Rare Kaon Decay Experiments and Future Plan

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(KEK)
Role of Kaon Physics

* To explore New Physics beyond the Standard Model (SM) through the processes which are suppressed/prohibited in SM and are precisely calculated in SM
  - Aiming to find deviation from SM prediction
  - Possible to reach higher mass scale than direct search.

* To study flavor structure beyond SM
  - Complimentary to other flavor physics programs
Experiments are not so easy…

* Kaon Physics has a long history
  - for ex., discovery of CP violation in $K_L \rightarrow \pi\pi$ 50 years ago and many studies had been already done.

* Remaining subjects are
  - rare processes,
  - difficult to define (with missing particles), and/or
  - requiring small systematic uncertainty.

* BUT, we can/should overcome difficulties and exploit the potential of Kaon physics for studying BSM.
Topics in this talk

Experiment @ J-PARC

**KOTO**

$K_L \rightarrow \pi^0 \nu \nu$

Running

**E36**

Lepton universality in

$R_K \equiv \frac{\text{Br}(K^+ \rightarrow e^+ \nu) / \text{Br}(K^+ \rightarrow \mu^+ \nu)}{\text{Commissioning}}$

[stopped $K^+$ decay technique]

Precision level: ~0.25%

Experiment @ CERN

**NA62**

$K^+ \rightarrow \pi^+ \nu \nu$

Commissioning

sensitivity level: $O(10^{-11} \sim 10^{-12})$

*record holder of $R_K$ measurement [decay in flight technique]

And, future plan… (brief and limited)
Before going to each topics, …

J-PARC hadron facility restarted!!

Hadron Experimental Facility (HEF)
KOTO, E36 are sitting here.

30 GeV proton beam from Main Ring (MR)
Slow extraction (SX) to hadron facility,
2sec spill/6sec cycle

The SX beam had been stopped since the accident on May 23, 2013.

After HEF renovation for safety, we finally restarted the SX beam in April 2015!!
$K \rightarrow \pi \nu \nu$ decay experiments

J-PARC KOTO

and

CERN NA62
$K \rightarrow \pi \nu \nu$ in the Standard Model

* s-d transition via loop diagrams, FCNC process

* $K_L \rightarrow \pi^0 \nu \nu$  
  \[ \text{Br} \propto \text{Im}(A_{s \rightarrow d Z^*})^2 \]
  - Top quark dominates
    * $K^0 - \bar{K}^0$ superposition extracts imaginary part of the amplitude
    - CP violating

* $K^+ \rightarrow \pi^+ \nu \nu$  
  \[ \text{Br} \propto |A_{s \rightarrow d Z^*}|^2 \]
  - Top and charm contribute
K$\rightarrow$$\pi\nu\nu$ in the Standard Model

- Theoretically clean: small long distance contribution
- Hadronic parts ($\kappa_L$, $\kappa_+$) are obtained from measured $\text{Br}(K^+ \rightarrow \pi^0 e^+ \nu)$

$$\text{Br}(K_L \rightarrow \pi^0 \nu\bar{\nu}) = \kappa_L \left( \frac{\text{Im}(V_{ts}^* V_{td})}{\lambda^5} \chi(x_t) \right)^2$$

$$\text{BR}_{SM}(K_L \rightarrow \pi^0 \nu\bar{\nu}) = (3.00 \pm 0.31) \times 10^{-11}$$

CKM uncertainties are dominant while intrinsic one $\sim 2\%$.

$$\text{Br} \left( K^+ \rightarrow \pi^+ \nu\bar{\nu} (\gamma) \right) = \kappa_+ (1 + \Delta_{EM})$$

$$\times \left| \frac{V_{ts}^* V_{td} X_t (m_t^2) + \lambda^4 \text{Re} V_{cs}^* V_{cd} \left( P_c (m_c^2) + \delta P_{c,u} \right)}{\lambda^5} \right|^2$$

$$\text{BR}_{SM}(K^+ \rightarrow \pi^+ \nu\nu) = (9.11 \pm 0.72) \times 10^{-11}$$

Exp: KEK E391a
$$\text{BR} < 2.6 \times 10^{-8}$$
Grossman Nir limit:
from measured $\text{Br}(K^+ \rightarrow \pi^+ \nu\nu)$
$$\text{BR} < 1.5 \times 10^{-9}$$

Exp: BNL E787/949
$$\text{BR} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

