Search for Charged Lepton Flavor Violation at J-PARC
- COMET Experiment -

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LBNL
Outline

• Why Flavor Physics? Why Charged Lepton Flavor Violation (CLFV)?
• CLFV Experiments
  • Muon to electron conversion in a muonic atom
  • COMET (at J-PARC)
    • for sensitivity of $<10^{-16}$ (x10000)
  • COMET Phase-I (at J-PARC)
    • for sensitivity of $<10^{-14}$ (x100)
• Summary
Why Flavor Physics?
Why Charged Lepton Flavor Violation (CLFV)?
The Standard Model has the Higgs boson, but no new particles are found yet...

The discovery of the Higgs boson has been made.

The Standard Model can explain most of the experimental results. However, there are many undetermined parameters and issues.

The Standard Model is considered to be incomplete. New Physics is needed.
Effective Lagrangian in the Standard Model (SM)

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{sym. break}}. \]

\[ V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 + Y^{ij} \Psi^i_L \Psi^j_R \Phi + \frac{g^{ij}}{\Lambda} \Psi^i_L \Psi^j_T \Phi \Phi^T, \]

Origin of flavor

1. **what determines the observed pattern of masses and mixing angle of quarks and leptons?**
2. **which sources of flavor symmetry breaking are accessible at low energy?**

Ques.(1) is difficult to address owing to the lack of theoretical guidance. Ques.(2) can be answered by a series of high-precision measurements.
New Physics Search in Charged Lepton Flavor

with new physics contributions

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{C_{\text{NP}}}{\Lambda^2} O_{ij}^{(6)}, \]

\( \Lambda \) is the energy scale of new physics

Charged Lepton Flavor

For instance, \( \mu \to e \gamma \) (\( B < 5.7 \times 10^{-13} \)),

\[ \frac{C_{\text{NP}}}{\Lambda^2} O_{ij}^{(6)} \to \frac{C_{\mu e}}{\Lambda^2} \bar{e}_L \sigma^{\rho \nu} \mu_R \Phi F_{\rho \nu} \]

\( \Lambda > 2 \times 10^5 \text{ TeV} \times (C_{\mu e})^{\frac{1}{2}} . \)

The constraint in CLFV is even more severe than in the quark flavor. The SM contribution to muon CLFV is small, of the order of \( O(10^{-54}) \).
Which Rare Decays at Low Energy?

- Processes which are forbidden or highly suppressed in the Standard Model would be the best ones to search for new physics beyond the Standard Model.
- **Flavor Changing Neutral Current Process (FCNC)**
  - **FCNC in the quark sector**
    - $b \rightarrow s \gamma$, $K \rightarrow \pi \nu \nu$, etc.
    - Allowed in the Standard Model.
    - Need to study deviations from the SM predictions.
      - Uncertainty of more than a few % (from QCD) exists.
  - **FCNC in the lepton sector**
    - $\mu \rightarrow e \gamma$, $\mu + N \rightarrow e + N$, etc. (*lepton flavor violation =LFV*)
    - Not allowed in the Standard Model ($\sim 10^{-50}$ with neutrino mixing)
    - Need to study deviations from none
      - clear signature and high sensitivity
Why Muons, not Taus?

• A number of taus available at B factories are about $1-10$ taus/sec. At super-B factories, about $100$ taus/sec are considered. Also some of the decay modes are already background-limited.

• A number of muons available now, which is about $10^8$ muons/sec at PSI, is the largest. Next generation experiments aim $10^{11}-10^{12}$ muons/sec. With the technology of the front end of muon colliders and/or neutrino factories, about $10^{13}-10^{14}$ muons/sec are considered.

a larger window to search for new physics for muons than taus
Observation of CLFV would indicate a clear signal of physics beyond the SM with massive neutrinos.

\[ B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_l (V_{MNS})_{\mu l}^* (V_{MNS})_{el} \frac{m_{\nu l}^2}{M_W^2} \right|^2 \]
Sensitivity to New Physics at High Energy

CLFV is unique and important to find new physics beyond the SM.

CLFV is sensitive to NP at high energy scale $\Lambda$.

Amplitude:

$$|A_{SM} + \varepsilon_{NP}|^2 \sim |A_{SM}|^2 + 2Re(A_{SM}\varepsilon_{NP}) + |\varepsilon_N|^2$$

subject to uncertainty of SM prediction.

Rate:

$$|A_{SM} + \varepsilon_{NP}|^2 \sim |A_{SM}|^2 + 2Re(A_{SM}\varepsilon_{NP}) + |\varepsilon_N|^2$$

could go higher energy scale.

$$R \propto \frac{1}{\Lambda^4}$$

CLFV for muons can be improved by a factor of 10,000 or more, implying 10 times in energy reach.
Various Models Predict CLFV......

