Rare K decays and $V_{td}$

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What can we learn from $K_L^0 \to \pi^0 \ell^+ \ell^-$, $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L^0 \to \pi^0 \nu \bar{\nu}$ about the unitarity triangle?


<table>
<thead>
<tr>
<th>K^+ → π^+ν̅ν</th>
<th>K_L^0 → π^0ν̅ν</th>
<th>K_L^0 → π^0e^+e^-</th>
<th>K_L^0 → π^0μ^+μ^-</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 × 10^{-11}</td>
<td>3 × 10^{-11}</td>
<td>4 × 10^{-11}</td>
<td>1 × 10^{-11}</td>
<td>B(SM)</td>
</tr>
<tr>
<td>(1.47^{+1.30}_{-0.89}) × 10^{-10}</td>
<td>&lt; 5.9 × 10^{-7}</td>
<td>&lt; 2.8 × 10^{-10}</td>
<td>&lt; 3.8 × 10^{-10}</td>
<td>B(expt)</td>
</tr>
<tr>
<td>10%</td>
<td>&lt; 2%</td>
<td>10%</td>
<td>10%</td>
<td>σ_B/B</td>
</tr>
<tr>
<td></td>
<td>Im(λ_t)</td>
<td>Im(λ_t)</td>
<td>Im(λ_t)</td>
<td>UT</td>
</tr>
<tr>
<td>E787/E949</td>
<td>E391a</td>
<td>NA48/5</td>
<td>NA48/5</td>
<td>Expts</td>
</tr>
<tr>
<td>1989-2002(+)</td>
<td>2002-</td>
<td></td>
<td></td>
<td>When</td>
</tr>
<tr>
<td>CKM2,NA48/3</td>
<td>KOPIO</td>
<td></td>
<td></td>
<td>Expts</td>
</tr>
<tr>
<td>2009?</td>
<td>2010-</td>
<td></td>
<td></td>
<td>When</td>
</tr>
</tbody>
</table>

λ_t ≡ V_{ts}^*V_{td},  All limits at 90% CL. * Assumes positive interference (next pages)

K → πν¯ν and K_L^0 → π^0ℓ^±ℓ^- detection overview

Large kaon flux (> 10^{14}), typical few % or less acceptance

K → πν¯ν  
Poor kinematic signature

Veto on extra particles

Acceptance loss from accidental vetos

K_L^0 → π^0ℓ^±ℓ^-  
Good kinematic signature

γγℓ^±ℓ^- irreducible background

More information available from decay dynamics

and K_S^0K_L^0 interference
Measuring $K_L^0 \to \pi^0 \ell^+ \ell^-$

$$B(K_L^0 \to \pi^0 \ell^+ \ell^-) = \left(C_{mix} \pm C_{int} \frac{Im\lambda_t}{10^{-4}} + C_{dir} \left(\frac{Im\lambda_t}{10^{-4}}\right)^2 + C_{CP}\right) \times 10^{-12}$$

<table>
<thead>
<tr>
<th>$\ell\ell$</th>
<th>$C_{mix}$</th>
<th>$C_{int}$</th>
<th>$C_{dir}$</th>
<th>$C_{CP}$</th>
<th>$B(K_L^0 \to \pi^0 \ell^+ \ell^-)$</th>
<th>$B(K_L^0 \to \gamma\gamma\ell\ell)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^-$</td>
<td>$15.7</td>
<td>a_S</td>
<td>^2$</td>
<td>$6.2</td>
<td>a_S</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$(1.7^{+0.7}_{-0.6}) \times 10^{-11}$ (−)</td>
<td>$10^{-10}$ with cuts</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>$3.7</td>
<td>a_S</td>
<td>^2$</td>
<td>$1.6</td>
<td>a_S</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$(1.0 \pm 0.2) \times 10^{-11}$ (−)</td>
<td>?</td>
</tr>
</tbody>
</table>

$B(K_L^0 \to \pi^0 e^+e^-)$ measurement: Effective $B$ of main background to $ee$ mode can be reduced with cuts, optimistically assuming signal/background of $1/2.5$, implies a $\sim 10\%$ measurement of $B$ would require $350\pi^0 ee$ events or $7 \times 10^{15} K_L$ with a $1\%$ acceptance (including the decay probability). This would take a year at J-PARC ($2 \times 10^{14}$p/spill) with $10^9 K_L / 3.4$s.