Correlation between $\text{Br}(K^+\rightarrow\pi^+\nu\nu)$ and $\text{Br}(K_L\rightarrow\pi^0\nu\nu)$

**Littlest Higgs**

**Randall - Sundrum**

**Z' with left-handed scenario**

Following discussion in PoS KAON13 (2013) 010
J-PARC KOTO

$K_L \rightarrow \pi^0 \nu\nu$ study

• Goal: a few SM events in 3-4 years run with S/N ratio $\sim 2$
KOTO

Principle of experiment

Signature of $K_L \rightarrow \pi^0\nu\bar{\nu} = 2\gamma + \text{nothing}$
Calorimeter + Hermetic veto detectors

+ kinematic feature (missing $P$)
Reconstruct $Z_{vtx}$ and transverse momentum of $\pi^0$

$$\cos \theta = 1 - \frac{M^2_{\pi^0}}{2E_1E_2}$$

$\pi^0$ (0,0, $Z_{vtx}$)
A narrow $K_L$ beam is the key.
To reduce the interaction between the beam particles and the residual gas, the evacuation started from 2013-Jan-4.

The current vacuum level of the decay region is $7 \times 10^{-5} \text{ Pa}$.

Most of detectors are inside vacuum.
1st physics run in 2013

* 1st physics run was done in May 2013.
  - SX beam power was 24 kW.
  - 100 hours of data taking (until the accident at HEF happened.)

* Though the data amount was not enough to exceed current upper limit, we learned a lot from it.
KOTO: from May 2013 run

Detector performance

Check EM calorimeter

Check veto detectors

Reconstructed $K_L \rightarrow 3\pi^0, 2\pi^0, (2\gamma)$ events are also used for KL flux calculation.
KOTO: from May 2013 run

Result of 100 hours run in May 2013

• Summary of #BG inside the signal box

<table>
<thead>
<tr>
<th>BG source</th>
<th>#BG</th>
</tr>
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<tbody>
<tr>
<td>Hadron interaction events</td>
<td>0.18±0.15</td>
</tr>
<tr>
<td>Kaon decay events</td>
<td>0.11±0.04</td>
</tr>
<tr>
<td>Upstream events</td>
<td>0.06±0.06</td>
</tr>
<tr>
<td>Sum</td>
<td>0.36±0.16</td>
</tr>
</tbody>
</table>

• Sensitivity of the 1st physics run
  \[= 1.29 \times 10^{-8}\]
  (cf) S.E.S. of KEK E391a: \[1.11 \times 10^{-8}\]

• Observed 1 event in the box (consistent with BG expectation)

Reported in CKM2014 conference last year

May 25-29, 2015
KOTO: from May 2013 run

Mechanism of backgrounds

$K_L \rightarrow \pi^0 \pi^+ \pi^-$ with $\pi^+ \pi^-$ disappearing due to interaction with the beam pipe

Single neutron makes two clusters in the calorimeter

$\pi^+$ and $\pi^-$

Downstream Vacuum pipe

CC05 CC06

Halo neutron

May 25-29, 2015
FPCP 2015 @ Nagoya, Japan
KOTO upgrade for 2015 run

For 2015 run: concerning neutron

Kapton vacuum window
0.125mm ➔ 0.0125mm ➔ to reduce scattering source in the beam

Cutaway plan view

New removable Al target inside the beam ➔ to collect control data for neutrons coming from various places

beam

added existed
KOTO upgrade for 2015 run

Upgrade downstream detectors

Beam Pipe Charged Veto

New Beam Hole Charged Veto (Wire chamber with CF$_4$+C$_5$H$_{12}$ gas)

Beam Profile Monitor (fluorescent plate+CCD+IIT)

Additional Beam Hole Photon Veto modules and near-by-beam detector most downstream
KOTO status and plan in 2015

* Upgrade to reduce backgrounds were done during 2-year beam break.

* KOTO restarted physics run in this April.
  * About twice of May 2013 data has been collected. (Analysis is ongoing.)

* Will run more in June and fall
  * Target sensitivity in 2015 will be $O(10^{-9})$ ~ Grossman Nir limit.

