CP VIOLATION in the KAON SYSTEM
1999 SLAC Summer Institute on Particle Physics

Aaron Roodman
SLAC
Neutral Kaons and their Classical Analog

Strong Interaction Eigenstates
\[ |K^0\rangle, |\bar{K}^0\rangle \]

Mixing
\[ K^0 \xrightarrow{\pi\pi} K^0 \]

CP Eigenstates
\[ |K_1\rangle = \frac{1}{\sqrt{2}} \left( |K^0\rangle + |\bar{K}^0\rangle \right) \]
\[ |K_2\rangle = \frac{1}{\sqrt{2}} \left( |K^0\rangle - |\bar{K}^0\rangle \right) \]

Weak Interaction Decay
\[ K_1 \to 2\pi \text{ CP Even} \]
\[ K_2 \to 3\pi \text{ CP Odd} \]

So \( \tau_{K_1} \ll \tau_{K_2} \)

CP Violation
\[ K_L \to 2\pi \text{ (1964) Fitch & Cronin} \]

CP Asymmetry
\[ A(K^0 \to \bar{K}^0) \neq A(\bar{K}^0 \to K^0) \]

Question 1: Can you think of a good Classical Analog for CP Violation?

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Overview of Kaon Phenomenology

$\epsilon'/\epsilon$

- $\epsilon'/\epsilon$ predictions
- KTeV
- NA-48

T-violation

- $A_T$
- $K_L \to \pi\pi\text{ee}$

What's Next?

- $K_L \to \pi^0\nu\bar{\nu}$
$K_L$ and $K_S$ States

$$|K_S\rangle = \frac{1}{\sqrt{2(1+|\epsilon|^2)}} \left[(1+\epsilon)|K^0\rangle + (1-\epsilon)|\overline{K}^0\rangle\right]$$

$$|K_L\rangle = \frac{1}{\sqrt{2(1+|\epsilon|^2)}} \left[(1+\epsilon)|K^0\rangle - (1-\epsilon)|\overline{K}^0\rangle\right]$$

Amplitude Ratios

$$\eta_{00} = \frac{\langle \pi^0 \pi^0 | H_w | K_L \rangle}{\langle \pi^0 \pi^0 | H_w | K_S \rangle}$$

$$\eta_{+-} = \frac{\langle \pi^+ \pi^- | H_w | K_L \rangle}{\langle \pi^+ \pi^- | H_w | K_S \rangle}$$

inserting $|K_S\rangle$ and $|K_L\rangle$ gives

$$\eta_{+-} = \epsilon + \frac{\langle \pi^+ \pi^- | H_w | K^0 \rangle - \langle \pi^+ \pi^- | H_w | \overline{K}^0 \rangle}{\langle \pi^+ \pi^- | H_w | K^0 \rangle + \langle \pi^+ \pi^- | H_w | \overline{K}^0 \rangle}$$

$$\eta_{00} = \epsilon + \frac{\langle \pi^0 \pi^0 | H_w | K^0 \rangle - \langle \pi^0 \pi^0 | H_w | \overline{K}^0 \rangle}{\langle \pi^0 \pi^0 | H_w | K^0 \rangle + \langle \pi^0 \pi^0 | H_w | \overline{K}^0 \rangle}$$

Two types of CP Violation
Indirect $K_L \sim K_2 + \epsilon K_1$
Direct $K_2 \rightarrow 2\pi$

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Isospin Amplitudes

\[ |\pi^+\pi^-\rangle = \sqrt{\frac{1}{3}}|2,0\rangle + \sqrt{\frac{2}{3}}|0,0\rangle \]
\[ |\pi^0\pi^0\rangle = \sqrt{\frac{2}{3}}|2,0\rangle - \sqrt{\frac{1}{3}}|0,0\rangle \]

\(\eta\) in terms of Isospin Amplitudes

\[ \eta_{+-} = \varepsilon + \epsilon'(1 - \omega/\sqrt{2}) \]
\[ \eta_{00} = \varepsilon - 2\epsilon'(1 + \sqrt{2}\omega) \]

where

\[ \varepsilon = \epsilon + \frac{\langle 0|H_w|K_2\rangle}{\langle 0|H_w|K_1\rangle} \]
\[ \epsilon' = \frac{1}{\sqrt{2}} \left[ \frac{\langle 2|H_w|K_2\rangle}{\langle 0|H_w|K_1\rangle} - \frac{\langle 0|H_w|K_2\rangle\langle 2|H_w|K_1\rangle}{\langle 0|H_w|K_1\rangle\langle 0|H_w|K_1\rangle} \right] \]
\[ \omega = \frac{\langle 2|H_w|K_1\rangle}{\langle 0|H_w|K_1\rangle} \]