Additional possibilities to extract more information from these decays using Dalitz plot information, $\mu$ polarization and/or $K_L$-$K_S$ interference.

Ref: Isidori, Smith, Unterdorfer EPJ C36 (2004) 15, $|a_S| = 1.2 \pm 0.2$, uncertainties in $C$ coefficients omitted from table.
\[ K^+ \rightarrow \pi^+ \nu\bar{\nu} \text{ at E787/E949} \]

Incident 710 MeV/c K\(^+\) beam at 6 MHz, 1.6 MHz stop in target.

Total of \(5.9 \times 10^{12}\) (E787) and \(1.8 \times 10^{12}\) (E949) stopped K\(^+\) used for analysis above K\(^+\) \(\rightarrow \pi^+\pi^0\) peak.

<table>
<thead>
<tr>
<th>Source</th>
<th>Suppression method</th>
<th>(\pi^+) momentum in K(^+) rest frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+ \rightarrow \mu^+\nu(\gamma))</td>
<td>Kine, PID, Veto</td>
<td>[Graph showing (\pi^+) momentum distribution]</td>
</tr>
<tr>
<td>(K^+ \rightarrow \pi^+\pi^0)</td>
<td>Kine, Veto</td>
<td>[Graph showing (\pi^+) momentum distribution]</td>
</tr>
<tr>
<td>Scattered beam</td>
<td>Veto</td>
<td>[Graph showing (\pi^+) momentum distribution]</td>
</tr>
<tr>
<td>CEX</td>
<td>Veto</td>
<td>[Graph showing (\pi^+) momentum distribution]</td>
</tr>
</tbody>
</table>

Veto includes both \(\gamma\) and charged particle vetoing.

CEX \(\equiv K^+n \rightarrow K^0p, K^0_L \rightarrow \pi^+\ell^-\nu\)

PID includes Cherenkov, \(dE/dx\) and \(\pi \rightarrow \mu \rightarrow e\) detection.

Kine: independent \(P, E, R\) measurements of outgoing \(\pi^+\)
E787/E949 technique

- “Blind” analysis. Don’t examine signal region until all backgrounds verified.
- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \rightarrow \pi^+ \pi^0)$. 
E787/E949 results

\[ \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10} \ \text{(68\%CL interval)} \]

\[ \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10} \ \text{(SM prediction)} \]

Range (cm) vs Energy (MeV) for combined E787 and E949 data after all other cuts applied.
Dashed line is E787 signal region.
Solid line is E949 signal region.
The probability that background alone gave rise to the three observed events or to any more signal-like configuration is 0.001.
\textbf{pnn2: }$K^+ \to \pi^+ \nu \bar{\nu}$ below $K^+ \to \pi^+ \pi^0$ peak

More phase space than pnn1
Less loss due to $\pi^+ N$ interactions
Probes more of $K^+ \to \pi^+ \nu \bar{\nu}$ spectrum

\textbf{E787: } 1 candidate

- $1.7 \times 10^{12}$ stopped $K^+$
- $1.22 \pm 0.24$ background

$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) < 22 \times 10^{-10}$

Main background is $K^+ \to \pi^+ \pi^0$ with $\pi^+$ scattered in target.

\textbf{E949 analysis of }$1.8 \times 10^{12}$ stopped $K^+$ in progress with improved $\gamma$ veto.