We collected $3.09 \times 10^{18}$ p.o.t (167 hours)
(We used $1.42 \times 10^{18}$ p.o.t for analysis of previous run data.)
CERN NA62

$K^+ \rightarrow \pi^+ \nu \nu$ measurement

- Aims to collect $O(100)$ events in 2 years of data
  $\Rightarrow \sim 10\%$ precision for $Br(K^+ \rightarrow \pi^+ \nu \nu)$
- Decay in flight technique

Figures are quoted from the slides by G. Ruggiero @CERN EP seminar, March 10, 2015
Signal and background

* $K^+ \rightarrow \pi^+ \nu \nu$ signature
  - Kaon ID for incoming charged particle
  - Pion ID for outgoing charged particle
  - No other activities

<table>
<thead>
<tr>
<th>$K^+$ major decay modes</th>
<th>[rejection method]</th>
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<tbody>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu$</td>
<td>63.6% $\leftarrow \pi/\mu$ separation</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0$</td>
<td>20.7% $\leftarrow$ extra $\gamma$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^+ \pi^-$</td>
<td>5.6% $\leftarrow$ extra charged particle</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0 e^+ \nu$</td>
<td>5.1% $\leftarrow \pi/e$ separation, extra $\gamma$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0 \mu^+ \nu$</td>
<td>3.4% $\leftarrow \pi/\mu$ separation, extra $\gamma$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0 \pi^0$</td>
<td>1.8% $\leftarrow$ extra $\gamma$</td>
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</table>
Signal and background

- BG suppression by kinematic constraint
  - Kinematic variable: \( m^2_{\text{miss}} = (P_K - P_\pi)^2 \)

Avoid regions of
- \( m^2_{\text{miss}} \approx 0 \)
  \( (K^+ \rightarrow \mu^+ \nu) \)
- \( m^2_{\text{miss}} \sim m_\pi^2 \)
  \( (K^+ \rightarrow \pi^+ \pi^0) \)
- \( m^2_{\text{miss}} > (2m_\pi)^2 \)
  \( (K^+ \rightarrow \pi^+ \pi^0 \pi^-) \)

Detector resolution is not included.
NA62 Apparatus

**Detectors for Secondary Beam**
- Kaon ID (KTAG, Cerenkov)
- Kaon Tracking

**SPS proton**
- 400 GeV
- $10^{12}$ p/s

**Secondary Beam**
- $p = 75$ GeV/c
- $\Delta p/p \sim 1\%$
- X,Y Divergence < 100 $\mu$rad
- K (6%), $\pi$ (70%), $p$ (23%)
- 750 MHz
- Beam size: 6.0 $\times$ 2.7 cm$^2$

**Kaon Decay**
- $\sim 5$ MHz
- $4.5 \times 10^{12}$/year
- 60 m length
- $10^{-6}$ mbar vacuum

**Detectors for decay products**
- Charged particle tracking
- Charged particle Time Stamping
- Photon detection
- Charged particle ID
- Pion and muon identification

**1 m**
- target
- Momentum selection & collimation

**~100 m**
- KTAG
- Beam tracker

**~150 m**
- E.M. calorimeter (forward)
- Hadron calorimeter
- E.M. calorimeters (large angles)
- E.M. calorimeters (small angles)
- RICH
- Magnetic Spectrometer

**photon veto**
Key detectors

Beam tracker: measure $P_K$

“Gigatracker”
3 planes of Si pixel detectors

Secondary tracker: measure $P_\pi$
magnetic spectrometer
with 4 stations of straw chambers in vacuum

RICH: $\pi/\mu$ separation
17m, Ne 1atm radiator, $10^{-2}$ $\mu$ rejection

RICH Vessel
RICH Mirrors
RICH PMs
2014 pilot run

* Detector commissioning (with almost all detectors installed)
* Data quality studies with loose trigger condition

Done in Oct.-Dec. 2014 with 5~20% of nominal beam intensity

\[ \theta_{K\pi\pi} \text{ vs } P_{\pi\pi} \] : Events with only 1 track
\[ M_{\text{miss}}^2 = (P_K - P_{\pi\pi})^2 \] : GTK not used

\[ P < 35 \text{ GeV/c} \]
Status and plan in 2015

* Almost all the detectors have been installed.

* Pilot run was done in 2014 (October - December)
  
  with lower intensity
  
  ▪ Good data quality at first look
  
  ▪ Reprocessing with the complete detector calibrations and reconstructions is on going.