Sensitivity to Different Muon Conversion Mechanisms

- **Supersymmetry Predictions at** $10^{15}$
  - \[ |U_{\mu N}^* U_{eN}|^2 = 8 \times 10^{-13} \]
  - \[ M_L = 3000 (\lambda_{d\mu} \lambda_{ed})^{1/2} \text{ TeV/c}^2 \]
  - \[ \Lambda_c = 3000 \text{ TeV} \]

- **Compositeness**
  - \[ g_{H\mu e} = 10^{-4} \times g_{H\mu\mu} \]
  - \[ M_{Z'} = 3000 \text{ TeV/c}^2 \]
  - \[ B(Z \rightarrow \mu e) < 10^{-17} \]

- **Heavy Neutrinos**
  - \[ \text{After W. Marciano} \]

- **Heavy Z', Anomalous Z coupling**
Example of Sensitivity to NP in High Energy Scale: SUSY models

For loop diagrams,

$$\text{BR}(\mu \rightarrow e\gamma) = 1 \times 10^{-11} \times \left(\frac{2\text{TeV}}{\Lambda}\right)^4 \left(\frac{\theta_{\mu e}}{10^{-2}}\right)^2$$

$$y = \frac{g^2}{16\pi^2} \theta_{\mu e}$$

> sensitive to TeV energy scale with reasonable mixing

example diagram for SUSY (~TeV)

Physics at about $10^{16}$ GeV

slepton mixing (from RGE)

SUSY-GUT model

SUSY neutrino seesaw model
CLFV Predictions

Various BSM models predict sizable muon CLFV, as well as tau CLFV.

SUSY model

little Higgs model

extra dimension model
CLFV and Neutrino Mass Generation

If two scales are well separated, LFVs are suppressed.

\[ \text{CLFV} \sim O(10^{-54}) \]

In supersymmetric models, large LFV signals are expected even if two scales are separated.

If two scales are close, large LFVs are expected.

Neutrino mass from loop
Tripletp Higgs for neutrino mass
Left–right symmetric model

Scale of the electroweak symmetry breaking

Scale of the neutrino mass generation

TeV

SUSY

TeV
TeV seesaw type-I models predict sizable branching ratio of CLFV with right-handed neutrino mass of $O(\text{TeV})$. 
"DNA of New Physics"
(a la Prof. Dr. A.J. Buras)

The pattern of measurement:

★ ★ ★ large effects
★ ★ visible but small effects
★ unobservable effects

is characteristic, often uniquely so, of a particular model.

<table>
<thead>
<tr>
<th>GLOSSARY</th>
<th>Description</th>
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<tbody>
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<td>AC [10]</td>
<td>RH currents &amp; U(1) flavor symmetry</td>
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<tr>
<td>RVV2 [11]</td>
<td>SU(3)-flavored MSSM</td>
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<td>AKM [12]</td>
<td>RH currents &amp; SU(3) family symmetry</td>
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<td>δLL [13]</td>
<td>CKM-like currents</td>
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<td>FBMSSM [14]</td>
<td>Flavor-blind MSSM</td>
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<td>LHT [15]</td>
<td>Little Higgs with T Parity</td>
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<td>RS [16]</td>
<td>Warped Extra Dimensions</td>
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<td>$\mu \to e\gamma$</td>
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<td>$(g - 2)_\mu$</td>
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These are a subset of a subset listed by Buras and Girrbach
MFV, CMFV, 2HDM$_{MFV}$, LHT, SM4, SUSY flavor. SO(10) – GUT, SSU(5)$_{HN}$, FBMSSM, RHMFV, L-R, RS$_0$, gauge flavor, ………
Quarks, Neutrinos, and Charged Leptons

Quarks

Neutrino mixing observed

Lepton

Charged lepton mixing not observed.

Charged Lepton Flavor Violation (CLFV)

Quark mixing observed

Nobel Prize-wining class research
CLFV Experiments
CLFV History

First cLFV search

Pontecorvo in 1947

Upper limits of Branching Ratio

\begin{align*}
\mu &\rightarrow e\gamma \\
\mu &\rightarrow eee \\
\mu &\rightarrow eA \\
K^0_L &\rightarrow \mu e \\
K^+ &\rightarrow \pi\mu e
\end{align*}

Year

# Present Limits and Expectations in Future

<table>
<thead>
<tr>
<th>process</th>
<th>present limit</th>
<th>future</th>
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<tbody>
<tr>
<td>$\mu \to e\gamma$</td>
<td>$&lt;5.7 \times 10$</td>
<td>$&lt;10$</td>
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<tr>
<td>$\mu \to eee$</td>
<td>$&lt;1.0 \times 10$</td>
<td>$&lt;10$</td>
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<tr>
<td>$\mu N \to eN$ (in Al)</td>
<td>none</td>
<td>$&lt;10$</td>
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<tr>
<td>$\mu N \to eN$ (in Ti)</td>
<td>$&lt;4.3 \times 10$</td>
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<tr>
<td>$\tau \to e\gamma$</td>
<td>$&lt;1.1 \times 10$</td>
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<td>$&lt;3.2 \times 10$</td>
<td>$&lt;10$</td>
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</table>
List of cLFV Processes with Muons

\( \Delta L=1 \)

- \( \mu^+ \rightarrow e^+\gamma \)
- \( \mu^+ \rightarrow e^+e^+e^- \)
- \( \mu^- + N(A, Z) \rightarrow e^- + N(A, Z) \)
- \( \mu^- + N(A, Z) \rightarrow e^+ + N(A, Z - 2) \)

\( \Delta L=2 \)

- \( \mu^+e^- \rightarrow \mu^-e^+ \)
- \( \mu^- + N(A, Z) \rightarrow \mu^+ + N(A, Z - 2) \)
- \( \nu_{\mu} + N(A, Z) \rightarrow \mu^+ + N(A, Z - 1) \)
- \( \nu_{\mu} + N(A, Z) \rightarrow \mu^+\mu^+\mu^- + N(A, Z - 1) \)
$\mu \rightarrow e$ conversion in a muonic atom
What is Muon to Electron Conversion?

