Kaon Decay Experiments at J-PARC

Takeshi K. Komatsubara (KEK-IPNS)
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Outline [in the next 24 slides, 25 minutes]

• past/current program at KEK-PS
  – history
    * E246/E470: T-violating $P_T$ in $K^+ \rightarrow \pi^0 \mu^+ \nu$, .. [J.Imazato]
    * E391a: CP-violating decay $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ [T.Inagaki]

• future program at J-PARC new 50GeV-PS
  – Physics Motivation
  – Letters of Intent for J-PARC kaon experiments
    * beamlines, detectors

• future kaon programs in foreign countries

• Roads to the J-PARC experiments
<table>
<thead>
<tr>
<th>KEK-PS</th>
<th>BNL-AGS</th>
<th>FNAL/CERN</th>
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</thead>
<tbody>
<tr>
<td>1964</td>
<td>$K^0_L \rightarrow \pi^+\pi^-$</td>
<td></td>
</tr>
<tr>
<td>1977</td>
<td>(the year I was born)</td>
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<tr>
<td></td>
<td>Experiments started (12GeV).</td>
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<tr>
<td></td>
<td>E10: $K^+ \rightarrow \pi^+\nu\bar{\nu}$</td>
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<tr>
<td></td>
<td>E89,104: $K^+ \rightarrow \mu^+\nu_H$</td>
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<tr>
<td></td>
<td>E99,195: $P_L$ in $K^+ \rightarrow \mu^+\nu$</td>
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<tr>
<td></td>
<td>E137: $K^0_L \rightarrow \mu\nu$</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>$K^0_L \rightarrow \mu e$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K^+ \rightarrow \pi^+\mu^+e^-$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K^+ \rightarrow \pi^+\nu\bar{\nu}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Booster</td>
<td></td>
</tr>
<tr>
<td></td>
<td>direct CPV: $\epsilon'/\epsilon$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K^0_L$ rare decays</td>
<td></td>
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<tr>
<td></td>
<td>$K^0_S$ decays</td>
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</tbody>
</table>

* 1992~ US-Japan kaon program (BNL-E787/E949, FNAL-KTeV)
KEK-PS experiments by International Collaborations

**E246/E470**

Japan +
Russia, Canada, USA, Korea

**E391a**

Japan +
Russia, USA, Taiwan, Korea

Jan/21/2004
Japan-US HEP program: kaon experiments

BNL-E949/E787

FNAL-KTeV

Re(\varepsilon'/\varepsilon)

USA, Canada, Russia +
KEK, RCNP, Osaka, Kyoto,
Fukui, NDA

USA, Brazil +
Osaka

USA, Canada, Russia +
KEK, RCNP, Osaka, Kyoto,
Fukui, NDA

Takeshi K. Komatsubara (KEK-IPNS) 5 Kaon Decay Experiments at J-PARC
What are we aiming at in the next @ J-PARC?

Standard Model of Particle Physics (Cabibbo-Kobayashi-Maskawa matrix)

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\simeq
\begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]

- CP is violated ($\eta \neq 0$)
- FCNC decays are really rare.

Then,

- Where is $(\rho, \eta)$ located?
- Does $\eta_{KM}$ explain everything??
“Golden” Modes: small theoretical uncertainties

B meson:
\[ B^0(\overline{B}^0) \rightarrow V K_S, \Delta M_s/\Delta M_d \]

K meson:
\[ K^+ \rightarrow \pi^+ \nu \overline{\nu}, \ K^0_L \rightarrow \pi^0 \nu \overline{\nu} \]

\[ |\Delta B| = 2 \text{ mixing processes} \quad |\Delta S| = 1 \text{ rare-decay processes} \]

different contributions from “New Physics” (Quark Flavor Physics)
B.R.($K \to \pi \nu \bar{\nu}$) in the SM

\[ K^+ : \frac{4.84 \times 10^{-11}}{2.12 \times 10^{-10}} \]

- \( A^4 \cdot X(x_t)^2 \cdot [ (\rho_0 - \rho)^2 + \eta^2 ] \)
- \( A^4 \cdot X(x_t)^2 \cdot \eta^2 \)

\( K_L^0 \) and the Unitarity Triangle

\( \rho \)