* 2015 run is scheduled from beginning of July to mid November
J-PARC E36: Lepton universality in $K^+$ decay

- Measure $R_K = \frac{\text{Br}(K^+ \rightarrow e^+\nu)}{\text{Br}(K^+ \rightarrow \mu^+\nu)}$ with accuracy of $\Delta R_K / R_K = 0.25\%$
- Stopped Kaon decay technique
Lepton universality in $K_{l2}$ decay

* Precise measurement of decay width ratio

$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$$

$$\Gamma(K_{l2}) = g_l^2 \frac{G^2}{8\pi} f_K m_K m_l \left\{1 - \frac{m_l^2}{m_K^2}\right\}^2$$

* In the ratio of the $\Gamma(K_{e2})$ to the $\Gamma(K_{\mu2})$, the hadronic form factors are cancel out, and $R_K^{SM}$ is highly precise.

$$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$$

$\Rightarrow \Delta R_K/R_K \sim 0.04\%$

* Some New Physics model calculate $O(10^{-3})$ deviation from SM.
**Experimental status of $R_K$**

* KLOE @ DAΦNE (in-flight decay) (2009)
  
  \[ R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5} \]

* NA62 @ CERN-SPS (in-flight decay) (2013)
  
  \[ R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5} \]

⇒ World average (2013)
  
  \[ R_K = (2.488 \pm 0.009) \times 10^{-5} \]

  \[ \delta R_K / R_K = 0.4\% \]

These experiments utilized $K^+$ decay in flight.

* J-PARC E36 characteristics:
  
  - Stopped $K^+$ experiment: different systematic properties
    
    2 body decay has a monochromatic charged particle.
  
  - Goal: \[ \delta R_K / R_K = \pm 0.2\% \text{ (stat)} \pm 0.15\% \text{ (syst)} \text{ [0.25\% total]} \]
Reasonable upgrade of KEK-PS E246 with the Toroidal spectrometer

**Stopped K method**
- K1.1BR beamline
- $K^+$ stopping target

**Momentum measurement**
- MWPC (C2, C3, C4)
- C1 GEM
- Spiral Fiber Tracker (SFT)

**PID**
- TOF
- Aerogel Cherenkov (AC)
- Pb glass counter (PGC)

**Gamma ray**
- CsI(Tl)
Photo of E36 apparatus
E36 status and plan in 2015

* The E36 detector, the toroidal magnet and its cryogenics have been installed at K1.1BR area.
* Commissioning with full magnetic field started in the April beam time.

* Next steps are
  * June : continue commissioning and then start physics runs
  * In fall : do physics runs

* (After the fall run, the E36 apparatus will be dismantled for the construction of other new beam lines.)
Scope in time domain

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<tbody>
<tr>
<td></td>
<td></td>
<td>24kW</td>
<td>24~40kW</td>
<td>50kW</td>
<td>~100kW</td>
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<tr>
<td>Goal: ~SM (10^{-11})</td>
<td>G-N limit (10^{-9})</td>
<td>Goal: ~SM (10^{-11})</td>
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K_{L} \to \pi^{0}\nu\nu

KOTO

1st physics run upgrade for high sensitivity

Lepton universality

E36

construction physics run

Goal: ~100 SM events

CERN

NA62

construction start commissioning physics run

Goal: ~100 SM events
Scope in time domain, further

<table>
<thead>
<tr>
<th>J-PARC SX power</th>
<th>JFY</th>
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<tbody>
<tr>
<td>24kW</td>
<td>24~40kW</td>
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**K_L \rightarrow \pi^0\nu\nu**

- **KOTO**
  - 1st physics run
  - Upgrade for high sensitivity
  - **At Extended Hadron Hall**
    - KOTO-II for O(100) measurement
    - T-violation study in K^+ decay

**Lepton universality**

- **E36**
  - Construction
  - Physics run

**CERN NA62**

- Construction
- Start commissioning
- Physics run

**Goal:**

- ~SM ($10^{-11}$)
- $G-N$ limit ($10^{-9}$)
- ~100 SM events
KOTO-II for observing ~100 $K_L \rightarrow \pi^0\nu\nu$ events

- smaller production angle ⇒ larger Kaon yield
Summary

* Kaon rare decay study is one of the important approaches to new physics beyond SM.

* Now, three kaon experiments in Japan and Europe are running or almost ready to run.
  - J-PARC KOTO ($K_L \rightarrow \pi^0 \nu \nu$) restarted physics run in April 2015 and will continue data taking.
  - CERN NA62 ($K^+ \rightarrow \pi^+ \nu \nu$) started commissioning in 2014 and will proceed to physics run.
  - J-PARC E36 (Lepton flavor universality in $K_{l2}$ decays) started commissioning and will complete physics run in this year.

* Look forward to interesting results coming !!

May 25-29, 2015 FPCP 2015 @ Nagoya, Japan