1s state in a muonic atom

\[ \mu^- \rightarrow e^- \nu \bar{\nu} \]

Nuclear muon capture

\[ \mu^- + (A, Z) \rightarrow e^- + (A, Z) \]

Event Signature:
a single mono-energetic electron of 105 MeV

Backgrounds:
(1) physics backgrounds
   ex. muon decay in orbit (DIO)
(2) beam-related backgrounds
   ex. radiative pion capture,
   muon decay in flight,
(3) cosmic rays, false tracking
µ-e Conversion Signal and Normal Muon Decays

normal muon decay

µ-e conversion and muon Michel decays are well separated.

energy window

µ-e conversion

High Intensity beam can be used only for µ-e conversion
**Effective theory**

**Electromagnetic vertex**

\[ \mu e q q ? \]

Often gives large \( B(\mu \rightarrow e\gamma) \)

**Contact interaction:**

May be no \( \mu \rightarrow e \) signal

Relative rates of conversion and \( \mu \rightarrow e \) are model dependent

Handle to discriminate New Physics models

**Parametrization:**

\[
L_{CLFV} = \frac{1}{1 + \frac{\kappa}{\Lambda^2}} \frac{m_\mu}{\Lambda^2} \tilde{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{1 + \frac{\kappa}{\Lambda^2}} (\bar{\mu}_L \gamma^\mu e_L)(\bar{q}_L \gamma_\mu q_L)
\]

**Photonic (dipole) interaction**

**Contact interaction**

**more sensitive to new physics**

For photonic contribution dominates,

\[
\frac{B(\mu N \rightarrow eN)}{B(\mu \rightarrow e\gamma)} = \frac{G_F^2 m_\mu^4}{96\pi^3\alpha} \times 3 \times 10^{12} B(A, Z) \sim \frac{B(A, Z)}{428}
\]

- for aluminum, about \( 1/390 \sim 0.003 \)
- for titanium, about \( 1/230 \)

**Physics Sensitivity:** \( \mu \rightarrow e\gamma \) vs. \( \mu - e \) conversion

\( B(\mu \rightarrow e\gamma) > 10^{-18} \)

\( B(\mu \rightarrow e\gamma) > 10^{-16} \)

\( B(\mu \rightarrow e\gamma) > 10^{-14} \)

\( B(\mu \rightarrow e\gamma) > 10^{-13} \)

\( B(\mu \rightarrow e\gamma) > 10^{-12} \)
μ-e Conversion : Target dependence (discriminating effective interaction)

Better matching of muon w.f. and nucleus size

normalized at Al

Experimental Comparison between $\mu \rightarrow e \gamma$ and $\mu$-e Conversion

<table>
<thead>
<tr>
<th></th>
<th>background</th>
<th>challenge</th>
<th>beam intensity</th>
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<tr>
<td>$\mu \rightarrow e \gamma$</td>
<td>accidentals</td>
<td>detector resolution</td>
<td>limited</td>
</tr>
<tr>
<td>$\mu$-e conversion</td>
<td>beam</td>
<td>beam background</td>
<td>no limitation</td>
</tr>
</tbody>
</table>

$\mu \rightarrow e \gamma$:
- Accidental background is given by $(\text{rate})^2$.
- The detector resolutions have to be improved, but difficult.
- The ultimate sensitivity would be about $10^{-14}$.

$\mu$-e conversion:
- A higher beam intensity can be taken because of no accidentals.
- Improvement of a muon beam can be possible.
  - high intensity and high purity

$\mu$-e conversion might be a next step.
Previous Measurements

SINDRUM-II (PSI)

Published Results (2004)

\[ B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13} \]

PSI muon beam intensity \( \sim 10^{7-8}/\text{sec} \)

beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.
Improvements for Signal Sensitivity

To achieve a single sensitivity of $10^{-17}$, we need $10^{11}$ muons/sec (with $10^7$ sec running) whereas the current highest intensity is $10^8$/sec at PSI.

Pion Capture and Muon Transport by Superconducting Solenoid System

(10$^{11}$ muons for 50 kW beam power)
Improvements for Background Rejection

Beam-related backgrounds

Beam pulsing with separation of 1 μsec

Muon DIO background

low-mass trackers in vacuum & thin target

Muon DIF background

curved solenoids for momentum selection

base on the MELC proposal at Moscow Meson Factory

proton extinction = protons between pulses/protons in a pulse < 10^{-9}

measured between beam pulses

improve electron energy resolution

eliminate energetic muons (>75 MeV/c)
The Mu2e experiment
Muon to electron conversion at Fermilab
Andrei Gaponenko
Fermilab
CIPANP-2012
http://mu2e.fnal.gov

• Reincarnation of MECO at BNL.
• Antiproton buncher ring is used to produce a pulsed proton beam.
• Approved in 2009, and CD0 in 2009, and CD1 in 2011.
• Data taking starts in about 2019.
What is COMET (E21) at J-PARC

8GeV proton beam

5T pion capture solenoid

3T muon transport (curved solenoids)

muon stopping target

electron transport

electron tracker and calorimeter

Experimental Goal of COMET

\[ B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17} \]
\[ B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \] (90% C.L.)

