I will here make some brief comments on the T- and CP-odd asymmetry observed by KTeV in the \( K_L \rightarrow \pi^+\pi^-e^+e^- \) decay.

1 \( K_L \rightarrow \pi^+\pi^-e^+e^- \) Studies in KTeV

The decay \( K_L \rightarrow \pi\pi e e \) stems from a \( \pi\pi\gamma \) decay followed by an internal photon conversion. Figure 1 shows the distributions in \( \pi\pi \) invariant mass for \( K_L \rightarrow \pi\pi \) candidates, this from the data set used for KTeV’s first \( \epsilon'/\epsilon \) result. There is a low-side tail in the \( \pi^+\pi^- \) distribution that does not show up in the \( 2\pi^0 \) distributions, and that is due to bremsstrahlung.

Another process, that of direct emission, also results in the same \( \pi\pi\gamma \) final state. These two processes cannot directly interfere since they are of different multipoles. However, if the gamma is internally converted, as was pointed out by Sehgal and Wanninger, interference is possible.

These two processes have been studied by KTeV and other groups, and they are of comparable magnitude. Since the inner-brem contribution is CP violating while the direct emission is CP conserving, one has a favorable situation for novel interference effects.

The interference is observable in the \( \Phi \) distribution in the \( K_L \rightarrow \pi\pi e e \) decay, where \( \Phi \) is the angle between the planes formed by the pions and by the electrons. The predicted distribution is of the form:

\[
dN/d\Phi = A + B\sin^2(\Phi) + C\sin(2\Phi)
\]

The latter term is proportional to:

\[
\sin(\Phi)\cos(\Phi) = (n_\pi \times n_e) \cdot p_\pi / |p_\pi| (n_\pi \cdot n_e),
\]

References:

\(^a\) A. Alavi-Harati et al., Phys. Rev. Lett. \textbf{83}, 22 (1999).
\(^b\) L.M. Sehgal and M. Wanninger, Phys. Rev. \textbf{D46}, 1035 (1992).
\(^c\) E. Ramberg et al., Phys. Rev. Lett. \textbf{70}, 2525 (1993).
\(^d\) J. Adams et al., Phys. Rev. Lett. \textbf{80}, 4123 (1998).
where $n_\pi$, $n_e$ are the normal unit vectors to the $\pi$, $e$ planes, respectively, and $p_\pi$ is the momentum of the two pions, all in the kaon center-of-mass system. Since each normal itself is a cross-product of two vectors, the above quantity is a product of 9 vectors and is both CP- and T-odd.

Figure 2 shows the 4-particle invariant mass distribution in KTeV at the earliest stages of the analysis, showing a clear peak at the kaon mass. Also shown is the asymmetry (in the number of events with $\sin(2\Phi)$ greater than zero vs. those less than zero) vs. invariant mass. A very clear effect is seen at the kaon mass, even with no attempt to suppress background. Figure 3 shows the same mass distribution after cuts; here the background is at the 2% level.

We also show in Figure 4 the $\Phi$ distribution for the $\pi^+\pi^-\pi^0$ decay with a Dalitz conversion. No asymmetry is expected; we find (-0.02 ± 0.05)%$, showing that the detector and analysis procedure do
not produce an artificial asymmetry.

Before extracting the final asymmetry, we first need to study the form factor in the direct decay and then we need to calculate and correct for the detector acceptance.

The form factor is traditionally described by the following expression:

$$ F = \tilde{g} M 1 \left\{ 1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2 + 2M_K(E_{e+} + E_{e-}))} \right\} $$

We have determined the quantity $a_1/a_2$ both using the $\pi\pi\gamma$ and $\pi\pi\gamma$ decays, finding consistent
Figure 4: Distribution in $\Phi$ for $K_L \rightarrow \pi^+\pi^-\pi^0$ Dalitz decays, showing no instrumental asymmetries.

results

\[ \frac{a1}{a2} = -0.72 \pm 0.03 \text{(stat) } \pm 0.009 \text{(syst)} \quad (\pi\pi e e); \text{ and,} \]
\[ \frac{a1}{a2} = -0.729 \pm 0.026 \text{(stat) } \pm 0.015 \text{(syst)} \quad (\pi\pi \gamma). \]