\(\omega\) parametrizes the \(\Delta I = 1/2\) rule, \(|\omega| \approx 0.045\)
\(\epsilon\) parametrizes Indirect CP violation 
\(Re(\epsilon) = 1.63 \times 10^{-3}\), and \(\phi_\epsilon = 43.5^\circ\)
\(\epsilon'\) parametrizes Direct CP Violation and \(\epsilon' \approx \frac{\langle \pi^+ \pi^- |H_w|K_2\rangle}{\langle \pi^+ \pi^- |H_w|K_1\rangle} \)

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We can use
\[ \langle 0 | H_w | K^0 \rangle = A_0 e^{i \delta_0} \quad \langle 2 | H_w | K^0 \rangle = A_2 e^{i \delta_2} \]
\[ \langle 0 | H_w | \bar{K}^0 \rangle = A_0^* e^{i \delta_0} \quad \langle 2 | H_w | \bar{K}^0 \rangle = A_2^* e^{i \delta_2} \]
to express \( \epsilon' \) and \( \epsilon \) in terms of Isospin Amplitudes as
\[
\epsilon' = \frac{i}{\sqrt{2}} e^{i (\delta_2 - \delta_0)} \frac{Re A_2}{Re A_0} \left( \frac{Im A_2}{Re A_2} - \frac{Im A_0}{Re A_0} \right)
\]
\[
\epsilon = \epsilon + \frac{i Im A_0}{Re A_0}
\]
so \( \epsilon' \) is due to a phase difference between Isospin Amplitudes.

Finally, evaluating \( |\eta_{00}/\eta_{+-}|^2 \) we can express
\[
Re(\epsilon'/\epsilon) \approx \frac{1}{6} \left[ 1 - \frac{\Gamma(K_L \to \pi^0 \pi^0)/\Gamma(K_S \to \pi^0 \pi^0)}{\Gamma(K_L \to \pi^+ \pi^-)/\Gamma(K_S \to \pi^+ \pi^-)} \right]
\]

Question 2: What is special about Isospin Amplitudes?

Question 3: Why is the phase of \( \epsilon \approx \) phase of \( \epsilon' \)
\( c'/c \) in the Standard Model

- **CKM Matrix**
  
  Phase in Quark coupling \( \eta \)

\[
A_{K \rightarrow f} = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM}^{i} C_i(\mu) \langle f | Q_i(\mu) | K \rangle
\]

Hadronic matrix element (long-distance contribution) difficult to calculate. Where possible use measurements (eg. \( ReA_0 \) and \( ReA_2 \)).

- **Operator Product Expansion**

- **Penguin Diagrams**

  ![Penguin Diagrams](image)

  **Strong Penguin** (\( Q_6 \))
  
  **EWK Penguin** (\( Q_8 \))

---

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\( \epsilon'/\epsilon \) in the Standard Model

- Contributions to \( \epsilon'/\epsilon \)  
  (Ciuchini)

- Simplified Expression for \( \epsilon'/\epsilon \)  
  (Buras)
  \[
  \mathcal{R}(\epsilon'/\epsilon) = 15 \times 10^{-4} \left[ \frac{\eta \lambda^5 A^2}{1.3 \times 10^{-4}} \right] \left[ \frac{120 \text{MeV}}{m_s(2 \text{GeV})} \right]^2 
  \times \left[ \frac{\Lambda_{\text{MS}}(4)}{300 \text{MeV}} \right]^{0.8} \left[ B_6 - 0.18 \left( \frac{m_t}{M_W} \right)^{1.86} B_8 \right]
  \]

- \( \epsilon'/\epsilon \) Predictions
  \[
  \mathcal{R}(\epsilon'/\epsilon) = (4.6 \pm 3.0 \pm 0.4) \times 10^{-4} \quad (\text{Ciuchini Jan 97})
  \]
  
  \[
  (3.4 \pm 3.4) \times 10^{-4} \quad \text{for } m_s = 150 \pm 20 \text{MeV}
  \]
  
  \[
  (10.4 \pm 8.3) \times 10^{-4} \quad \text{for } m_s = 100 \pm 20 \text{MeV}
  \quad (\text{Buras Aug 96})
  \]
  
  \[
  (17^{+14}_{-10}) \times 10^{-4} \quad \text{for } m_s = 80 \pm 20 \text{MeV}
  \quad (\text{Bertololini Feb 98})
  \]

where hadronic matrix elements are estimated using lattice QCD, 1/N, and the chiral quark model

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Comments on $\epsilon'/\epsilon$ predictions

- **Range of Standard Model Predictions for $\epsilon'/\epsilon$**
  Values range from $(0 - 30) \times 10^{-4}$. However, the central value for 2/3 theorists is in the range $(0 - 10) \times 10^{-4}$.