- \(10^{11}\) muon stops/sec for 56 kW proton beam power.
- \(2 \times 10^{7}\) running time (~1 year)
- C-shape muon beam line
- C-shape electron transport followed by electron detection system.
- Stage-1 approved in 2009.

Electron transport with curved solenoid would make momentum and charge selection.
The COMET Collaboration


1 Department of Physics, Brookhaven National Laboratory, USA
2 University of British Columbia, Vancouver, Canada
3 Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
4 Institute of High Energy Physics (IHEP), China
5 Institute of High Energy Physics of J. Javakhishvili State University (HEPI-TSU), Tbilisi, Georgia
6 Indian Institute of Technology, Bombay, India
7 Ibar State University (ISU), Tbilisi, Georgia
8 Imperial College London, UK
9 Institute for Nuclear Science and Technology, Vietnam
10 Institute for Theoretical and Experimental Physics (ITEP), Russia
11 Joint Institute for Nuclear Research (JINR), Dubna, Russia
12 High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
13 Institute for Chemical Research, Kyoto University, Kyoto, Japan
14 Research Reactor Institute, Kyoto University, Kyoto, Japan
15 Kyushu University, Fukuoka, Japan
16 Laboratory of Nuclear and High Energy Physics (LPNHE), CNRS-IN2P3 and University Pierre and Marie Curie (UPMC), Paris, France
17 University of Malaya, Malaysia
18 University Technology Malaysia, Johor, Malaysia
19 University of Manchester, UK
20 Nagoya University, Nagoya, Japan
21 College of Natural Science, National Vietnam University, Vietnam
22 Osaka University, Osaka, Japan
23 Saitama University, Japan
24 TRIUMF, Canada
25 University College London, UK
26 Utsunomiya University, Utsunomiya, Japan

The COMET Collaboration is international.

129 collaborators
28 institutes, 11 countries
Proton Beam
A pulsed proton beam is needed to reject beam-related prompt background.
Time structure required for proton beams.
- Pulse separation is ~ 1μsec or more (muon lifetime).
- Narrow pulse width (<100 nsec)

Pulsed beam from slow extraction.
- fill every other rf buckets with protons and make slow extraction
- spill length (flat top) ~ 0.7

Proton Beam at J-PARC

1.17 µs (584 ns x 2)

100 ns

0.7 second beam spill

3.64 second accelerator cycle

Fast Extraction at 50GeV

3 GeV Ring
2 Buckets

25 Hz
(40nsec/cycle)

Injection at 3GeV

50 GeV Ring
9 Buckets

room for layout: 300nsec

room for layout: 300nsec

1, 2, 4, 3
The COherent Muon to Electron Transition (COMET) experiment

- Background rate needs to be low in order to achieve sensitivity of $<10^{-16}$.
- Extinction is very important. Without sufficient extinction, all processes in the prompt background category could become a problem.

- $0.7\text{s spill time}$
- $5.3\times10^5$ Bunches per Spill
- $1.2\times10^8$ Protons per Bunch
- $100\text{ns bunch length}$
- $10^{-9}$ Extinction
- $1.3\mu\text{s bunch separation}$

- Muonic lifetime is dependent on target $Z$. For Al, lifetime is $880\text{ns}$.
Muon Beam
Charged Particle Trajectory in Curved Solenoids

- A center of helical trajectory of charged particles in a curved solenoidal field is drifted by

\[ D = \frac{p}{qB} \theta_{\text{bend}} \frac{1}{2} \left( \cos \theta + \frac{1}{\cos \theta} \right) \]

- This drift can be compensated by an auxiliary field parallel to the drift direction given by

\[ B_{\text{comp}} = \frac{p}{qr} \frac{1}{2} \left( \cos \theta + \frac{1}{\cos \theta} \right) \]

- This can be used for charge and momentum selection.

\( D \): drift distance  
\( B \): Solenoid field  
\( \theta_{\text{bend}} \): Bending angle of the solenoid channel  
\( p \): Momentum of the particle  
\( q \): Charge of the particle  
\( r \): Major radius of the solenoid  
\( \theta \): \( \text{atan}(P_T/P_L) \)
For helical trajectory in a curved mag. field, a centrifugal force gives $E$ in the radial direction.