The expected distributions in $\Phi$ are shown in Figures 5 and 6 superimposed upon the data. There is good agreement, the observed asymmetry being:

\[ A_{\Phi} = 23.3 \pm 2.3 \text{(stat)} \% \quad \text{(raw asymmetry).} \]

This is certainly the largest CP asymmetry yet observed. It is an “$\epsilon$” effect, just like the other indirect effects observed to date: $K_L \rightarrow \pi\pi$, $K_L \rightarrow \pi l\nu$, $K_{L,S} \rightarrow \pi\pi\gamma$. It is so large because of the happy circumstance that the two interfering amplitudes are of comparable size, allowing an amplification factor of two orders of magnitude.

The acceptance actually enhances the observed asymmetry. The interference is maximal at ee invariant masses around 60 MeV, where we have good acceptance, and falls to zero as the ee mass goes to zero, a region where we have poor acceptance. Hence the acceptance corrected asymmetry is smaller than the observed asymmetry:

\[ A_{\Phi} = 13.6 \pm 2.5 \text{(stat)} \% \pm 1.2 \text{(syst)} \% \quad \text{(corrected asymmetry).} \]

The value we see is in good agreement with that predicted, namely 14.4%.

2 Is Time Reserval Symmetry Violated?

We now discuss the issue of whether this observation is manifest T-violation.

The effect we see is clearly CP-odd and T-odd. One issue that can affect our conclusions is final state interactions (FSI). The relevant FSIs for this reaction are strong – leading to phase shifts, and electromagnetic. Since both conserve CP, the observed asymmetry is manifest CP violation.

\[ S. \text{ Ledovskoy, contribution to the Chicago Conference on Kaon Physics, June, 1999, to be published in the proceedings, U. of Chicago Press, Editors J. Rosner and B. Winstein.} \]
The same cannot be said for T-violation. But we can argue that strong FSIs cannot fake an effect. The effect we see comes about because of the non-zero value for $\eta_{+-}$ and the strong phase shifts only serve to moderate the effect, not to generate such an effect.

What about electromagnetic FSIs? The only process that can alter the distribution between the $\pi$ and $e$ planes is the exchange of photons between the pions and electrons. Such diagrams will indeed slightly alter the distribution in the $\Phi$ angle, but they will not generate, or even moderate, an asymmetry. This can be shown by construction but it also results from the knowledge that such an asymmetry would be CP violating and FSIs (where the interaction is CP conserving) cannot generate CP violating effects.
So we conclude that FSIs cannot generate the asymmetry we have observed. Can we conclude, therefore, that we have unambiguously seen T-violation? This subject is under intense discussion in the literature and we will briefly recap the situation here.

One issue is whether, from this asymmetry observation alone, one can conclude T-violation. Wolfenstein\(^f\) has pointed out that were the phase of \(\eta_{+}^{-}\) closer to 135° rather than 45°, and were \(T\) a good symmetry, we would observe exactly the same effect but it would arise from CPT violation in the mixing of the neutral kaons. Thus his point is that this decay alone is not enough to establish T-violation. Of course in KTeV and in many other experiments, we observe that 135° can be definitively ruled out so this objection can be met.

Ellis and Mavromatos\(^g\) have hypothesized a very large CPT violating effect in the MI \(K_L \rightarrow \pi\pi\gamma\) decay which could be responsible for the observed effect, again in a T-invariant world. This can probably be ruled out from other information but we are not sure at this time.

Finally (for now), Bigi and Sanda\(^h\) have elected to abandon unitarity and can reproduce the observed effect (as well as the asymmetry observed by CPLEAR\(^i\)) by an admittedly unnatural but still possible scheme with large, finely tuned, CPT violation in a number of channels. Again this has other experimental consequences which can perhaps be used to rule it out.

We remain confident that even if these ideas are rejected, others will be proposed to save the notion of symmetry under time reversal.

\(^f\)L. Wolfenstein, Phys. Rev. Lett. 83, 911-912 (1999).
\(^g\)J. Ellis and N.E. Mavromatos, hep-ph/9903386.
\(^h\)I.I. Bigi and A.I. Sanda, hep-ph/9904484 (revised).
\(^i\)CPLEAR collaboration, Phys. Lett. B444, 43-51 (1998).