- **Standard Model vs. SuperWeak Model**
  Standard Model generally predicts $\epsilon'/\epsilon > 0$, SuperWeak $\epsilon'/\epsilon = 0$

- **$m_s$**
  Some Lattice QCD calculations point to smaller $m_s$, but this issue is not settled

- **$\Delta I = 1/2$ Rule**
  To explain the value of $\omega$ the $I = 0$ amplitudes need to be greatly enhanced - is this relevant for $\epsilon'/\epsilon$?, there is not agreement on the connection

Question 4: Why do Strong Penguins and EWK Penguins have opposite contributions to $\epsilon'/\epsilon$?

Question 5: One might expect that Strong/EWK Penguins would go as $\alpha_s/\alpha$, however their contribution to $\epsilon'/\epsilon$ is nearly equivalent - why?

Question 6: Why aren’t there any reliable calculations of Direct CP violation in the B system?

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Exploit the double ratio

\[
\frac{K_L \rightarrow \pi^0 \pi^0 / K_S \rightarrow \pi^0 \pi^0}{K_L \rightarrow \pi^+ \pi^- / K_S \rightarrow \pi^+ \pi^-}
\]

- **Double Beam Technique - Simultaneous** $K_L$ **and** $K_S$ **Beams**
  - Alternating Beams (KTeV) or Convergent Beams (NA-48)
  - Detector Drifts, Inefficiencies, and Asymmetries (almost) Cancel

- **Simultaneous Charged and Neutral**
  - Beam Intensity and $K_S$ Production Cancel

- **Acceptance Corrections**
  - Correct using Simulation and $K_L \rightarrow \pi^0 \pi^0 \pi^0$, $K_L \rightarrow \pi^\pm e^\mp \nu$ decays (KTeV), or Normalize $K_L$ decays to $K_S$ (NA-48)

- **$K_L$ vs. $K_S$ Identification**
  - Separate beams (KTeV), or Proton Tagger (NA-48)

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Almost all $K_S$ decay before reaching the KTeV decay volume.

$K_S$ produced by Regeneration $K_L + \rho K_S$

\[
\sigma(K^0 C^{12}) \neq \sigma(\bar{K}^0 C^{12})
\]

\[
\text{Rate}(\tau) = \Gamma_S \left\{ |\eta|^2 e^{\Gamma_{LT}} + |\rho|^2 e^{\Gamma_{ST}} + 2|\rho||\eta|e^{(\Gamma_S + \Gamma_L)\tau/2}\cos(\Delta m\tau - \phi + \phi_\rho) \right\}
\]

- Coherent $P_T^2 = 0$
  Identical $K_S$ and $K_L$ Beam Profiles

- Diffractive $P_T^2 > 0$ and Inelastic Background, especially in $K \rightarrow \pi^0 \pi^0$

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KTeV Detector

MUON FILTERS
LEAD WALL
CsI CRYSTAL CALORIMETER
HODOSCOPES
DRIFT CHAMBER 4
DRIFT CHAMBER 3
MAGNET
DRIFT CHAMBER 2
DRIFT CHAMBER 1
SPECTROMETER ANTI
HELIUM BAG
RING VETOS
REGENERATOR (E832)
MASK-ANTI (E832)
BEAM
MUON COUNTERS
BACK-ANTI
HADRON-ANTI
TRD'S (E799)

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CP Violation in the Kaon System  

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The NA48 Detector

- Muon veto counters
- Hadron calorimeter
- Liquid krypton calorimeter
- Hodoscope
- Anti counter
- Wire chamber 4
- Wire chamber 3
- Magnet
- Wire chamber 2
- Wire chamber 1
- Beam pipe
- 10 m
K → π⁺π⁻ Reconstruction - KTeV

KTEV Event Display

Run Number: 6918
Spill Number: 1
Event Number: 36632
Trigger Mask: 1

All Slices

Track and Cluster Info
HCC cluster count: 0

ID Xcsi Ycsi Zcsi
C1 0.2100 0.2526 -34.05
C2 0.2129 0.2659 0.45
C3 -0.0009 -0.4219 42.98
C4 0.0042 -0.4036 3.51
C5 -1.1020 -0.4519 3.20
C6 -0.1062 -0.5349 1.23
C7 -0.0739 -0.5346 1.52
C8 -0.1541 -0.2790 0.84