To compensate a vertical shift, an electric field in the opposite direction shall be applied, or a vertical mag. field that produces the desired electric field by $v \times B$, can be applied.
## Mu2e vs. COMET

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<tr>
<th></th>
<th>Mu2e</th>
<th>COMET</th>
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<tbody>
<tr>
<td>muon beam line</td>
<td>2x 90° bends (opposite direction)</td>
<td>2x 90° bend (same direction)</td>
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<tr>
<td>electron</td>
<td>straight solenoid</td>
<td>curved solenoid</td>
</tr>
<tr>
<td>spectrometer</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Dipole Coils**

COMET curved solenoids have dipole coils on top of the solenoids, to keep muons with momentum of interest in the bending plane.
**Mu2e vs. COMET**

<table>
<thead>
<tr>
<th></th>
<th>Mu2e</th>
<th>COMET</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon beam line</td>
<td>2x 90° bends (opposite direction)</td>
<td>2x 90° bend (same direction)</td>
</tr>
<tr>
<td>electron spectrometer</td>
<td>straight solenoid</td>
<td>curved solenoid</td>
</tr>
</tbody>
</table>

Select low momentum muons

eliminate muon decay in flight

Selection of 100 MeV electrons

eliminate protons from nuclear muon capture.

eliminate low energy events to make the detector quiet.
Electron Spectrometer

- One component that is not included in the Mu2e design.
- 1T solenoid with additional 0.17T dipole field.
- Vertical dispersion of toroidal field allows electrons with $P<60\text{MeV/c}$ to be removed.
  - reduces rate in tracker to $\sim 1\text{kHz}$. 

Osaka University
Electron Detection

Electron Tracker to measure electron momentum
• work in vacuum and under a magnetic field.
• Straw tube chambers
  • Straw tubes of 25μm thick, 5 mm diameter.
  • five plane has 2 views (x and y) with 2 layers per view.
• Planar drift chambers

Under a solenoidal magnetic field of 1 Tesla.
In vacuum to reduce multiple scattering.

Electron calorimeter to measure electron energy, make triggers and give additional hit position.
• Candidate are LYSO, GSO
• MPPC or APD readout
Sensitivity and Backgrounds
Signal Sensitivity (preliminary) - $2 \times 10^7$ sec

- Single event sensitivity

$$B(\mu^- + Al \rightarrow e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

- $N_\mu$ is a number of stopping muons in the muon stopping target. It is $2 \times 10^{18}$ muons.
- $f_{cap}$ is a fraction of muon capture, which is 0.6 for aluminum.
- $A_e$ is the detector acceptance, which is 0.04.

| total protons | $8.5 \times 10^0$ |
| muon transport efficiency | 0.008 |
| muon stopping efficiency | 0.3 |
| # of stopped muons | $2.0 \times 10^0$ |

$$B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$$

$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$
### Background Rates

Table 11.9: Summary of Estimated Backgrounds.

<table>
<thead>
<tr>
<th>Background Type</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiative Pion Capture</td>
<td>0.05</td>
</tr>
<tr>
<td>Beam Electrons</td>
<td>&lt; 0.1‡</td>
</tr>
<tr>
<td>Muon Decay in Flight</td>
<td>&lt; 0.0002</td>
</tr>
<tr>
<td>Pion Decay in Flight</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Neutron Induced</td>
<td>0.024</td>
</tr>
<tr>
<td>Delayed-Pion Radiative Capture</td>
<td>0.002</td>
</tr>
<tr>
<td>Anti-proton Induced</td>
<td>0.007</td>
</tr>
<tr>
<td>Muon Decay in Orbit</td>
<td>0.15</td>
</tr>
<tr>
<td>Radiative Muon Capture</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>$\mu^-$ Capt. w/ n Emission</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>$\mu^-$ Capt. w/ Charged Part. Emission</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Cosmic Ray Muons</td>
<td>0.002</td>
</tr>
<tr>
<td>Electrons from Cosmic Ray Muons</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.34</strong></td>
</tr>
</tbody>
</table>

‡ Monte Carlo statistics limited.

Expected background events are about 0.34.
COMET Milestones
R&D Milestones for \( \mu \)-e conversion

1. Reduction of Backgrounds

   Beam pulsing measurement is done between beam pulses to reduce beam related backgrounds. And proton beam extinction of \(<10^{-9}\) is required.

2. Increase of Muon Intensity

   Pion capture system \(\times 10^3\)

   high field superconducting solenoid magnets surrounding a pion production target

\[
B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}
\]

single event sensitivity: \(2.6 \times 10^{-17}\)
Proton Extinction Measurements at J-PARC

J-PARC MR proton extinction ~ $O(10^{-7})$

Single Bunch Kicking

Tested at the abort (2010) x additional $O(10^{-6})$

COMET is confident to achieve proton extinction of $<O(10^{-9})$. 

Measured at abort beamline (2010)

Measured at secondary beamline (2010)
Research Center for Nuclear Physics (RCNP), Osaka University has a cyclotron of 400 MeV with 1 microA. The energy is above pion threshold.

Muon Source with low proton power at Osaka U.?
What is the MUSIC@RCNP?

- MUSIC (=MUon Science Innovative Channel)
- Muon particle experiments
- Muon nuclear experiments
- and other applications
- Accelerator R&D with muons
- Muon transport system
- Proton beam
- Pion capture system
- funded in FY2009
Production and Collection of Pions and Muons

**Conventional muon beam line**
- Proton beam
- Capture magnets
- SuperOmega
- Proton beam loss < 5%

**Much efficient**
- MuSIC, COMET, PRISM, Neutrino factory, Muon collider
- Proton beam
- Target: graphite t20mm φ70mm
- Transport solenoid
- Capture solenoid
- Collect pions and muons by 3.5T solenoidal field
- Large solid angle & thick target

**MuSIC**
- Proton beam: -0.4kW
- Target: graphite t200mm φ40mm
Pion Capture System at MuSIC@Osaka-U

- Pion Capture SC Solenoid:
  - 3.5 T at central
  - diameter 740mm
  - SUS radiation shield
- Transport SC solenoids
  - 2 T magnetic field
  - 8 thin solenoids
- Graphite target for pion production

Figure 4.2: Schematic layout of the pion capture system, which consists of the pion production target (proton target), the superconducting coils, the iron yoke, and its radiation shield.