Assuming same acceptance as pnn1 with $S/B = 1$, yields an estimated improvement in $\sigma(\mathcal{B})/\mathcal{B}$ of $\approx 15\%$. 
Next measurements(s) of $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$?

LOI to measure $\sim 50$ $K^+ \to \pi^+ \nu \bar{\nu}$ decays at rest at J-PARC. There are also two efforts to accumulate $K^+ \to \pi^+ \nu \bar{\nu}$ samples of $\sim 100$ events from $K^+$ decay-in-flight using high momentum beams.

1. NA48/3 at CERN would use upgraded NA48/2 beam and detector.

2. The CKM experiment (E921) was approved at FNAL to measure $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ with 100 events in 22 GeV/c separated kaon beam. October 2003 : P5 stops CKM “...an elegant world class experiment...” which “...based on present budgetary models should not proceed” Adapt to $\sim 45$ GeV/c unseparated beam in KTeV hall (P940*), reuse some of KTeV detector.

Photon vetoing ($K^+ \to \pi^+ \pi^0$ suppression) easier at high energies.

Backgrounds above and below $K^+ \to \pi^+ \pi^0$ peak should be similar, so more acceptance possible compared to E787/E949.

High rate (30-40 MHz/cm$^2$) beam tracking needed and possible with KABES (NA28/2).

*P940 is referred to as “CKM2” in this talk.
**Next measurements(s) of $B(K^+ \to \pi^+\nu\bar{\nu})$?**

Assumes 2 years running and $B(K^+ \to \pi^+\nu\bar{\nu}) = 1 \times 10^{-10}$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>CKM2</th>
<th>NA48/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(K)$ GeV/c</td>
<td>37 to 53</td>
<td>75 ± 1</td>
</tr>
<tr>
<td>$p/\pi^+/K^+$ MHz</td>
<td>120/100/10</td>
<td>160/480/48</td>
</tr>
<tr>
<td>$K^+$ ID</td>
<td>RICH + mag.spect.</td>
<td>Thres Č and double mag. spect.</td>
</tr>
<tr>
<td>$\pi^+$ ID</td>
<td>RICH + mag.spect.</td>
<td>double mag. spect.</td>
</tr>
<tr>
<td>Sensitive K decays</td>
<td>$2.5 \times 10^{13}$</td>
<td>$0.8 \times 10^{13}$</td>
</tr>
<tr>
<td>Acceptance</td>
<td>4%</td>
<td>10%</td>
</tr>
<tr>
<td>pnn Total</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>Signal/bkgd</td>
<td>$\sim 10$</td>
<td>2</td>
</tr>
<tr>
<td>$\sigma(B)/B$</td>
<td>&lt; 12%</td>
<td>14%</td>
</tr>
<tr>
<td>Year</td>
<td>?</td>
<td>2009</td>
</tr>
</tbody>
</table>

**Note:** E787/E949 acceptance $\sim 0.2\%$
$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ History, Progress and Prospects

KTeV result with “pencil” $K_L^0$ beam (PLB447 (1999) 240). E391a, JHF/J-PARC expts use a similar technique.
E391a at KEK: sensitivity goal of $10^{-10}$
±2 mrad “pencil” beam
peak $P(K) = 2 \text{ GeV/c}$, mean $P(K) = 3.4 \text{ GeV/c}$
2.4% decay prob. in fiducial volume
$5 \times 10^5 \ (3 \times 10^7)$ incident $K_L^0(n)$ per 2s spill at detector entrance
CsI calorimeter to detect $\pi^0 \rightarrow \gamma\gamma$
$M_{\pi^0}$ constraint determines decay vertex along beam line
Accept events with $P_T > 120 \text{ MeV/c}$
4π veto detectors
E391a backgrounds

Main $K_L^0$ background is $K_L^0 \rightarrow \pi^0\pi^0$ when $2\gamma$ escape detection. $\mathcal{B}(K_L^0 \rightarrow \pi^0\pi^0) = 9.32 \times 10^{-4}$ implies a need for $\sim 10^{-4} \gamma$ veto inefficiency to suppress to SM signal level. Hermetic $\gamma$ veto required.

