K-decay experiments at KEK-PS

Contents
E391a $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay
Brief review of KEK-PS
Future prospects

Takao Inagaki
(IPNS, KEK)
Motivation 1

- $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay is a **FCNC** process, which is forbidden in a tree diagram and allowed in a loop diagram mediated by two gauge bosons.
- It is a purely weak-interaction process, which contains a very high energy effect.
Motivation 2

- Small ambiguity in theoretical calculation.
  - Cancelled by taking ratio with $K\nu\nu_3$
  - Only top loop $\Rightarrow$ high mass: short range $\Rightarrow$ good for a perturbation.
  - No long-range force (particle)

1-2%
Motivation 3

- Purely direct CP ($\Delta S=1$)

Mixing term ($\Delta S=2$) is negligibly small.

- $K_L = (K_2 + \varepsilon K_1) / (1 + \varepsilon^2)^{1/2}$, $\varepsilon$: mixing term, $\sim 10^{-3}$
- $K_1$ ($\sim K_S$) contribution is given as $\varepsilon \cdot Br(K_S \rightarrow \pi \nu \nu)$
- $K_1 \sim K_S$ decay also proceeds through electro-weak penguin.

$$\Gamma (K_S \rightarrow \pi \nu \nu) \sim \Gamma (K_L \rightarrow \pi \nu \nu) \Rightarrow$$
$$\Gamma_{tot}(K_S) > \Gamma_{tot}(K_L) \Rightarrow Br(K_S \rightarrow \pi \nu \nu) < Br(K_L \rightarrow \pi \nu \nu)$$

$K_L \rightarrow \pi \nu \nu$ is a unique process to measure the CP violation of $\Delta S=1$.

Meanwhile, the CP parameters in all possible FCNC processes, $\Delta S=1,2$ and $\Delta B=1,2$, will be determined accurately.

$\Rightarrow$ Origin of CP violation.
Motivation 4

In the SM, unique determination of the height of unitarity triangle

\[ K_L = \frac{(K^0 - \bar{K}^0)}{\sqrt{2}} \]

\[ A(K_L \rightarrow \pi^0 \nu \bar{\nu}) \propto V_{td}^* V_{ts} - V_{ts}^* V_{td} \]
\[ = 2 \times V_{ts} \times \text{Im}(V_{td}) \]
\[ \propto \eta \]

\[ Br(K_L \rightarrow \pi^0 \nu \bar{\nu})_{SM} = (2.8 \pm 0.4) \times 10^{-11} \]
Motivation 5

- Experiment is very challenging and the first dedicate trial.

⇒ **Step-by-step approach**
  - Feed-back the learned information to the next.
  - Start from recycles and replace to appropriate detectors.
  - Increase the rate, step-by-step.
Our method to detect $K_L \rightarrow \pi^0 \nu \bar{\nu}$

- detect $2\gamma$ from $\pi^0$ decay + require no other particles

1. Measure gamma hit position and energy
2. Reconstruct decay vertex assuming $M_{2\gamma} = M_{\pi^0}$ (along the beam axis)
3. Require missing Pt and decay vertex in the fiducial region
### $K^0_L$ Decay Modes

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\Gamma_i/\Gamma$</th>
<th>Scale factor/Confidence level</th>
<th>$p$ (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^\pm e^\mp \nu_e$</td>
<td>$[\pi^\pm]$</td>
<td>$(38.81 \pm 0.27)$ %</td>
<td>$S=1.1$</td>
</tr>
<tr>
<td>$\pi^\pm \mu^\mp \nu_\mu$</td>
<td>$[\pi^\pm]$</td>
<td>$(27.19 \pm 0.25)$ %</td>
<td>$S=1.1$</td>
</tr>
<tr>
<td>$\pi^0 \pi^\pm e^\mp \nu_e$</td>
<td>$[\pi^0]$</td>
<td>$(1.06 \pm 0.11 \times 10^{-7})$</td>
<td>188</td>
</tr>
<tr>
<td>$\pi^0 \pi^0 e^\mp \nu_e$</td>
<td>$[\pi^0]$</td>
<td>$(5.18 \pm 0.29 \times 10^{-5})$</td>
<td>207</td>
</tr>
</tbody>
</table>

