Introduction of the COMET Experiment

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Outline

• cLFV and Muon to electron conversion
• The COMET experiment
• BINP and IHEP group in COMET
• Summary
Charged Lepton Flavor Violation (cLFV)

The establishment of the Standard Model and the observation of Neutrino Oscillation worked out very much in the particle physics. However there are still mysteries.

Process of CLFV
- Highly prohibited (O(<10^{-54})) in the SM
- No/less background from SM
- Very rare decays and not found yet!
- Clean field to search for new physics!
\( \mu - e \) conversion

- Atomic capture of \( \mu^- \)
  - Generate “muonic atom” by muon stopping at the target
- Measure emitted electron momentum from muonic atom
  - Decay in obit (DIO) is Michael edge up to 105 MeV
  - \( \mu - e \) conversion signal is mono-energetic \(~105 \text{ MeV}\) peak
- Spectroscopic search for \( \mu - e \) conversion
Search for $\mu - e$ Conversion

With a different design, > 4 orders of magnitude improvement is possible!
COherent Muon Electron Transition (COMET)

Search for $\mu$-e conversion in Japan at J-PARC hadron hall

➢ Experiment Target:

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

➢ This is **10000 times improvement!**

➢ Current world limit:

$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$
given by SINDRUM II experiment (2006)

➢ Likely to get 100000 times improvement!

still being optimized

$$SES = Br(\mu^- + Al \rightarrow e^- + Al) = \frac{1}{N_\mu \cdot f_{cap} \cdot f_{gnd} \cdot A_{\mu-e}}$$

$f_{cap} = 0.61$ (Al), fraction of muon capture

$f_{gnd} = 0.9$ is the fraction of $\mu$-e conversion to the ground state in the final state

$A_{\mu-e} = 0.041$ is the signal acceptance

$N_\mu$ is the number of muons stopping in the muon target
The COMET collaboration

Oct 2018, COMET collaboration at Tbilisi

~200 members,
41 institutes from 17 countries

Still growing!
Design of the COMET
Overview

- Thick Production Target + Pion Capture Solenoid ~5T
- Electron Spectrometer ~1T
- Straw Tracker & Calorimeter ~1T
- Muon Transport Solenoid ~3T
- Stopping target section ~2T
- 8GeV, 56kW Proton Beam

• Thick target with capture magnet
  ➢ Improve production efficiency
• Long muon beam line
  ➢ Clean muon beam
• Light detector system
  ➢ Search for signal with special momentum precisely

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BINP-IHEP Seminar, Novosibirsk, BINP
Background rejection (1)

• **Intrinsic physics background**
  - Mostly from muon decay in orbit (DIO)
    - Calculated by Czarnecki with radiative correction. Branching ratio drops very quickly near end point
    - **Momentum resolution** required to be better than 200 keV/c
Background rejection (2)

• Beam related background
  ➢ Energetic particles in beam with $E>100\text{MeV}$
  • Long muon beam line
  • Can be suppressed by pulse beam and a delayed measurement window (~700 ns)
  • Some due to leaked proton. Proton extinction factor required to be $< 10^{-10}$

  • Radiative pion capture, $\pi^- (A,Z) \rightarrow (A,Z-1) \gamma, \gamma \rightarrow e^+ e^-$
  • Muon decay in flight, $p_\mu > 75 \text{ MeV/c}$
  • Anti-proton induced, etc.

Material of muon stopping target
  • Heavier nucleus has large overlap with muon wave function
  • Lighter nucleus has longer life time of muon in muonic atoms
  • Aluminum stopping target will be used in COMET
  $\tau_\mu$ in Al $\sim 0.9\mu\text{sec}$
Cosmic rays may create $e^-$ in signal region that come into a detector and make trigger.

