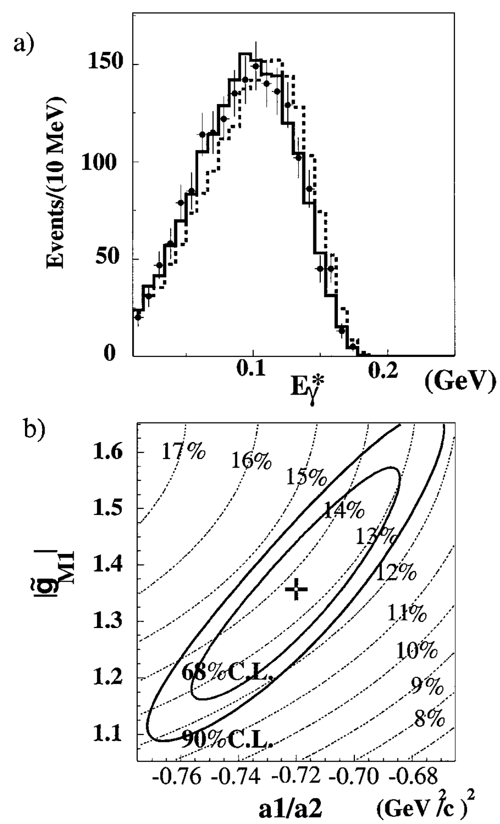

FIG. 4. (a) E^*_γ spectrum of data (dots), Monte Carlo using a constant $|g_{M1}|$ (dashed histogram), Monte Carlo with E^*_γ dependent form factor (solid histogram). (b) Likelihood contours of a_1/a_2 and $|\tilde{g}_{M1}|$; constant asymmetry contours calculated from the data as described in the text are superimposed.

the likelihood function at the point where the log of the likelihood has decreased by one-half unit (39% C.L.). The E_γ^* spectrum predicted by the Monte Carlo with these parameters is shown in Fig. 4a, together with the prediction for a constant $|g_{M1}|$. Figure 2 shows the good agreement obtained using these parameters between the observed ϕ and $\sin\phi\cos\phi$ angular distributions and the Monte Carlo. When this form factor is included in the $M1$ amplitude, the constant $|g_{M1}| = 0.76$ used in Ref. [3] can no longer be directly compared to the new $|\tilde{g}_{M1}|$ obtained in the likelihood fit. Rather, the average of the form factor F of Eq. (3) over the range of $E_{e^+} + E_{e^-}$ must be compared with the constant $|g_{M1}|$ value of 0.76 ± 0.11. An average for F of 0.84 ± 0.10 was found, consistent within errors with 0.76. The branching ratio calculated using the form factor was increased by 5.7% compared with that obtained using $|g_{M1}| = 0.76$.

Using the acceptance obtained from the Monte Carlo generated with the maximum likelihood values of $|\tilde{g}_{M1}|$ and a_1/a_2, the asymmetry of the acceptance corrected $\sin\phi\cos\phi$ distribution is found to be $[13.6 \pm 2.5(\text{stat})]\%$. The contours of acceptance corrected asymmetry shown superimposed on the likelihood contours of a_1/a_2 and $|\tilde{g}_{M1}|$ in Fig. 4 were determined from the $\sin\phi\cos\phi$ distribution of the data, corrected for acceptances determined using the particular a_1/a_2 and $|\tilde{g}_{M1}|$ values.

We have considered whether the asymmetry is caused by final-state interactions. Effects due to final-state electromagnetic interactions are small. In addition, while the magnitude of the asymmetry depends on the $\pi\pi$ phase shifts and the phase of η_{+-}, such phase shifts cannot generate the observed angular asymmetry without the presence of both CP-conserving and CP-violating amplitudes. Therefore, the asymmetry, while modulated by final-state interactions, cannot be created by them.

Systematic errors on a_1/a_2 and $|\tilde{g}_{M1}|$ due to analysis cuts, resolutions, and variations of parameters of the Monte Carlo were studied. By varying each analysis cut over a reasonable range and observing the variation of a_1/a_2 and $|\tilde{g}_{M1}|$, a_1/a_2 and $|\tilde{g}_{M1}|$ systematic errors of $\pm 0.008\ \text{GeV}^2/c^2$ and ± 0.04 were obtained.