### Hadronic modes, including Charge conjugation×Parity Violating (CPV) modes

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\Gamma_i/\Gamma$</th>
<th>Scale factor/Confidence level</th>
<th>$p$ (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3\pi^0$</td>
<td>$[\pi^0]$</td>
<td>$(21.05 \pm 0.23)$ %</td>
<td>$S=1.1$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^0$</td>
<td>$[\pi^+]$</td>
<td>$(12.59 \pm 0.19)$ %</td>
<td>$S=1.6$</td>
</tr>
<tr>
<td>$\pi^+ \pi^-$</td>
<td>$[\pi^+]$</td>
<td>$(2.090 \pm 0.025 \times 10^{-3})$</td>
<td>$S=1.1$</td>
</tr>
<tr>
<td>$\pi^0 \pi^0$</td>
<td>$[\pi^0]$</td>
<td>$(9.32 \pm 0.12 \times 10^{-4})$</td>
<td>$S=1.1$</td>
</tr>
</tbody>
</table>

### Semileptonic modes with photons

<table>
<thead>
<tr>
<th>Decay Mode</th>
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<th>$p$ (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^\pm e^\mp \nu_e \gamma$</td>
<td>$[\pi^\pm]$</td>
<td>$(3.53 \pm 0.06 \times 10^{-3})$</td>
<td>229</td>
</tr>
<tr>
<td>$\pi^\pm \mu^\mp \nu_\mu \gamma$</td>
<td>$[\pi^\pm]$</td>
<td>$(5.7 \pm 0.6 \times 10^{-7})$</td>
<td>216</td>
</tr>
</tbody>
</table>

### Hadronic modes with photons or $\ell\bar{\ell}$ pairs

<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 \pi^0 \gamma$</td>
<td>$[\pi^0]$</td>
<td>$(5.6 \times 10^{-6})$</td>
<td>209</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \gamma$</td>
<td>$[\pi^+]$</td>
<td>$(4.39 \pm 0.12 \times 10^{-5})$</td>
<td>$S=1.8$</td>
</tr>
<tr>
<td>$\pi^0 2\gamma$</td>
<td>$[\pi^0]$</td>
<td>$(1.41 \pm 0.12 \times 10^{-6})$</td>
<td>$S=2.8$</td>
</tr>
<tr>
<td>$\pi^0 \gamma e^+ e^-$</td>
<td>$[\pi^0]$</td>
<td>$(2.3 \pm 0.4 \times 10^{-8})$</td>
<td>231</td>
</tr>
</tbody>
</table>

### Other modes with photons or $\ell\bar{\ell}$ pairs

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\Gamma_i/\Gamma$</th>
<th>Scale factor/Confidence level</th>
<th>$p$ (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\gamma$</td>
<td>$(5.90 \pm 0.07 \times 10^{-4})$</td>
<td>$S=1.1$</td>
<td>249</td>
</tr>
<tr>
<td>$3\gamma$</td>
<td>$(2.4 \times 10^{-7})$ CL=90%</td>
<td>249</td>
<td></td>
</tr>
<tr>
<td>$e^+ e^- \gamma$</td>
<td>$(1.0 \pm 0.5 \times 10^{-6})$</td>
<td>$S=1.5$</td>
<td>249</td>
</tr>
<tr>
<td>$\mu^+ \mu^- \gamma$</td>
<td>$(3.59 \pm 0.11 \times 10^{-7})$</td>
<td>$S=1.3$</td>
<td>225</td>
</tr>
<tr>
<td>$e^+ e^- \mu^- \gamma$</td>
<td>$(5.95 \pm 0.33 \times 10^{-7})$</td>
<td>249</td>
<td></td>
</tr>
<tr>
<td>$\mu^+ \mu^- \mu^- \gamma$</td>
<td>$(1.0 \pm 0.8 \times 10^{-8})$</td>
<td>225</td>
<td></td>
</tr>
</tbody>
</table>