Vertex: 2 tracks
X Y Z
0.0944 -0.0032 138.075

Mass = 0.4972 (assuming pions)

Chisq = 8.66, PTV = 0.000042

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$K \rightarrow \pi^0\pi^0$ Reconstruction - KTeV

Use $\pi^0$ Mass constraint to select best Pairing of 4 $\gamma$ into 2 $\pi^0$

$Z^2 = \frac{E_1 E_2 (D_{12})^2}{M^2_{\pi^0}}$

$\chi^2 = \frac{(Z_a - Z_b)^2}{\sigma^2_{Z_a} + \sigma^2_{Z_b}}$

- Measure $Z_{\pi^0\pi^0}$
- Measure $M_{\pi^0\pi^0}$
- Measure Energy Centroid $X_{\pi^0\pi^0}$ and $Y_{\pi^0\pi^0}$
Electrons from $K \rightarrow \pi \nu$

$N_{\text{events}} = 1.92 \times 10^8$

$\sigma_{E/P} = 0.75\%$

$E/P$ vs. Energy/Momentum

---

*CP Violation in the Kaon System*  
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Here \( K \to \pi^0\pi^0 \) are reconstructed using the \( \pi^0 \) mass.

*CP Violation in the Kaon System*  
Aaron Roodman
Here $K \rightarrow \pi^0\pi^0$ are reconstructed using the Kaon Mass as a constraint.
Kaon Decay Distributions - KTeV

\[ K_{L,S} \rightarrow \pi^+\pi^- \]

\[ K_{L,S} \rightarrow \pi^0\pi^0 \]

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Verify $K \to \pi^+\pi^-$ acceptance using $K_L \to \pi^\pm\pi^\mp\nu$ decays.

There is a slope in the ratio of Data/Monte Carlo for $K_L \to \pi^+\pi^-$. KTeV assigns a systematic uncertainty of $1.6 \times 10^{-4}$ on $\epsilon'/\epsilon$ to account for this discrepancy.
Verify $K \rightarrow \pi^0\pi^0$ acceptance using $K_L \rightarrow \pi^0\pi^0\pi^0$ decays.

There is no significant slope in the ratio of Data/Monte Carlo for $K_L \rightarrow \pi^0\pi^0$. KTeV conservatively assigns a systematic uncertainty of $0.7 \times 10^{-4}$ on $\epsilon'/\epsilon$ based on the $K_L \rightarrow \pi^0\pi^0\pi^0$ slope and error.

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Energy Scale Systematic - $K \rightarrow \pi^0 \pi^0$ decays

Length of Decay region, and hence $K_L$ Acceptance, is determined in $K \rightarrow \pi^0 \pi^0$ decays using the reconstructed Z vertex. However a shift in the calorimeter Energy scale will also shift the Z scale. Both KTeV and NA-48 adjust their Energy scale to match a detector edge.

Energy Scale in $K_S \rightarrow \pi^0 \pi^0$ Events

Regenerator Edge, Data vs. Simulation

the Energy scale in both experiments were off by $\sim 0.1\%$, with systematic uncertainties of less then $1 \times 10^{-4}$
**Kaon Decay Distributions - NA48**

![Graph showing normalized events vs. reconstructed lifetime](image)

**$K_L$ Weighting:** use $K_L$ to measure Acceptance

- **Pros:**
  
  accounts for most of large Acceptance Correction remaining Acceptance correction is $\sim 0.5\%$

- **Cons:**
  
  lose statistical power: 40\% of $K_L$ events
Effect on the double ratio was $\Delta R = (-29 \pm 11 \pm 5) \times 10^{-4}$
$K \to \pi^0\pi^0$ Backgrounds - KTeV

For $K \to \pi^0\pi^0$ decays $K_L$ and $K_S$ are separated using the Energy Centroid

Background is due to diffractive and inelastic regeneration, and is subtracted using a regeneration model fit to $K \to \pi^+\pi^-$ data

where the Ring Number is the distance from the center of the beam.

KTeV assigns a systematic error of on $\epsilon'/\epsilon$ of $0.8 \times 10^{-4}$ from $K \to \pi^0\pi^0$ backgrounds.