\( \eta \)
\((\rho, \eta)\) constraints @LP03

SM prediction | Buras et al
---|---
| hep-ph/0405132 | accuracy | theoretical uncertainties |
| \(K^+ \rightarrow \pi^+ \nu \bar{\nu}\) | \((7.8 \pm 1.2) \times 10^{-11}\) | ±15% | ±7% |
| \(K^0_L \rightarrow \pi^0 \nu \bar{\nu}\) | \((3.0 \pm 0.6) \times 10^{-11}\) | ±20% | 1-2% |
\[ \Delta S = 1 \ (\rho, \eta) \quad \text{Isidori & Unterdorfer, hep-ph/0311084} \]
B.R. \((K^+ \rightarrow \pi^+ \nu \bar{\nu})\) beyond the SM

- Minimal Flavor Violation  
  Buras, hep-ph/0310208

<table>
<thead>
<tr>
<th></th>
<th>SM</th>
<th>MFV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+ \rightarrow \pi^+ \nu \bar{\nu})</td>
<td>((7.8 \pm 1.2) \times 10^{-11})</td>
<td>(19.1 \times 10^{-11})</td>
</tr>
<tr>
<td>(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})</td>
<td>((3.0 \pm 0.6) \times 10^{-11})</td>
<td>(9.9 \times 10^{-11})</td>
</tr>
</tbody>
</table>

- \(B \rightarrow \pi \pi, K \pi\) and New Physics  

<table>
<thead>
<tr>
<th></th>
<th>SM</th>
<th>NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+ \rightarrow \pi^+ \nu \bar{\nu})</td>
<td>((7.8 \pm 1.2) \times 10^{-11})</td>
<td>((7.5 \pm 2.1) \times 10^{-11})</td>
</tr>
<tr>
<td>(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})</td>
<td>((3.0 \pm 0.6) \times 10^{-11})</td>
<td>((3.1 \pm 1.0) \times 10^{-10})</td>
</tr>
</tbody>
</table>

\(* \ (\sin 2\Phi_1)_{B^0 \rightarrow \Phi K_S} \approx +0.9 \leftarrow -0.96 \pm 0.50 \) by Belle
5 LoI’s (out of 30) for J-PARC kaon experiments

- $K_L$ neutral beamline
  - L-05: $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ [T.Inagaki(KEK)]
    \[\Leftarrow\text{KEK-E391a}]

- $K^+$ beamline of low-momentum ($0.6 - 0.8$ GeV/$c$): $K^+$ decay at rest
  - L-04: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ [T.Komatsubara(KEK)]
    \[\Leftarrow\text{BNL-E949/E787}]
  - L-19: T-violation in $K^+$ decays [J.Imazato(KEK)/Yu.Kudenko(INR)]
    \[\Leftarrow\text{KEK-E246}]
  - L-16: medium-rare $K^+$ decays [C.Rangacharyulu(Saskatchewan)]
    \[\Leftarrow\text{KEK-E470}]
  - L-20: $K_{e3}$ branching ratio [S.Shimizu(Osaka)]
    \[\Leftarrow\text{KEK-E470/E246}]

* L-05, L-04, and L-19 were regarded as “highlight” experiments of J-PARC Phase-1 in the assessment of NPFC.
• T-violating $P_T$
  in $K^+ \to \pi^0 \mu^+ \nu$, $K^+ \to \mu^+ \nu \gamma$

$\bullet K^+ \to \pi^0 e^+ \nu \implies |V_{us}|$

more sensitive search
for New CPV physics

Hadron Hall Layout Plan

Instructions of Project Director: Prof. Nagamiya
to the NP Construction Group (Sep 2003)

• ...

• Design the experimental hall so as to accommodate the three kaon decay experiments (L-05, L-04 and L-19) in the future.

• Don’t shout the doors on the experiments which received a lower evaluation. It may be that they would develop to become good experimental proposals in course of time.

• ...

Report on the Beamline Layout plan of the Hadron Exp Hall (Feb 2004)
http://www-ps.kek.jp/jhf-np/Layout/Layout.html
KL line at 16deg and K1.1 line (S-type)

Fig. 2 Layout of K1.1 (S-type) and KL lines
K0.8/K1.1 line (C-type) and high-momentum line

Fig. 3 High momentum line and beam crossing scheme
\( L-05: \quad K^0_L \rightarrow \pi^0\nu\bar{\nu} \)

\( L-04: \quad K^+ \rightarrow \pi^+\nu\bar{\nu} \)

- KEK-PS E391a
  → Phase-1 → Phase-2
- > 100 signal events

- solenoidal spectrometer
  as BNL E949/E787
- high-magfield (>2.0-Tesla),
  compact and segmented detector
- > 50 signal events
L-19/-16:  \( K^+ \rightarrow \pi^0 \mu^+ \nu \),  
\( K^+ \rightarrow \mu^+ \nu \gamma \), ..