To determine the systematic errors due to resolution, resolution functions in the five variables were estimated by comparing generated and reconstructed Monte Carlo events. Using these functions to smear each independent variable for each data event, 1000 passes through the 1811 $K_L \to \pi^+\pi^-e^+e^-$ signal events were made. The 1000 smeared data samples were refit, and a_1/a_2 and $|\tilde{g}_{M1}|$ were determined for each of the samples. The variation of a_1/a_2 and $|\tilde{g}_{M1}|$ for these samples resulted in errors of $\pm 0.002\ \text{GeV}^2/c^2$ and ± 0.01 for a_1/a_2 and $|\tilde{g}_{M1}|$.

The systematic errors in a_1/a_2 and $|\tilde{g}_{M1}|$ due to uncertainties [8] in the magnitude and phase of η_{+-}, and the uncertainties in $|g_{E1}|$ and $|g_{CR}|$, estimated by varying the magnitude of the ratio of $|g_{E1}|$ to $|\tilde{g}_{M1}|$ from 0.0 to 0.05 (nominal 0.038) and $|g_{CP}|$ from 0.10 to 0.17 (nominal 0.15), resulted in systematic errors in a_1/a_2 and $|\tilde{g}_{M1}|$ of $\pm 0.004\ \text{GeV}^2/c^2$ and ± 0.01, respectively.

All systematic errors in a_1/a_2 and $|\tilde{g}_{M1}|$ were added in quadrature to obtain an overall error of $\pm 0.009\ \text{GeV}^2/c^2$ and ± 0.04 in a_1/a_2 and $|\tilde{g}_{M1}|$, respectively.

The systematic error in the ϕ asymmetry due to variations in the corrections for acceptance arising from the systematic errors of the a_1/a_2 and $|\tilde{g}_{M1}|$ and one sigma uncertainties of other parameters of the Monte Carlo model discussed above was determined to be $\pm 0.7\%$. The variation in asymmetry due to analysis cuts was also estimated to be $\pm 0.7\%$. Finally, the systematic error due to resolution effects was determined to be $\pm 0.7\%$ using generated tracks from the Monte Carlo rather than reconstructed tracks in the analysis. Adding in quadrature the systematic errors from these three sources, a total systematic error of $\pm 1.2\%$ was obtained for the acceptance corrected asymmetry of the $\sin\phi\cos\phi$ distribution.

In conclusion, the KTeV experiment has observed a CP-violating asymmetry in the distribution of T-odd angle ϕ in $K_L \to \pi^+\pi^-e^+e^-$ decays. This effect, the largest CP violation effect yet observed and the first in an angular variable, is T violating barring possible exotic phenomena [2] such as direct CPT violation in the $K_L \to \pi^+\pi^-e^+e^-$ matrix element. The magnitude of the acceptance corrected asymmetry is $[13.6 \pm 2.5(\text{stat}) \pm 1.2(\text{syst})]\%$, consistent with the theoretically expected asymmetry [3]. In addition, the $M1$ photon emission amplitude requires a vector form factor as given in Eq. (3) with $a_1/a_2 = -0.720 \pm 0.028(\text{stat}) \pm 0.009(\text{syst})\ \text{GeV}^2/c^2$ and $|\tilde{g}_{M1}| = 1.35^{+0.20}_{-0.17}\ (\text{stat}) \pm 0.04(\text{syst})$. The rich structure of the $K_L \to \pi^+\pi^-e^+e^-$ mode has provided a new opportunity for the study of novel CP- and T-violation effects. In the future, it may be possible to use this mode to search for direct CP violation [4] and more exotic phenomena [2].

We thank Fermilab, the U.S. Department of Energy, the U.S. National Science Foundation, and the Ministry of Education and Science of Japan for their support.

*To whom correspondence should be addressed. Electronic address: cox@uvahep.phys.virginia.edu

†On leave from C.P.P. Marseille/C.N.R.S., France.

[1] J. Adams *et al.*, Phys. Rev. Lett. **80**, 4123 (1998).
[2] I. I. Bigi and A. I. Sanda, hep-ph/9904484, 1999.
[3] L. M. Sehgal and M. Wanninger, Phys. Rev. D **46**, 1035 (1992); **46**, 5209(E) (1992).
[4] P. Heiliger and L. M. Sehgal, Phys. Rev. D **48**, 4146 (1993).
[5] J. K. Elwood *et al.*, Phys. Rev. D **52**, 5095 (1995); J. K. Elwood *et al.*, *ibid.* **53**, 2855(E) (1996); J. K. Elwood *et al.*, *ibid.* **53**, 4078 (1996).
[6] A. Angelopoulos *et al.*, Phys. Lett. B **444**, 43 (1998).
[7] E. J. Ramberg *et al.*, Phys. Rev. Lett. **70**, 2525 (1993).
[8] C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998).