The Measurement of $\epsilon' / \epsilon$ by KTeV collaboration

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For the KTeV Collaboration:
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Fermilab – Osaka – Rice – Rutgers
UCLA – UCSD – Virginia – Wisconsin
Introduction to $\epsilon'/\epsilon$

- Weak eigenstates contain small admixture of "wrong" $CP$ state

$$|K_S\rangle \sim |K_1\rangle + \epsilon|K_2\rangle$$
$$|K_L\rangle \sim |K_2\rangle + \epsilon|K_1\rangle$$

$$K_L = \overset{CP}{K_2} + \epsilon \overset{CP+1}{K_1}$$

- "Direct" in decay process
- "Indirect" from asymmetric $K^0-\bar{K}^0$ mixing

- Useful to define the following measurable quantities

$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+ \pi^-)}{A(K_S \to \pi^+ \pi^-)} = \epsilon + \epsilon'$$

$$\eta_{00} \equiv \frac{A(K_L \to \pi^0 \pi^0)}{A(K_S \to \pi^0 \pi^0)} = \epsilon - 2\epsilon'$$

$$\left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 \simeq 1 + 6\Re(\epsilon'/\epsilon)$$
Define amplitudes to $\pi\pi$ states of a definite isospin:

\[
< I|T|K^0 > = (A_I + B_I) e \\
< I|T|\bar{K}^0 > = (A_I^* - B_I^*) e
\]

$\Im(A_I)$ – CP violation  
$\Re(B_I)$ – CP & CPT violation  
- final state interaction phase shifts,

\[
\epsilon'_{CP} \approx \frac{i}{\sqrt{2}} \frac{\Re(A_2)}{\Re(A_0)} \left[ \frac{\Im(A_2)}{\Re(A_2)} - \frac{\Im(A_0)}{\Re(A_0)} \right] e \\
\epsilon'_{CPT} \approx \frac{1}{\sqrt{2}} \frac{\Re(A_2)}{\Re(A_0)} \left[ \frac{\Re(B_2)}{\Re(A_2)} - \frac{\Re(B_0)}{\Re(A_0)} \right] e
\]

\[
\frac{\Re(A_2)}{\Re(A_0)} = \omega = 0.045, \text{ "\Delta = 1/2 rule"}
\]
— a 50 years old problem!

As numerically $\epsilon$ is almost parallel to $\epsilon'_{CP}$, 
  
- $\Re(\epsilon'/\epsilon)$ – Measure of direct CP violation.
- $\Im(\epsilon'/\epsilon)$ – Measure of CPT violation.
With the interference information in the regenerator beam, KTeV can measure not only decay rates but also phases as well as other kaon sector parameters:

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- 
- 

For small $\imath \left( e'/e \right) = -\frac{1}{3} \Delta \phi$
The KTeV Detector

beam \approx K_L \text{ beam}

"Regenerator" beam \approx K_S \text{ beam}
- Magnetic spectrometer to reconstruct kinematics.
- Regenerator/Vacuum beam identification using X-vertex position
- Clearance cuts to define detector volume.
• CsI calorimeter to reconstruct photons energies and positions
• $Z_v$ determined as average of

• Regenerator/Vacuum beam identification using X-center of energy
• Detector volume defined by veto detectors and $Z_v$
Data Collection

\[ \eta_{\pm} \]

Data yields in Vacuum beam (mln):

<table>
<thead>
<tr>
<th>Year</th>
<th>$K \rightarrow \pi^+\pi^-$</th>
<th>$K \rightarrow \pi^0\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>-</td>
<td>0.8</td>
</tr>
<tr>
<td>97</td>
<td>8.6</td>
<td>2.5</td>
</tr>
<tr>
<td>99</td>
<td>14.9</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Combination of 96 and 97 datasets.
Due to the different lifetimes \( \tau_L \gg \tau_S \), the \( K_S \) beam probes a different region of the detector that the \( K_L \) beam, and hence has a different acceptance.

Need an analysis technique to put two beams on equal footing.
Acceptance correction based on Monte Carlo with ideal detector response: $\Delta(\mathcal{R}(\epsilon'/\epsilon)) \approx 12 \times 10^{-4}$, out of that $\sim 10 \times 10^{-4}$ is seen as a $Z$-slope.

$\rightarrow$ corrections due to detector simulation $\sim 10 \times 10^{-4}$. 
Final Test of MC Acceptance

The final check of the acceptance is the vertex $z$ distribution in the vacuum beam, due to different vertex $z$ distributions in vac/reg beams.

\[ K \rightarrow \pi^+ \pi^- \& K_{e3} \text{ (data 1997b)} \]
\[ N(p, z) \sim |\rho|^2 e^{-\Gamma_s t} + |\eta|^2 e^{-\Gamma_L t} + 2|\rho||\eta|\cos(\Delta m t + \phi_\rho - \phi_\eta)e^{-\Gamma t} \]

- Regeneration amplitude \( \rho \) cancels out for \( \epsilon'/\epsilon \).
- For \( \Re(\epsilon'/\epsilon) \) fit integrated yield in Regenerator beam. Assume CPT, \( \Delta m, \tau_S, \Re(\epsilon'/\epsilon) = 0 \).
- For \( \Im(\epsilon'/\epsilon) \) fit shape in Regenerator beam. \( \Delta m, \tau_S, \epsilon'/\epsilon \)
### Uncertainties in $\epsilon'/\epsilon$