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- $K_L \rightarrow K_S$ transitions "dilute" the value of $R$
  \[ \Delta \text{Re}(\varepsilon'/\varepsilon) \simeq 0.3 \Delta (\alpha_{LS}^{00} - \alpha_{LS}^{+-}) \]

- $K_S \rightarrow K_L$ transitions
  From tails in time reconstruction of decays
  \[ \Delta \text{Re}(\varepsilon'/\varepsilon) \simeq 0.9 \Delta (\alpha_{SL}^{+-} - \alpha_{SL}^{00}) \]
In $K \rightarrow \pi^+\pi^-$ use decay vertex to select $K_S$.

and determine $\alpha_{SL}^+ = (1.5 \pm 0.1) \times 10^{-4}$.

Use $K_S$ only runs, $K \rightarrow \pi^0\pi^0$ decays with $\pi^0 \rightarrow e^+e^-\gamma$ or $\gamma \rightarrow e^+e^-$ to limit the change in the double ratio to

$$\Delta R = (0 \pm 6) \times 10^{-4}$$
In $K \rightarrow \pi^+\pi^-$ use decay vertex selected $K_S$ to determine

$$\alpha_{LS}^{+-} = 11.19 \pm 0.03\%$$

Then use side-bands of $\Delta t$ to determine that

$$\alpha_{LS}^{+-} - \alpha_{LS}^{00} = 0.10 \pm 0.05,$$

corresponding to a change to the double ratio of

$$\Delta R = (-18 \pm 9) \times 10^{-4}$$

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KTeV extracts $\epsilon'/\epsilon$ from a fit to $N_{K_L \rightarrow \pi^0\pi^0}(E_t)$, $N_{K_S \rightarrow \pi^0\pi^0}(E_t)$, $N_{K_L \rightarrow \pi^+\pi^-}(E_t)$, $N_{K_S \rightarrow \pi^+\pi^-}(E_t)$ in 10 GeV Kaon Energy bins. The parameters fit were $\epsilon'/\epsilon$, the regeneration phase and amplitude, and separate $K \rightarrow \pi^0\pi^0$ and $K \rightarrow \pi^+\pi^-$ normalizations in 10 GeV Kaon Energy bins.

In addition KTeV performed the analysis **BLIND** to the value of $\epsilon'/\epsilon$. This was done by hiding the fitted value of $\epsilon'/\epsilon$, and instead looking at the parameter

$$\{\epsilon'/\epsilon\}^* = \begin{cases} 1 \\ -1 \end{cases} \times \epsilon'/\epsilon + C$$

where C was an hidden constant with a sigma of 0.006, and the choice of $-1$ or $1$ was also hidden.

The value of $\epsilon'/\epsilon$ was hidden until one week before the result was announced.

This technique reduces or eliminates **Experimenters Bias** from systematically affecting a measurement.

*CP Violation in the Kaon System*  
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### KTeV Result and Systematics

<table>
<thead>
<tr>
<th>Systematics</th>
<th>( \pi^+\pi^- ) Analysis ((\times 10^{-4}))</th>
<th>( \pi^0\pi^0 ) Analysis ((\times 10^{-4}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger (L1/L2/L3)</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Energy Scale</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>CsI non-linearity</td>
<td>—</td>
<td>0.6</td>
</tr>
<tr>
<td>Calibration/Alignment</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Analysis Cuts</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Apertures (incl Reg Edge)</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Detector Resolution</td>
<td>0.4</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>DC simulation</td>
<td>0.6</td>
<td>—</td>
</tr>
<tr>
<td>Overall Acceptance</td>
<td>1.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Monte-Carlo Statistics</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Attenuation Slope</td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>Movable Absorber</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>External Parameters</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Total Systematic</td>
<td></td>
<td>2.8</td>
</tr>
</tbody>
</table>

### KTeV Number of Events

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>(10^6) events</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_L \rightarrow \pi^0\pi^0)</td>
<td>0.86</td>
</tr>
<tr>
<td>(K_S \rightarrow \pi^0\pi^0)</td>
<td>1.43</td>
</tr>
<tr>
<td>(K_L \rightarrow \pi^+\pi^-)</td>
<td>2.61</td>
</tr>
<tr>
<td>(K_S \rightarrow \pi^+\pi^-)</td>
<td>4.52</td>
</tr>
</tbody>
</table>

### KTeV Result is

\[
Re(\epsilon'/\epsilon) = (28.0 \pm 3.0\text{(stat)} \pm 2.8\text{(syst)}) \times 10^{-4}
\]

\[
Re(\epsilon'/\epsilon) = (28.0 \pm 4.1 \times 10^{-4})
\]
Includes only Statistical Errors.
Dividing data into various sub-samples shows no systematic effects.