Neutron flux is $\sim 60 \times$ the $K_L^0$ flux or $\sim 3 \times 10^7$ per 2s spill.

Neutron interactions ($nN \rightarrow \pi^0X$) in residual gas suppressed with decay region vacuum $10^{-5}$ Pa ($< 10^{-7}$ Torr).

Collimation system suppresses halo-to-core flux ratio to $< 10^{-4}$. 
The first dedicated $K_L^0 \to \pi^0 \nu \nu$ experiment.

1. Run I (Feb-Jun 2004)
   - 187 physics
   - $1.6 \times 10^{10} K_L^0$ decays
   - 300 shifts:
     - 24 calibration
     - 89 tuning, studies
   - A small portion of the data set is being analyzed now to understand the detector performance.

2. Run II (Feb 2005 - end March 2005) 100 shifts so far
   - Added Be absorber to reduce neutron flux.
   - $0.52 \times 10^{10} K_L^0$ decays (100 shifts)

3. Run III (autumn 2005) 100 shifts requested

Runs I+II+II : $2.7 \times 10^{10}$ total $K_L^0$ decays
If acceptance = 8% as in proposal, SES $\approx 5 \times 10^{-10}$.

There is an LOI to move an upgraded E391a to J-PARC, if the “pencil” beam and hermetic veto concept can be demonstrated to be successful.
The KOPIO Technique: Work in $K_L^0$ CMS

Measure everything possible.
Microbunched $K_L^0$ beam
Measure $\gamma$ directions in PR
Measure $\gamma$ energy in CAL
Reconstruct $\pi^0$ from $\gamma\gamma$
Measure $K_L^0$ velocity from TOF
Photon veto
Charged track veto
Kinematic veto
Expected results from KOPIO

KOPIO final result at $B(K^0_l \rightarrow \pi^0 \nu \bar{\nu}) = 3 \times 10^{-11}$

<table>
<thead>
<tr>
<th>s: signal</th>
<th>b: background</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>b / s</th>
<th>integral number of events</th>
<th>$\Sigma b$, statistical error (right scale)</th>
<th>$\Sigma (b+s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>60</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1.0</td>
<td>50</td>
<td>0.01</td>
<td>0.16</td>
</tr>
<tr>
<td>1.5</td>
<td>40</td>
<td>0.02</td>
<td>0.14</td>
</tr>
<tr>
<td>2.0</td>
<td>30</td>
<td>0.03</td>
<td>0.12</td>
</tr>
<tr>
<td>2.5</td>
<td>20</td>
<td>0.04</td>
<td>0.10</td>
</tr>
<tr>
<td>3.0</td>
<td>10</td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td>3.5</td>
<td>0</td>
<td>0.06</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Equivalent Standard Model Events

- 4th generation
- SUSY w/ R (LFV)
- Extra vector quarks

Excluded Region ($5\sigma$)

Enhanced Z-Penguins
MSSM
Z' Technicolor
MFV
Isosinglet d quark

Standard Model

Excluded Region ($5\sigma$)

KOPIO Run Duration (Hours @ 100TP/pulse)

Grossman-Nir Limit from E949
What can rare K decays tells us in the next few years?

If E391a sees a $K^0_L \to \pi^0\nu\bar{\nu}$ signal, the SM is wrong.

Otherwise we’ll have to wait five or more years for $K^+ \to \pi^+\nu\bar{\nu}$ and $K^0_L \to \pi^0\nu\nu$ decays to tell us something about $V_{td}$.

The figure shows what rare kaon decays might tell us at the CKM2015 workshop.

Thanks to T. Inagaki, G.-Y. Lim, L. Littenberg, S. Kettell, T. Komatsubara, M. Sivertz.