L-20:  \( K^+ \rightarrow \pi^0 e^+ \nu \)

- \( \pi^0 \) detector, \( \mu^+ \) polarimeter
- sensitivity to \( P_T \): \( \sim 10^{-4} \)
- semileptonic, hadronic and radiative modes

- \( |V_{us}| \): precision of \( 10^{-3} \)
- high-magfield (>2.0-Tesla), compact and segmented detector
- slowed-down \( K^+ \) decay in flight
### J-PARC 50GeV-PS operation (Slow Ext)

**Main Ring Cycle**

<table>
<thead>
<tr>
<th></th>
<th>KEK-PS</th>
<th>AGS</th>
<th>J-PARC Phase-1</th>
<th>J-PARC mod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Energy</td>
<td>12 GeV</td>
<td>24 GeV</td>
<td>30 GeV</td>
<td>30 GeV</td>
</tr>
<tr>
<td>Protons per pulse</td>
<td>2.5 (10^{12}/\text{spill} )</td>
<td>65 (10^{12}/\text{spill} )</td>
<td>200 (10^9 )</td>
<td>100 (10^9 )</td>
</tr>
<tr>
<td>cycle</td>
<td>4.0 sec</td>
<td>6.4 sec</td>
<td>3.42 sec</td>
<td>4.42 sec</td>
</tr>
<tr>
<td>Average Current</td>
<td>0.1 (\mu A)</td>
<td>1.63 (\mu A)</td>
<td>9.5 (\mu A)</td>
<td>3.6 (\mu A)</td>
</tr>
<tr>
<td>Beam Spill</td>
<td>2.0 sec</td>
<td>4.1 sec</td>
<td>0.7 sec</td>
<td>1.7 sec</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>0.50</td>
<td>0.64</td>
<td>0.20</td>
<td>0.39</td>
</tr>
<tr>
<td>Instantaneous Rate</td>
<td>1.3 (10^{12}/\text{sec} )</td>
<td>16 (10^{12}/\text{sec} )</td>
<td>286 (10^{12}/\text{sec} )</td>
<td>59 (10^{12}/\text{sec} )</td>
</tr>
</tbody>
</table>

Takeshi K. Komatsubara (KEK-IPNS) 20 Kaon Decay Experiments at J-PARC
$K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ in the US: KOPIO experiment @ BNL

- RSVP ($K^0_L \rightarrow \pi^0 \nu \bar{\nu} + \mu$-$e$ conversion) as NSF Major Research Equipment program
- construction from FY05, first physics run in FY10 (expected)
- Kyoto team from Japan

Takeshi K. Komatsubara (KEK-IPNS)
\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \] in the US: CKM(E921) experiment @ FNAL

- RF-separated \( K^+ \) beam at 22 GeV/c
- \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \) decay in-flight for the first time

... was stopped by P5 (Oct 2003) due to budgetary limits of US-HEP.

Takeshi K. Komatsubara (KEK-IPNS) 22 Kaon Decay Experiments at J-PARC
• FNAL-CKM(E931) is being redesigned to P940:
  – un-separated $K^+$ beam at $\sim 45$ GeV/$c$ in KTeV hall
  – $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay in-flight

• CERN-NA48 working group’s EoI for NA48/3:
  – un-separated $K^+$ beam at $\sim 75$ GeV/$c$
  – $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay in-flight

• medium-rare K decays
  – DAΦNE-KLOE
  – Russia IHEP-OKA: RF-separated $K^\pm$ beam @ U-70
Strategy (my personal view)

Perform the best particle-physics experiment in Hadron Hall.

1. $K_L$ neutral beamline:
   - investigate the possibility of first evidence for $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ at A-line T1-target with the E391a apparatus [expressway]
   - long-term: investigate the best way for precise measurement of the branching ratio with $> 100$ signal events

2. low-momentum $K^+$ beamline
   - establish the design of K0.8 beamline

   • concerning $K^+ \rightarrow \pi^+ \nu \bar{\nu}$:
     - watch the future of BNL-E949, FNAL-P940 and CERN-NA48/3
     - fully optimize the design of the new detector for $K^+$ decay at rest
• We have had a long and strong history of kaon-decay experiments at KEK-PS in Japan

• The tradition continues at J-PARC 50GeV-PS with its strong program.

• We would proceed to prepare a full-Proposal of “Kaon Physics at J-PARC”.
  – NP04 is a point of departure for it.