- To avoid these CR induced BG, target and detector region have to be covered by veto counters.
- Required performance: CRV inefficiency $\sim 10^{-4}$
- CR background $\propto$ data taking time (shorter running time with higher beam intensity is better)
Production target and the capture magnet

- 8 GeV 56 kW proton beam
- Thick target with 1~2 hadron interaction length
- Powerful capture magnet: 5 T
  - Large inner bore to fit in the shielding
  - Adiabatic decreasing field: focusing and mirroring
- Expected muon yield: $10^{11}$ muon/sec! ($10^8$ @ PSI)
Use **C shape** curved solenoid
- Beam gradually disperses
- Charge & momentum
- **Dipole field** to pull back muon beam
- Can be used to tune the beam
- Collimator placed in the end
- Utilize the dispersion in **180 degrees**
Stopping target and detector system

- Use straw tracker to measure the momentum
  - Really light: put in vacuum, 12 micro meter thin

Tracker with Straw-tubes
- Operational in vacuum in 1T
- $\Delta p = 150\text{~}200 \text{ keV/c} \ (for \ p=105 \text{ MeV/c})$
- Straw tube
  - 20 $\mu$m thick, 9.75 mm diameter for Phase-I
  - 12 $\mu$m thick, 5 mm diameter for Phase-II
- More than 5 stations (xx'yy' > 5)
- Ar:C$_2$H$_6$ (50:50)

- Electromagnetic calorimeter

  - 1,920 LYSO crystals
    - $2\times2\times12 \text{ cm} \ (10.5 \text{ radiation length})$
  - $\Delta E/E = 5\% \ (for \ E=105 \text{ MeV})$
  - 40-ns decay time
  - APD + read-out(EROS)
Physics Sensitivity

COMET Phase-II, One year data taking, 8 GeV, 7 mA, 56 kW proton beam

- Search for $\mu - e$ conversion with $S.E.S. = 2.6 \times 10^{-17}$ (4 orders of magnitude improvement)
- Further optimization on the way
  - Likely to improve sensitivity by factor of $10 (O(10^{-18}))$
  - with the same beam power and beam time
  - More muons with in-depth optimization of target
  - Higher acceptance after redesigning of collimator

<table>
<thead>
<tr>
<th>Event selection</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Online event selection efficiency</td>
<td>0.9</td>
</tr>
<tr>
<td>DAQ efficiency</td>
<td>0.9</td>
</tr>
<tr>
<td>Track finding efficiency</td>
<td>0.99</td>
</tr>
<tr>
<td>Geometrical acceptance + Track quality cuts</td>
<td>0.18</td>
</tr>
<tr>
<td>Momentum window ($\epsilon_{\text{mom}}$)</td>
<td>0.93</td>
</tr>
<tr>
<td>Timing window ($\epsilon_{\text{time}}$)</td>
<td>0.3</td>
</tr>
<tr>
<td>Total</td>
<td>0.041</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phase-I</th>
<th>Phase-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending</td>
<td>$90^0$ (beam)+$0^0$(detector)</td>
<td>$180^0$ (beam)+$180^0$(detector)</td>
</tr>
<tr>
<td>Beam power</td>
<td>3.2 kW (8 GeV)</td>
<td>56 kW (8 GeV)</td>
</tr>
<tr>
<td>Running time</td>
<td>$9.5 \times 10^6$ sec</td>
<td>$2 \times 10^7$ sec</td>
</tr>
<tr>
<td>POT</td>
<td>$3.2 \times 10^{19}$</td>
<td>$8.5 \times 10^{20}$</td>
</tr>
<tr>
<td>Stopped muons on target</td>
<td>$1.5 \times 10^{16}$</td>
<td>$2 \times 10^{18}$</td>
</tr>
<tr>
<td>S.E.S.</td>
<td>$3.1 \times 10^{-16}$</td>
<td>$2.6 \times 10^{-17}$</td>
</tr>
</tbody>
</table>
**Staged plan of COMET**

**COMET Phase-I**, 5 months data taking
Proton beam: 8 GeV, 0.4 mA, 3.2 kW

- Search for $\mu - e$ conversion with cylindrical detector (CyDet) with:
  S.E.S. = $3 \times 10^{-15}$
  (2 orders of magnitude improvement).