Conservative design values, namely of $B = 3.5$ T and $R = 10$ cm. A solenoid magnet with a magnetic field of 3.5 T and the bore radius of 10 cm accepts most pions with $p_{\text{max}} = 52.5$ MeV/$c$.

Figure 4.3: Layout of the pion capture solenoid system.

4.2.3 Superconducting solenoid design

A large bore superconducting coil with diameter of 900 mm is placed surrounding the pion-production target. The length of the coil is 1000 mm. The target is located at the magnet.
MuSIC Beam Test in 2011

Preliminary MuSIC muon yields

\( \mu^+ : 3 \times 10^8 / s \) for 400W

\( \mu^- : 1 \times 10^8 / s \) for 400W

cf. \( 10^8 / s \) for 1MW @PSI

Req. of \( x10^3 \) achieved...

Great opportunities to carry out muon particle physics from NOW!

Measurements on June 21, 2011 (62 pA)
Common R&D with COMET and Mu2e
Superconducting Magnet R&D (2010~)

...through the US-Japan Program

R&D of solenoid coils with aluminum-stabilized superconductors

Prototype coil of aluminum-stabilized superconductors were wound in Japan and sent to FNAL (2010-2012).

Indirect cooling test bench was prepared at FNAL to test the prototype coil (2013~, not yet?)
AlCap Experiment at PSI (2013~)

...through the US-Japan Program

Measurements of particle (proton) production after muon capture on Al.

- Proton emission rate after muon capture is important, since it determines single rates of tracking chambers if no charge selection is made before detection.
- That rate for aluminum has not been measured.
- As a joint effort of Mu2e and COMET, the AlCap experiment (P. Kammel (UW) and YK (Osaka), co-spokespersons) is being done at PSI in December, 2013.
- The measurements of neutron emission will be done in 2014?
COMET Phase-I
COMET Staged Approach (2012~)

COMET Phase-I

COMET Phase-II

long enough so that # of muons/proton is the same as Phase-II.
Goals of COMET Phase-I

1. Background Study for COMET Phase-II

   - Direct measurement of potential background sources for the full COMET experiment by using the actual COMET beamline constructed at Phase-I

2. Search for $\mu^-e^-$ conversion

   - A search for $\mu^-e^-$ conversion at intermediate sensitivity which would be more than 100 times better than the SINDRUM-II limit
COMET Phase-I detector:
About $10^{16}$ muons are stopped in the target. Electron from $\mu$-e conversion will be measured.

COMET muon beam-line:
6x$10^9$ muon/sec with 3kW beam produced. The world highest intensity.
COMET Beam line
Funds for Phase-I is secured.....

Budget for COMET Phase-I has been approved.

J-PARC Hadron Experimental Hall

Items done by
proton beam-line general use KEK
muon beam-line exp. proper COMET collaboration
COMET detector

Detector budget (CDC and detector solenoid) has been secured.

High momentum proton beam line for nuclear physics

JFY2012 Supplemental budget

will be completed by end of JFY2015
Cylindrical Drift Chamber Detector (CyDet)

For Phase-I, no curved solenoid electron transport to momentum and charge select the particles is available. In the CyDet geometry, no beam particles hit the detector, and low momentum tracks do not reach the detector.

Why CyDet?

- to avoid hits of beam particles, DIO $e^-$, and low energy protons

DIO $e^-$ and low E protons with $p_T < 60$ MeV/c cannot reach the detector

Beam goes thorough
Cylindrical Drift Chamber Detector (CyDet)

- **z hit position by stereo layers (all stereo layers)**
- **reduction of multiple scattering by helium based gas mixture**
- **large inner radius to reduce DIO electron hits. (rate)**
- **proton absorber of CFRP to reduce protons from muon capture**

**Features**

- A large bore CDC in a 1T solenoid magnet
- All stereo wire
- He based low mass gas
- Proton absorber

**Trigger hodoscope (Plastic scintillator + Cherenkov)** for the photon readout: Avalanche photodiodes (APDs) and Multi Pixel Photon Counters (MPPCs).

APDs, with typical gains of 50–100, are now generally available but require an amplifier to get a sizeable signal and whose noise output depends on the APD size. Two strategies to optimise the light collection from APDs are being pursued: one using a diode with a wrapped/coated crystal and the second using a diode with a wavelength shifter on the crystal.

SiPM MPPCs are a novel form of multi-pixel photosensor where each pixel is an APD biased to be in the Geiger mode. When all the pixels are connected together in parallel they can provide photon-counting with gains of the order of $10^6$, which is comparable to that achieved with PMTs. They also provide similar or better photo-detection efficiencies and response times, and excellent linearity (when the number of hit pixels is small). They are also practically immune to magnetic fields and require a bias voltage of less than 100 V. Typical devices have dimensions of one to a few mm squared, and pixel counts ranging from a hundred to the tens of thousands.