### Charge conjugation×Parity (CP) or Lepton Family number (LF) violating modes, or $\Delta S = 1$ weak neutral current ($S1$) modes

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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+ \mu^-$</td>
<td>$S1$</td>
<td>$(7.27 \pm 0.14 \times 10^{-9})$</td>
<td>225</td>
</tr>
<tr>
<td>$e^+ e^-$</td>
<td>$S1$</td>
<td>$(9 \pm 6 \times 10^{-12})$</td>
<td>249</td>
</tr>
<tr>
<td>$\pi^+ \pi^- e^+ e^-$</td>
<td>$S1$</td>
<td>$(3.11 \pm 0.19 \times 10^{-7})$</td>
<td>206</td>
</tr>
<tr>
<td>$\pi^0 \pi^0 e^+ e^-$</td>
<td>$S1$</td>
<td>$(6.6 \times 10^{-9})$ CL=90%</td>
<td>209</td>
</tr>
<tr>
<td>$\mu^+ \mu^- e^+ e^-$</td>
<td>$S1$</td>
<td>$(2.69 \pm 0.27 \times 10^{-9})$</td>
<td>225</td>
</tr>
<tr>
<td>$e^+ e^- e^+ e^-$</td>
<td>$S1$</td>
<td>$(3.75 \pm 0.27 \times 10^{-8})$</td>
<td>249</td>
</tr>
</tbody>
</table>

### Additional $2\gamma$ and/or 2-charged in the other decays except $K_L \rightarrow \gamma \gamma$.

High $p_T$ selection reduces $3\pi^0$ and the odd combination of $2\gamma$ from $2\pi^0$. 
Extremely challenging

- Very rare decay ($10^{-11}$) ⇒ Many complicate sources of background
- Three body decay of all neutrals with two neutrinos ⇒ No distinct signature
- $n/KL \sim 60$ (~10 at J-Parc) ⇒ Another source of backgrounds
- Pencil beam (halo/core $\sim 10^{-5}$)
- Differential Pumping
  high vacuum ($10^{-5}$ Pa) with little material (20mg/cm$^2$) in front of the detectors
- Tight veto (down to 1 MeV)
- Several R&D
  - Six stages of collimation with a GdO$_2$ section
  - Double decay chambers
  - Calibration in situ using cosmic muons and gammas from Al-target and K$\pi$3
  - Temperature stability for CsI within 0.1$^\circ$C
  - Techniques of wlsf readout, new scintillator (MS resin) and new PMT(EGP)
  - Fabrication, assembling and installation of large detectors
  - Reproduction of spectra down to sub-MeV energy-deposit by simulation

Many valuable knowledge, which will be used at E14 of J-Parc
The techniques were established (1)

**Pencil beam**

Halo reduction by five orders of magnitude.

NIM A 545 (2005) 542, NIM A

**4 \( \pi \) coverage with thick calorimeters**

CsI stacking with gap <0.1mm

New MS-resin extrusion scintillator, New EGP PMT

Several know-how to fabricate large calorimeters with WLSF readout: machining, gluing, reflector, stacking, etc. Two large calorimeters, FB and MB were assembled with <0.1 and <1mm.

CsI: NIM A 545 (2005) 278,
EGP-PMT: NIM A 522 (2004) 477,
FB and MB and MS scintillator will be soon published.
The techniques were established (2)

**High vacuum**

Vacuum region was divided into two regions by a thin membrane, and they were differentially pumped.

Outside: $10^5$ Pa (1 atm)
Middle: $10^0$ Pa
Inside: $10^{-5}$ Pa

The dead material in front of detectors is only 20 mg/cm$^2$

**Calibration in situ**

Energy and timing responses of all detector were calibrated by using cosmic and punch-through $\mu$ in situ.

The accuracies were a few % in energy and <1 ns in time.