Note that the KTeV result used $K \to \pi^0\pi^0$ taken in 1996, and $K \to \pi^+\pi^-$ taken in 1997; the $K \to \pi^+\pi^-$ data from 1996 was not used because of a triggering problem which had a 20% inefficiency and an additional systematic uncertainty of $4 \times 10^{-4}$. As a check the 1996 $K \to \pi^+\pi^-$ data was analyzed and found to be consistent with the quoted result.

*CP Violation in the Kaon System*  
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NA-48 Result and Systematics

<table>
<thead>
<tr>
<th>Correction</th>
<th>Correction (10^{-4})</th>
<th>Uncertainty (10^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tagging dilution</td>
<td>+18</td>
<td>9 (stat.)</td>
</tr>
<tr>
<td>Tagging inefficiency</td>
<td>0</td>
<td>6 (stat.)</td>
</tr>
<tr>
<td>Charged trigger eff.</td>
<td>+9</td>
<td>23 (stat.)</td>
</tr>
<tr>
<td>Reconstruction eff.</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Neutral background</td>
<td>-8</td>
<td>2</td>
</tr>
<tr>
<td>Charged background</td>
<td>+23</td>
<td>4</td>
</tr>
<tr>
<td>Beam scattering</td>
<td>-12</td>
<td>3</td>
</tr>
<tr>
<td>Accidental activity</td>
<td>-2</td>
<td>14 (stat.)</td>
</tr>
<tr>
<td>Energy scale/linearity</td>
<td>-</td>
<td>12</td>
</tr>
<tr>
<td>Charged vertex</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Acceptance</td>
<td>+29</td>
<td>12 (MC stat.)</td>
</tr>
<tr>
<td>Total</td>
<td>+57</td>
<td>35</td>
</tr>
</tbody>
</table>

Total Systematic on $\epsilon'/\epsilon$ is $5.8 \times 10^{-4}$.

The systematic from Charged Trigger Efficiency is derived from a limited Data sample used to study the 10% inefficiency in this trigger. Likewise the Accidental Activity systematic is limited by the statistics of the accidental Data sample.

NA-48 Number of Events (before $K_L$ weighting)

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>10^6 events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow \pi^0\pi^0$</td>
<td>0.49</td>
</tr>
<tr>
<td>$K_S \rightarrow \pi^0\pi^0$</td>
<td>0.98</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^+\pi^-$</td>
<td>1.07</td>
</tr>
<tr>
<td>$K_S \rightarrow \pi^+\pi^-$</td>
<td>2.09</td>
</tr>
</tbody>
</table>

NA-48 Result is

\[
Re(\epsilon'/\epsilon) = (18.5 \pm 4.5{stat} \pm 5.8{syst}) \times 10^{-4}
\]

\[
Re(\epsilon'/\epsilon) = (18.5 \pm 7.3 \times 10^{-4}
\]

CP Violation in the Kaon System

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NA-48 Checks

\[ \chi^2/\text{ndf} \]

\[ 6.944 / 5 \]

\[ \chi^2/\text{ndf} \]

\[ 1.620 / 4 \]

\[ \chi^2/\text{ndf} \]

\[ 4.098 / 4 \]

\[ \chi^2/\text{ndf} \]

\[ 7.424 / 6 \]

No systematic effects

*CP Violation in the Kaon System*  
Aaron Roodman
Includes Kaon Energy dependent corrections, and systematics errors which depend on Kaon Energy.
Combining recent $\varepsilon'/\varepsilon$ measurements

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\varepsilon'/\varepsilon \times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-731</td>
<td>7.4 ± 6.0</td>
</tr>
<tr>
<td>NA-31</td>
<td>23.0 ± 6.5</td>
</tr>
<tr>
<td>KTeV</td>
<td>28.0 ± 4.1</td>
</tr>
<tr>
<td>NA-48</td>
<td>18.5 ± 7.3</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>21.2 ± 2.8</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>21.2 ± 4.7</td>
</tr>
</tbody>
</table>

$CP$ Violation in the Kaon System

Aaron Roodman
**$\epsilon'/\epsilon$ Prospects**

- **KTeV**
  
  KTeV 1996-1997 run has four times more data - with roughly $5 \times 10^6$ $K_L \rightarrow \pi^0\pi^0$ decays. Analysis is ongoing.  
  
  Also, KTeV is running now, with a goal of doubling the total data sample. Small inefficiencies in the Drift Chamber, and Calorimeter electronics problems have been improved.