<table>
<thead>
<tr>
<th>Type of measurement</th>
<th>Counting experiment</th>
<th>Z-E shape (proper time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainty</td>
<td>1.6</td>
<td>13.</td>
</tr>
<tr>
<td>Main systematics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceptance</td>
<td>1.4</td>
<td>16.</td>
</tr>
<tr>
<td>Migrations</td>
<td>1.4</td>
<td>22.</td>
</tr>
<tr>
<td>Background</td>
<td>1.1</td>
<td>8.</td>
</tr>
<tr>
<td>Total systematics</td>
<td>2.3</td>
<td>28.</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>2.7</td>
<td>31.</td>
</tr>
</tbody>
</table>

Acceptance: all data collection uncertainties and Z slope

Migrations: mainly calorimeter energy scale and non-linearity

Background: regenerator scattering background
Use $E/p$ for electrons to calibrate response of individual crystals.
- Perform final correction using sharp edge of the distribution in the regenerator beam \( \left( \Delta \mathcal{R}(\epsilon'/\epsilon) = +2.1 \times 10^{-4} \right) \)

- Use \( P_K \) dependent correction.

- Applying of a flat scale is different by \( \Delta \mathcal{R}(\epsilon'/\epsilon) = 0.6 \times 10^{-4} \)
Cross Checks of the Energy Scale

- Use different methods to cross-check energy calibration: $K \rightarrow \pi^+ \pi^- \pi^0$, $K_S^* \rightarrow \pi^0 K_S$, $K \rightarrow 2\pi^0$ Dalitz, $\eta \rightarrow 3\pi^0$ hadronic production of $2\pi^0$.
- Use hadronic production of $2\pi^0$ at the Vacuum Window to set uncertainty in the energy scale.
- Assume linear scale variation from Regenerator edge. Use $\pi^+ \pi^- \pi^0$ to check that.
Kaon Sector Parameters as Measured in KTeV

\[
\begin{align*}
\Delta m &= (52.62 \pm 15) \times 10^8 \text{fs}^{-1} \\
\tau_S &= (89.65 \pm 6) \times 10^{-12} \text{s} \\
\phi_{+-} &= [44.12 \pm 0.72 \text{ (stat)} \pm 1.14 \text{ (syst)}]^{\circ}
\end{align*}
\]

KTeV results for \(\Delta m\) and \(\tau_S\) are as precise as current world averages.
KTeV Result on $\mathcal{R}(\epsilon'/\epsilon)$

Fit to $\mathcal{R}(\epsilon'/\epsilon)$ with CPT conservation assumption:

$\mathcal{R}(\epsilon'/\epsilon) = [20.7 \pm 1.5 \text{ (stat)} \pm 2.4 \text{ (syst)}$

$\pm 0.5 \text{ (MC stat)}] \times 10^{-4}$

$= [20.7 \pm 2.8 \text{ (tot)}] \times 10^{-4}$

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Re($\epsilon'/\epsilon$)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E731</td>
<td>7.4 ± 5.9</td>
</tr>
<tr>
<td>NA31</td>
<td>23 ± 6.5</td>
</tr>
<tr>
<td>NA48 01</td>
<td>15.3 ± 2.6</td>
</tr>
<tr>
<td>$&lt;$1eV 01 (prel)</td>
<td>20.7 ± 2.8</td>
</tr>
<tr>
<td>New World Ave.</td>
<td>17.2 ± 1.8</td>
</tr>
</tbody>
</table>

(prob = 13%)
Top secret:
In the fit to determine \( \xi(\epsilon'/\epsilon) \) we must float \( \Re() \) part as well. Because of the correlation, the error in \( \Re(\epsilon'/\epsilon) \) is increased:

up from \( \Delta \) by \( \Delta \).

\[ \rightarrow \text{NA48 beats KTeV if CPT is violated!} \]
\[ \Im(\epsilon'/\epsilon) = [-24.1 \pm 12.8 \text{ stat} \pm 27.9 \text{ syst}] \times 10^{-4} \]
\[ = [-24.1 \pm 30.7] \times 10^{-4} \]

- Different Fermilab experiments have various regenerator lengths \((K_L \text{ to } K_S \text{ ratios})\) different correlation of \(\Re(\epsilon'/\epsilon)\) and \(\Im(\epsilon'/\epsilon)\)
- Inclusion of NA48 helps to reduce error on \(\Im(\epsilon'/\epsilon)\) by about 15%.
Conclusions

- Direct CP violation in kaon sector is established. $\Re(\epsilon'/\epsilon)$ is known to 10%.

- Measurements of $\Im(\epsilon'/\epsilon)$ are not quite as precise yet. Current data is consistent with CPT conservation.

- Results from KTeV and NA48 are consistent/complimentary.

- With more KTeV data (99) and improvements in the understanding of the calorimeter energy scale we might hope to reduce uncertainty in $\Im(\epsilon'/\epsilon)$.

- The current round of experiments might end up with knowledge of $\Re(\epsilon'/\epsilon)$ and about uncertainty in ... It is a great progress but there is certainly some room for improvement!