To be published soon in NIM A

NIM A 545 (2005) 278.
About a photon veto miss due to detection inefficiency for photon

- The inefficiency is large for low energy incident photons
  \[ \downarrow \]
  \[ \text{High } P_T \text{ selection} \]

- The inefficiency strongly depends on the detection threshold
  \[ \downarrow \]
  \[ \text{Low detection threshold} \]

To kill $K_L \rightarrow 2 \pi^0 \ (Br \sim 10^{-3} \text{ and } + 2 \gamma)$

Inefficiency for single photon

\[ \left( \frac{10^{-11}}{10^{-3}} \right)^{1/2} \sim 10^{-4} \]
Collaboration and run summary

- Data taking
  - Run-I: Feb. – July, 2004
  - Run-II: Feb. – April, 2005
  - Run-III: Oct. – Dec., 2005
Run-1 one week

Reached $0.91 \times 10^{-7}$ and set an upper limit of $2.1 \times 10^{-7}$

Published in PRD (PRD 74, 051105)

Suffered seriously from the drooping membrane
Tentative final-plot of one-third of Run-2
Well-constrained decays
(check & normalization)

Number of KL decays in fiducial estimated from

- $K_L \rightarrow 3\pi 0$
  - $164446 \text{(rec.data)} / (26982 / 5 \times 10^9) \text{(rec.MC)}$
    - $(0.1956 \text{(Br)} \times (0.98797)^3) \times 0.024 \text{(P\_decay)} / 0.845$
    - $= 4.59 \times 10^9$

- $K_L \rightarrow 2\pi 0$
  - $11955 / (75814 / 1 \times 10^9) / (8.69 \times 10^{-4} \times (0.98797)^2)$
    - $\times 0.024 / 0.845 = 5.28 \times 10^9$

- $K_L \rightarrow 2\gamma$
  - cuts
    - photon veto, gamma shape
    - $P T 2 < 0.001, \text{acop. angle} < 10 \text{ deg.}$
  - $7503 / (45099 / 2 \times 10^8) / 5.48 \times 10^{-4} \times 0.024 / 0.845 \times 3$
    - $= 5.17 \times 10^9$
Sensitivity

- pi0nn MC
- 46435 events in fiducial / $1 \times 10^8$ KL
- $A = \frac{46431}{10^8}$
  $\div 0.024$ (decay prob.) $\times 0.845$ (acc. loss)
  $= 1.64 \times 10^{-2}$
- NKL = $5.28 \times 10^9$
- SES = $1 / (1.64 \times 10^{-2} \times 5.28 \times 10^9)$
  $= 1.15 \times 10^{-8}$
Kpi2 background (MC)

- CC00
  - critical to the events that KL decayed before FB
- BA
  - vetoes down stream events

result
- 1 event in the box: 0.03 events for 1/3 data
Halo neutron background (MC)

- **Statistics**
  - Neutrons: $2.7 \times 10^{17}$ pot
  - Data (1/3 sample): $4.8 \times 10^{17}$ pot
  - $n/data = 1/1.76$

- CC02 events
  - $148 \pm 18$ (data: 149)
- CV events
  - $112 \pm 15$ (data: 119)
- Necessary to move the fiducial’s boundary at CC02 to downstream
**BR(\(K^0 \rightarrow \pi^0 \nu\nu\)) in time**

**talk at ICHEP in Moscow by Misha**

- **New current limit**
  - 2006: 2.1x10^{-7} (E391)

- **Prospect**
  - SES ~ 3x10^{-9} (E391 full sample)
  - SES ~ 8x10^{-12} (J-PARC, Step1)
  - SES ~ 10^{-13} (J-PARC, Step2)

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**Upper limit and expected sensitivity of \(K_L \rightarrow \pi^0 \nu\nu\)**

- Littenberg
- E731
- E799
- KTeV
- KTeV
- E391a–first

**Limit from \(K^+ \rightarrow \pi^+ \nu\nu\)**

**Standard Model expectation**

- J-PARC(Step-1)
- J-PARC(Step-2)
It is clearly observed for the main barrel having both-end readout.
Collateral cluster made by single gamma
(by Takita)