- Directly measure the muon beam with prototypes of Phase-II detector.
  - Very useful to guide Phase-II
Cylindrical Detector (CyDet) for Phase-I

Specially designed for Phase-I. Consists of:

- **Cylindrical trigger hodoscope (CTH):**
  - Two layers: plastic scintillator for trigger time and Cerenkov counter for PID.
  - Finemesh PMT readout
  - 4-fold coincidence trigger

- **Cylindrical drift chamber (CDC):**
  - 20 stereo layers: z information with few layers' hits
  - Helium based gas: minimize multiple scattering
  - Large inner bore: to avoid beam flash and DIO electrons.
  - Momentum resolution: 200 keV/c (for p=105 MeV/c)

- **Stopping target**
  - Aluminum target with 17 disks
  - 100-mm radius, 0.2-mm thickness, 50-mm spacing.
Monte Carlo study of COMET Phase-I

- The optimization of COMET Phase I is finished. Detailed performance is estimated with Monte Carlo studies. TDR was published on arXiv (arXiv:1812.09018 [physics.ins-det])
- Sensitivity:
  - Total acceptance of signal is 0.041.
  - Can reach $3 \times 10^{-15}$ SES in 150 days.
- Background:
  - With 99.99% CRV total expected BG is 0.032
- Trigger rate:
  - Average trigger rate $\sim 10$kHz (after trigger with drift chamber hits)

\[
B(\mu^- + Al \rightarrow e^- + Al) = \frac{1}{N_\mu \cdot f_{capt} \cdot f_{grad} \cdot A_{\mu-e}}
\]
\[
B(\mu^- + Al \rightarrow e^- + Al) = 3 \times 10^{-15} \text{ (S.E.S)}
\]
\[
B(\mu^- + Al \rightarrow e^- + Al) < 7 \times 10^{-15} \text{ (90\% C.L.)}
\]

<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></td>
<td>Radiative muon capture</td>
<td>0.0019</td>
</tr>
<tr>
<td></td>
<td>Neutron emission after muon capture</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td></td>
<td>Charged particle emission after muon capture</td>
<td>$&lt; 0.001$</td>
</tr>
</tbody>
</table>

- Prompt Beam
  - * Beam electrons
    - Muon decay in flight
    - Pion decay in flight
    - Other beam particles
  - All (*) Combined $\leq 0.0038$
  - Radiative pion capture $0.0028$
  - Neutrons $\sim 10^{-5}$

- Delayed Beam
  - Beam electrons $\sim 0$
  - Muon decay in flight $\sim 0$
  - Pion decay in flight $\sim 0$
  - Radiative pion capture $\sim 0$
  - Anti-proton induced backgrounds $0.0012$

- Others
  - Cosmic rays $< 0.01$

Total $0.032$

[1] This estimate is currently limited by computing resources.
Other Physics Topics on COMET

- $\mu^- N_Z \rightarrow e^+ N_{Z-2}$: Lepton number violation (LNV)
  - Current limits: $\mu^- Ti \rightarrow e^+ Ca(gs) \leq 1.7 \times 10^{-12}$
  - $\mu^- Ti \rightarrow e^+ Ca(ex) \leq 3.6 \times 10^{-12}$
  - Can improve with a proper target
- $\mu^- e^- \rightarrow e^- e^-$: $\mu^-$ and $e^-$ overlap proportional to $Z^3$
- $\mu^- \rightarrow e^- X$: $X$ can be a new light boson, axion, etc.
  - feasibility being studied in COMET

References:
- Phys. Rev. D93 (2016) 076006
- Phys. Rev. D84. 113010 (2011)
Current Status of the COMET
COMET Facility

- Experimental Hall building completed
- Cryogenic system under construction
- Proton beamline will be ready this year
  - Shield wall & power station completed. 2 more magnets to be located soon.
Proton beam from J-PARC MR

• To make the proton extinction factor \(< 10^{-10}\)
  • Shift the kicker phase by half period to avoid residual protons in the empty bucket

• Measurement at Hadron Hall MR using 8 GeV proton beam, Slow extraction

Extinction factor \(< 6 \times 10^{-11}\) achievable
Production Target System

- Phase-I graphite target (IG-43) can be cooled under radiation with 3.2 kW beam.
- Remote handling and cask design of target is in progress.
- Shielding blocked with water cooling is being designed.