- **NA-48**
  
  NA-48 1998 run took three times more data. Calorimeter capacitor problem fixed, and Charged trigger inefficiency reduced.  
  
  Goal for 1999 run is to double the statistics.

- **KLOE**
  
  $\phi \rightarrow K_LK_S$. Coherence of the $K_L$ and $K_S$ allows for a different $\epsilon'/\epsilon$ measurement. KLOE is just beginning to take data.

- **$\epsilon'/\epsilon$ Predictions**
  
  Optimism that predictions can improve - Lattice QCD

**Question 7** : Which technique for measuring $\epsilon'/\epsilon$ would you choose?

**Question 8** : New Physics?
DAΦNE φ Factory

\( \phi \to |K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle \)

\[
R(\pi^+\pi^-\pi^0\pi^0, \Delta t) = \\
\frac{1}{2\Gamma} |\langle \pi^+\pi^-|K_S\rangle\langle \pi^0\pi^0|K_S\rangle|^2 \\
\left\{ |\eta_{+-}|^2 e^{-\gamma_{\Delta t}} + |\eta_{00}|^2 e^{-\gamma_{\Delta t}} - \\
2|\eta_{+-}||\eta_{00}| e^{-\gamma_{\Delta t}/2} \cos (\Delta m\Delta t + \Delta \phi) \right\} \\
\text{for } \Delta t = 0
\]

Events/cm

\[
\int L \, dt = 10^{40} \text{ cm}^{-2}
\]

Re (\(\epsilon'\epsilon\))=0.01

Im (\(\epsilon'\epsilon\))=0.0

\(D=D_1-D_2\) (cm)

\(CP\) Violation in the Kaon System

Aaron Roodman
T-violation at CPLEAR

CPLEAR

\[ p\bar{p} \rightarrow \begin{cases} 
K^-\pi^+K^0 \\
K^+\pi^-K^0 
\end{cases} \]

Decay of \( \bar{K}^0 \rightarrow \pi^-e^+\nu_e \)

Tag Kaon flavor at \( t=0 \) by detecting \( K^+ \) or \( K^- \)
T-violation at CPLEAR

If time reversal invariance is violated

\[ P \left\{ K^0(t = 0) \rightarrow \bar{K}^0(t = \tau) \right\} \neq P \left\{ \bar{K}^0(t = 0) \rightarrow K^0(t = \tau) \right\} \]

\[ A_T(\tau) = \frac{R(\bar{K}^0_{t=0} \rightarrow e^+\pi^-\nu_{t=\tau}) - R(K^0_{t=0} \rightarrow e^-\pi^+\nu_{t=\tau})}{R(\bar{K}^0_{t=0} \rightarrow e^+\pi^-\nu_{t=\tau}) + R(K^0_{t=0} \rightarrow e^-\pi^+\nu_{t=\tau})} \]

\[ A_T(\tau) = 4 \text{Re}(\epsilon) - 4 \text{Re}(y + x_-) \]

CPLEAR limits on CPT violation in \( K_L \rightarrow \pi^\pm e^\mp \nu \) decays are \( \text{Re}(y + x_-) = (-0.2 \pm 0.3) \times 10^{-3} \)

\[ A_T = (6.6 \pm 1.3(\text{stat}) \pm 1.0(\text{syst})) \times 10^{-3} \]
T-odd asymmetry in $K_L \rightarrow \pi \pi ee$

Bremstrahlung term is CP Violating
Direct Emission (M1) term is CP Conserving
Interference is CP Violating and produces an Angular asymmetry $\sim \sin \phi \cos \phi$

\[ \hat{n}_{ee} = \frac{\hat{p}_e \times \hat{p}_e}{|\hat{p}_e \times \hat{p}_e|} \]

\[ \hat{n}_{\pi\pi} = \frac{\hat{p}_{\pi^+} x \hat{p}_{\pi^-}}{|\hat{p}_{\pi^+} x \hat{p}_{\pi^-}|} \]

\[ \hat{z} = \frac{\hat{p}_{\pi^+} + \hat{p}_{\pi^-}}{|\hat{p}_{\pi^+} + \hat{p}_{\pi^-}|} \]

\[ \sin \phi \cos \phi = (\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \cdot \hat{z}(\hat{n}_{ee} \cdot \hat{n}_{\pi\pi}) \]

\[ A = \frac{N_{\sin \phi \cos \phi > 0} - N_{\sin \phi \cos \phi < 0}}{N_{\sin \phi \cos \phi > 0} + N_{\sin \phi \cos \phi < 0}} \]

$A = 14.4\%$ is predicted

Question 9: Is this asymmetry T-violating?