E_{\gamma}=0.5\text{GeV/c},\ E_{th}=5.0\text{MeV,500 MeV incident}

:QGSP (w/o photo nuclear interaction)
:QGSP-GN

Many of Distant collateral cluster are generated through P.N
Motivation 4

In the SM, unique determination of the height of unitarity triangle

\[ K_L = \frac{K^0 - \bar{K}^0}{\sqrt{2}} \]

\[ A(K_L \rightarrow \pi^0 \nu \bar{\nu}) \propto V_{td}^* V_{ts} - V_{ts}^* V_{td} \]
\[ = 2 \times V_{ts} \times \text{Im}(V_{td}) \propto \eta \]

\[ Br(K_L \rightarrow \pi^0 \nu \bar{\nu})_{SM} = (2.8 \pm 0.4) \times 10^{-11} \]
Additional discussion on physics

CKM parameters are being well determined by B-factories.

However, let’s remind that the primary goal of quark flavor physics is to see the deviation from SM.
$K_L \to \pi^0\nu\nu$ decay is the best to see the deviation

- Advantages
  - Very small theoretical ambiguity
  - Suppressed by FCNC

$<3 \times 10^{-13} \Rightarrow >100$ SM-events $\Rightarrow \Delta \eta / \eta <5\% \Rightarrow >5\sigma$ for $1.75 \times$ SM

Energy scale ($\Lambda$)

For $K_L \to \pi^0\nu\nu$, 

$$|1 + (M_W/\Lambda)^2/(A^2\lambda^5/(16\pi^2))|^2 \sim 1+r$$

For $B \to X_S \mu^+\mu^- \quad B_s \to \mu^+\mu^-$, 

$$|1 + (M_W/\Lambda)^2/(A\lambda^2/(16\pi^2))|^2 \sim 1+r$$

$r=0.75 \quad \Rightarrow \quad \Lambda(\quad K_L \to \pi^0\nu\nu \quad) \sim 100$ TeV,

$\Lambda(\quad B \to X_S \mu^+\mu^- \quad B_s \to \mu^+\mu^- \quad \text{at LHC} \quad) \sim 10$ TeV,

$\Lambda(\quad B-\text{factories} \quad) \sim 0.1-1$ TeV
Brief review of the KEK 12-GeV proton synchrotron

  - Similar machines, Nimrod PS and Argonne ZZS, were closed during construction.
  - The competing machines, CERN-PS(SPS), BNL-AGS and Fermilab –Tevatron, were too strong in power.
  - There was a revolution of high energy physics in 1974.
  - Another facility of $e^+ e^-$ colliders, Tristan and B-Factory, has been operated at KEK since 1985.

Why it could be so active.
Reasons of the activeness

- Stable operation
  - Operation per year: >6000 hours / 8800 hours with downtime of <5%, and machine study time of 10%. PS operation has been crucial for all KEK activities.

- Effective organization
  - Combination of experiments on strong interaction (smaller size) and weak interactions (larger size).

- Variety
  - The experiments at the final stage were never expected at the beginning, as ordinarily in fixed-target experiments using proton machine. Even KEK-PS had some advantages.
Examples of advantages

- **K-decay**
  - Low momentum K-on yield does not depend on the power of protons but only on the intensity. ⇒ **many stopped K experiments**
  - Momentum resolution $\Delta p/p \propto p$: low momentum is better. ⇒ **KL-$\mu\,\epsilon$ search**
  - s-quark is better than c-quark for FCNC physics ⇒ **Rare decay experiments**

- **Neutrino**
  - $E_\nu (12\text{GeV}) \sim E_\nu (\text{atmospheric}) + \text{SK}$
  ⇒ **K2K**
We have glorious history of discovering many fundamental phenomena and establishing the Standard Model using high-energy accelerators.

However, the situation has been specially severe since the termination of SSC. Only the conversions to B-factories from existed accelerators and a few new constructions, Main injector at Fermilab, LHC and J-Parc, have been achieved.

Many people are now going up to the sky or into the earth.

I would really encourage young physicists in Japan as:
J-Parc

We will soon get beam of world highest intensity.

Please make your original experiments, which no one has planned.