**11.3 Readout Electronics**

The readout electronics for the electron calorimeter system is chosen to be ROESTI, which has waveform digitizer chips (DRS4). The DRS4 is a switched capacitor array running with fast sampling. It has been developed at PSI for the MEG experiment. The ROESTI prototypes that were tested at KEK used an amplifier-shaper-discriminator (ASD) ASIC which had been developed for a drift chamber. However, for the application of the electron calorimeter readout, a new ASD with different time constant to integrate signal charges will need to be developed for either the APD or MPPC photo-detector.
Cylindrical Drift Chamber Detector (CyDet)

Table 13: Main parameters of the CDC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner wall Length</td>
<td>1500 mm</td>
</tr>
<tr>
<td>Inner wall Radius</td>
<td>500 mm</td>
</tr>
<tr>
<td>Outer wall Length</td>
<td>1740.9 mm</td>
</tr>
<tr>
<td>Outer wall Radius</td>
<td>831 mm</td>
</tr>
<tr>
<td>Number of sense layers</td>
<td>20</td>
</tr>
<tr>
<td>Sense wire Material</td>
<td>Au plated W</td>
</tr>
<tr>
<td>Sense wire Diameter</td>
<td>30 µm</td>
</tr>
<tr>
<td>Number of wires</td>
<td>4986</td>
</tr>
<tr>
<td>Tension</td>
<td>50 g</td>
</tr>
<tr>
<td>Radius of innermost wire at EP</td>
<td>530 mm</td>
</tr>
<tr>
<td>Radius of outermost wire at EP</td>
<td>802 mm</td>
</tr>
<tr>
<td>Field wire Material</td>
<td>Al</td>
</tr>
<tr>
<td>Field wire Diameter</td>
<td>80 µm</td>
</tr>
<tr>
<td>Number of wires</td>
<td>14562</td>
</tr>
<tr>
<td>Tension</td>
<td>50 g</td>
</tr>
<tr>
<td>Gas</td>
<td>90%He-10%isoC 4H</td>
</tr>
</tbody>
</table>

Each cell has one sense wire surrounded by an almost-square grid of field wires. The ratio of field to sense wires is 3:1. The cell size is 16.8 mm wide and 16.0 mm height. It is nearly constant over the entire CDC region. Square cells are well-suited to the low momentum tracks (such as those from the $\mu^-$N → e^-N conversion signal), which might enter the drift cells with a large angle with respect to the radial direction. The stereo angle $\varepsilon$ is set to $54 \sim 69$ mrad, which is selected to achieve the longitudinal spatial resolution $\sigma_z$ of about 3 mm. The CyDet will have 4,986 sense wires and 14,562 field wires.
Signal Sensitivity with CyDet

Signal Acceptance

<table>
<thead>
<tr>
<th>Event selection</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical acceptance and tracking cuts</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>Momentum selection</td>
<td>0.97</td>
<td>$103.6 \text{ MeV/c} &lt; P_e &lt; 106.0 \text{ MeV/c}$</td>
</tr>
<tr>
<td>Timing window</td>
<td>0.3</td>
<td>$700 \text{ ns} &lt; t &lt; 1100 \text{ ns}$</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>DAQ efficiency</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Track reconstruction efficiency</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.043</td>
<td></td>
</tr>
</tbody>
</table>

Signal Sensitivity

- $f_{\text{cap}} = 0.6$
- $A_e = 0.056$
- $N_\mu = 9.4 \times 10^{15}$ muons

$$B(\mu^- + Al \rightarrow e^- + Al) \sim \frac{1}{N_\mu \cdot f_{\text{cap}} \cdot A_e}$$

$$B(\mu^- + Al \rightarrow e^- + Al) = 3.1 \times 10^{-17}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 7 \times 10^{-17} \quad (90\% \text{C.L.})$$

Muon intensity

- About 0.00064 muons stopped/proton

With 0.4 $\mu$A, a running time of about 90 days is needed.
The COherent Muon to Electron Transition (COMET) experiment

Proton Beam for COMET

- Background rate needs to be low in order to achieve sensitivity of \(<10^{-16}\).
- Extinction is very important. Without sufficient extinction, all processes in prompt background category could become a problem.

<table>
<thead>
<tr>
<th>Bunch Structure</th>
<th>0.7s Spill time</th>
<th>5.3x10^5 Bunches per Spill</th>
<th>1.2x10^8 Protons per Bunch</th>
<th>100ns Bunch Length</th>
<th>10^{-9} Extinction</th>
<th>1.3 ( \mu )s Bunch Separation</th>
</tr>
</thead>
</table>

Muonic lifetime is dependent on target Z. For Al lifetime is 880ns.