Tungsten shielding with water cooling

Phase-I production target prototype
Solenoids

- Capture solenoid
  - Last coil under winding.
- Transport solenoid
  - Installed and ready for cryogenic test.
- Bridge & detector solenoid
  - DS coil and cryostat ready. BS coil delivered.
- Cryogenic system:
  - Refrigerator test completed.
  - Helium transfer tube in production.
StrEcal

- Straw tube detector
  - Finished vacuum test with 20 um straw tubes.
  - Mass production for Phase-I finished.
  - Tested with 100 MeV electron beam. 150 um spatial resolution achieved.

- R&D of Straw tube
  - **12 micro meter** thin straw produced for Phase-II!
  - Diameter 5 mm
    - 1 bar overpressure straw tube diameter measurement shows 0.1 um accuracy.
  - Over pressurization test holding more then 4 bar

Straw tube prototype

- Electromagnetic calorimeter
  - Tested GSO and LYSO. Preliminary resolutions are 5.7% and 4.6% for each. LYSO chosen as final option.
- Front end electronics
  - Finished designing (ROESTI/EROS) based on DRS4 with GHz sampling rate. Radiation tests results published.
CyDet (Phase-I)

• Cylindrical Drift chamber (CDC)
  – Prototype tests finished in 2015. 150 um spatial resolution and 99% hit efficiency were achieved.
  – Construction of the chamber was finished in 2016.
  – Cosmic ray test is under data taking phase.

• Front end electronics
  – Based on RECBE boards from BELLE-II
  – Finished the production and mass tests of 108 boards.
  – Radiation tests are published / to be published.

• Trigger system
  Cylindrical trigger hodoscope (CTH) under mechanical design. Trigger logic and trigger board design finished. Communication tests with FCT-FC7 trigger system is on going.
Software

• Development of frame “ICEDUST”
  • Based on ND280 framework
  • Almost ready, still being implemented more
• Optimizing design using MC simulation
  • Simulation of production target, translation, magnetic field, collimator, stopping target, detector shield ……
  • Mass MC events generation is ongoing for more higher statistic study

Detector simulation
Contribution of Chinese Group
--- Production of drift chamber readout

- The production of 128 readout board – RECBE has finished by IHEP, China in 2015
  - The design is based on BELLE-II CDC readout board
  - 48 input channels
  - TDC Time resolution: 1 nsec
  - ADC Sampling rate: 30 MHz
- A performance test, threshold scanning and aging test have been done

![COMET-CDC readout board](image1)

![128 pcs RECBE in the dry box](image2)

![Automatic Test System](image3)
Contribution of Chinese Group
--- Phase-I design optimization

• Beam simulation
• Experiment optimization
  • Production target, Collimator, CTH
• Sensitivity and Backgrounds
  • Muon decay in orbit (DIO)
  • Radiative muon capture (RMC)
  • Radiative pion capture (RPC)
  • anti-proton
  • Other beam related backgrounds

Collimator after optimization
Contribution of Chinese Group
--- Offline software development and analysis

• Drift chamber track finding and track fitting
  • Line circle combinational track finding
  • Multi-turn track fitting based on genfit2

• Magnetic field calculation

• Mass production on Tianhe2 super computer
Contribution from BINP
--- ECAL electronics and straw tracking etc.

- Y. Yudin, L. Epshteyn, R. Akhmetshin, L. Epshteyn, D. Grigoriev, V. Kazanin
  - ECAL electronics
  - ECAL trigger
- Fedor Ignatov
  - Track finding in the Straw Tracker
Summary
• COMET is an experiment at J-PARC searching for muon to electron process.
  • Aims at S.E.S = $2.6 \times 10^{-17}$ (4 orders of magnitude improvement) with 1 year beam time using 56 kW 8 GeV proton beam.
  • With the same beam power, 10 times better sensitivity ($\mathcal{O}(10^{-18})$) is likely and optimization is on the way.

• COMET will be carried out in two phases and Phase-I is under construction.
  • Aims at S.E.S = $3 \times 10^{-15}$ (2 orders of magnitude improvement) with 150 days beam time using 3.2 kW 8 GeV proton beam.
  • Will directly measure the muon beam.

• COMET Phase-II R&D study is on going and will be adjusted based on Phase-I result.