Can Violation in the Kaon System

Aaron Roodman
Asymmetry in $K_L \rightarrow \pi \pi ee - KTeV$

$K_L \rightarrow \pi^+ \pi^- \pi^0$ Decays show no Asymmetry - Detector acceptance is symmetric

$$Br(K_L \rightarrow \pi\pi ee) = (3.32 \pm 0.14\text{(stat)} \pm 0.28\text{(syst)}) \times 10^{-7}$$

$$A = 13.6 \pm 2.5\text{(stat)} \pm \text{(syst)}\%$$

CP Violation in the Kaon System

Aaron Roodman
\[ \phi_{+-} \text{ and } \Delta \phi = \phi_{+-} - \phi_{00} \]

- KTeV - Interference in Regenerator Beam \( K_L + \rho K_S \)

![Graph showing π⁺π⁻ data and prediction without interference for 1997a dataset, 30-35 GeV.]

Preliminary results:

\[ \phi_{+-} = 43.66^o \pm 0.30^o + 0.23^o \left( \frac{\Delta m - 0.5286}{0.0010} \right) + 0.26^o \left( \frac{\tau - 0.8967}{0.0010} \right) \]

\[ \Delta \phi = 0.09 \pm 0.43 \text{(stat)} \pm 0.15 \text{(syst)} \]

- CPLEAR - Asymmetry between \( K^0 \) and \( \bar{K}^0 \)

![Graph showing asymmetry between \( K^0 \) and \( \bar{K}^0 \).]

\[ \phi_{+-} = 43.19^o \pm 0.23^o \pm 0.26 \pm 0.007 \tau_s \]

- CPT still conserved

---

*CP Violation in the Kaon System*  
*Aaron Roodman*
\[ K_L \rightarrow \pi^0 \nu \bar{\nu} \]

Leading order electroweak diagrams contributing to \( K \rightarrow \pi \nu \bar{\nu} \) in the Standard Model.

\[
\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = 3.0 \times 10^{-11} \left( \frac{\eta}{0.39} \right)^2 \left( \frac{m_u(m_d)}{170 \text{GeV}} \right)^{2.3} \left( \frac{|V_{us}|}{0.040} \right)^4
\]

Clean measurement of \( \eta \) in the Standard Model. The Decay is due to Direct CP violation, with negligible CP conserving contributions. The theoretical predictions do not suffer from hadronic matrix uncertainties - no long distance effects.

The Predicted \( \text{Br} \sim 3 \times 10^{-11} \) and the experimental signature is a single \( \pi^0 \) at \( P_T > 0 \)

Conservation of Experimental Difficulty \times Theoretical Simplicity

Question 10: Why is \( K_L \rightarrow \pi^0 \nu \bar{\nu} \) theoretically clean?
KTeV limits on $K_L \rightarrow \pi^0 \nu \bar{\nu}$

$\pi^0 \rightarrow \gamma \gamma$

$K_L \rightarrow \pi^0 \nu \bar{\nu}$

Z vertex with $\pi^0 \rightarrow \gamma \gamma$

Br $< 1.6 \times 10^{-6} (90\% C.L.)$

$\pi^0 \rightarrow e^+ e^- \gamma$

Br $< 5.9 \times 10^{-7} (90\% C.L.)$
Proposed $K_L \rightarrow \pi^0 \nu \bar{\nu}$ experiments

Dominant background is $K_L \rightarrow \pi^0 \pi^0$ where 2 $\gamma$ are lost

Signal to Background can be approximated by

$$\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \sim \left\{ \text{Br}(K_L \rightarrow \pi^0 \pi^0) = 1 \cdot 10^{-3} \right\} \cdot \left\{ \gamma \text{Rejection} = 10^{-5} \right\}^2$$

- **KAMI**
  Relies on hermetic Veto. Higher Energy Kaons implies that more $\gamma$ are at higher Energy - where photon inefficiency is lowest.

- **KEK**
  Also relies on hermetic veto. Somewhat less ambitious projected sensitivity.

- **BNL E-942**
  Relies on both Kinematic constraints and hermetic Veto. Kinematic constraints derived from measurement of $\gamma$ angles, which provides an independent measurement of the decay vertex, and from Kaon timing, which permits a complete reconstruction of the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay.
Rejection for $K_L \rightarrow \pi^0 \nu \bar{\nu}$

Pb/Scintillator $\gamma$ veto

CsI $\gamma$ veto

$CP$ Violation in the Kaon System

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