### Background List

#### Intrinsic physics backgrounds

1. Muon decay in orbit (DIO)
   - Bound muons decay in a muonic atom
2. Radiative muon capture (external)
   - \( \mu^- + A \rightarrow \nu_\mu + A' + \gamma, \) followed by \( \gamma \rightarrow e^- + e^+ \)
3. Radiative muon capture (internal)
   - \( \mu^- + A \rightarrow \nu_\mu + e^+ + e^- + A', \)
4. Neutron emission after muon capture
   - \( \mu^- + A \rightarrow \nu_\mu + A' + n, \) and neutrons produce \( e^- \)
5. Charged particle emission after muon capture
   - \( \mu^- + A \rightarrow \nu_\mu + A' + p \) (or \( d \) or \( \alpha \)), followed by charged particles produce \( e^- \)

#### Beam related prompt/delayed backgrounds

6. Radiative pion capture (external)
   - \( \pi^- + A \rightarrow \gamma + A', \gamma \rightarrow e^- + e^+ \)
7. Radiative pion capture (internal)
   - \( \pi^- + A \rightarrow e^+ + e^- + A' \)
8. Beam electrons
   - \( e^- \) scattering off a muon stopping target
9. Muon decay in flight
   - \( \mu^- \) decays in flight to produce \( e^- \)
10. Pion decay in flight
    - \( \pi^- \) decays in flight to produce \( e^- \)
11. Neutron induced backgrounds
    - neutrons hit material to produce \( e^- \)
12. \( \bar{p} \) induced backgrounds
    - \( \bar{p} \) hits material to produce \( e^- \)

#### Other backgrounds

14. Cosmic-ray induced backgrounds
15. Room neutron induced backgrounds
16. False tracking
### Background Estimate with CyDet

#### Table 26: Summary of the estimated background events for a single-event sensitivity of $3.1 \times 10^{-15}$ with a proton extinction factor of $3 \times 10^{-11}$.

<table>
<thead>
<tr>
<th>Type</th>
<th>Background</th>
<th>Estimated events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics</td>
<td>Muon decay in orbit</td>
<td>0.01</td>
</tr>
<tr>
<td>Physics</td>
<td>Radiative muon capture</td>
<td>$5.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>Physics</td>
<td>Neutron emission after muon capture</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Physics</td>
<td>Charged particle emission after muon capture</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Prompt Beam</td>
<td>Beam electrons (prompt)</td>
<td>$7.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>Prompt Beam</td>
<td>Muon decay in flight (prompt)</td>
<td>$\leq 1.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>Prompt Beam</td>
<td>Pion decay in flight (prompt)</td>
<td>$\leq 2.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>Prompt Beam</td>
<td>Other beam particles</td>
<td>$\leq 2.4 \times 10^{-6}$</td>
</tr>
<tr>
<td>Prompt Beam</td>
<td>Radiative pion capture(prompt)</td>
<td>$4.24 \times 10^{-4}$</td>
</tr>
<tr>
<td>Delayed Beam</td>
<td>Beam electrons (delayed)</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>Delayed Beam</td>
<td>Muon decay in flight (delayed)</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>Delayed Beam</td>
<td>Pion decay in flight (delayed)</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>Delayed Beam</td>
<td>Radiative pion capture (delayed)</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>Delayed Beam</td>
<td>Anti-proton induced backgrounds</td>
<td>0.007</td>
</tr>
<tr>
<td>Others</td>
<td>Electrons from cosmic ray muons</td>
<td>&lt; 0.00001</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.019</td>
</tr>
</tbody>
</table>
Schedule (Facility)

<table>
<thead>
<tr>
<th>JFY</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMET</td>
<td>building</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>design</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solenoid magnet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC wire</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capture magnet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport magnet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryogenic system</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnet system test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation shield</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam dump</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pion target</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design &amp; test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation of the building &amp; beam line</td>
<td>2013</td>
<td>2014</td>
<td>2015</td>
<td>2016</td>
</tr>
<tr>
<td>Bid tendering and start construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design of superconducting solenoid magnets and start of construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production of SC wires as well</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design of the pion production target</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Completion of the building</td>
<td></td>
<td></td>
<td>2014</td>
<td>2015</td>
</tr>
<tr>
<td>Construction of superconducting solenoid magnets</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start magnet and radiation shielding (and beam dump) installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport solenoid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start preparation of cryogenic system</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tests of the target production target</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction of superconducting solenoid magnets</td>
<td>2015</td>
<td>2016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preparation of cryogenic system</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction of the pion production target</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation of the capture solenoid</td>
<td></td>
<td></td>
<td></td>
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## Schedule (Detector)

### Detector construction

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Future Future Prospects of $\mu$-e conversion of $3 \times 10^{-19}$
μ-e conversion at S.E. sensitivity of $3 \times 10^{-19}$
PRISM/PRIME (with muon storage ring)

- PRIME detector
- momentum slit
- extract kickers
- PRISM beamline
- injection kickers
- PRISM-FFAG muon storage ring
- matching section
- curved solenoid (short)
- SC solenoid / pulsed horns
R&D on the PRISM-FFAG Muon Storage Ring at Osaka University

PRISM-FFAG (6 sectors) in RCNP, Osaka

demonstration of phase rotation has been done.
Summary

- CLFV would give the best opportunity to search for BSM. (So far, no BSM signals at the LHC.)
- Muon to electron conversion could be one of the important CLFV processes in terms of theoretical and experimental points of view.
- COMET (Phase-II) at J-PARC is aiming at S.E. sensitivity of $3 \times 10^{-17}$.
- After the staged approach, COMET Phase-I is aiming at S.E. sensitivity of $3 \times 10^{-15}$. The beam line construction has been funded at KEK and the construction will start in 2013. Hope to do a measurement in 2016.