



Search for Muon to Electron Conversion at J-PARC: COMET Phase-I Experiment

MyeongJae Lee (Institute for Basic Science, Korea) Sep 25, 2017, NUFACT 2017



ER B

μ OMET e



OMET e









Signal

- Muon stops at Al (or Ti) target, captured in 1s orbit
- Decay with monoenergetic electron

$$- E = m_{\mu} - E_{rec} - E_{B} \sim 105 MeV$$



Background

Decay-In-Orbit (DIO)



- Muon/pion decay in flight
- Radiative pion capture: $\pi N \rightarrow \gamma X; \gamma \rightarrow e+e-$
- Cosmic, Anti-proton...



Sep 25, 2017

Stopped μ - in matter



- Muon capture : 61% (Al)
 - $-\mu^- + p \to \nu_\mu + n$
 - Muon decay coherently with nucleus
 - Source of background hits



Decay in orbit (DIO) : 39% (Al)

$$-\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

- (Dynamically) free decay of muon inside atom
- E(e,max,Al) ~< m_{μ} ~ 104MeV
 - (peak at 50 MeV)



M.J.Lee, COMET Phase-I, NUFACT2017

Muon conversion

- $-\mu^- + N \to e^- + N$
- Muon
 conversion
 coherently with
 nucleus





COMET Experiment









Pion Capture Section

A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet

Transport Section

Production

Target

Protons

Pion decays to muon, with momentum and charge selection

> Stopping Target

Detector Section

A detector to search for muon-to-electron conversion process

COMET Phase-II

For R~10⁻¹⁷ muon conversion measurement

- 56 kW proton beam
- 1 year DAQ

COMET-Phase-I

For BG measurement, R~10⁻¹⁵ muon conversion

- 3.2kW proton beam
- Half year DAQ

Facility / Beams





Experimental Principle







- 1. Protons arrive at production target
- 2. Pions and muons arrive at stopping target
- 3. Captured muon decay with finite lifetime
- 4. Some time after muon beam arrival, electron is measured
 - Any other beam particles in this time window are backgrounds
 - Bunch beam with high extinction factor

Pulsed Proton Beam





Beam Power	3.2 kW
Energy	8 GeV
Average current	ο.4 μΑ
Beam Emittance	10π mm∙mrad
Proton/bunch	<1010
Extinction	10 ⁻⁹
Bunch separation	1~2 µS
Bunch length	100NS



Pulsed proton beam

- Beam background with proton pulse is major BG hit source
- High extinction between beam enables localizing signal event in time
- ~10⁻¹¹ extinction factor measured by increasing MR RF voltage (May 2014), both at 8GeV and 30GeV, in Fast Extraction (@ Abort line)
- More test with Slow Extraction early next year

Accelerator Facility





OMET e

Solenoids



- Pion Capture Solenoid
 - Downstream parts ready, Upstream parts this and next year
 - All SC wires prepared







- Transport Solenoid
 - Ready, test and installation, alignment



Cylindrical Detector system







- All stereo-wire drift chamber, 18 layers, ~5000 sense wires
- Hodoscope for timing and trigger
- Construction completed June 2016, Cosmic ray test from August 2016

OMET



Electronics Installation

- **RECBE** installation
- #1: trigger making
- #2-5: upper region#6-8: lower region
 - ev 575 High Voltage Side











M.J.Lee, COMET Phase-I, NUFACT2017

-2

-1.5

-1

for Basi



CTH: Trigger Hodoscope





- Twisted, overlapped two scintillators + two Cerenkov detectors
- Primary hit rate too high for trigger

	Upstream	Upstream	Downstream	Downstream
	Scintillator	Cherenkov	Scintillator	Cherenkov
Average rate @200 ~ 1170 ns (MHz)	3.5	1.5 - 2	4	3

Adding lead shielding, require 4-fold coincidence for trigger
 primary trigger rate 20 – 30 kHz



Trigger / DAQ



FC7

(CMS)

- High trigger rate (20-30 kHz) for DAQ
 - Mostly background hits
 - Beam electron, secondary from capture neutron/gamma
 - Online trigger suppress BG hits
- A configurable and flexible Trigger system
 - Central system based on commercial CERN product and a custom interface board
 - Ensuring commonality in 适直 interfacing with different systems.



riggei data



Analoc

signat

СТН

Analog signal

CDC

Straw - Electron Calorimeter Detector (Detector for background measurement)



StrEcal

Detector for Phase-II

- 5 station of straw detectors + ~2000 LYSO calorimeter
- Beam measurement program at Phase-
 - Particle composition, beam profile
 - 1/1000 reduced beam
 - no radiation tolerance, pile-up issue.
 - CyDet rolls out and StrEcal installed





MEt Integrated Beam Test for StrEcal









- Integrated test with beam at Tohoku univ.
- Mar 2016 and Mar 2017
- Including
 - **One Straw chamber** prototype
 - 8x8 LYSO calorimeter
 - MIDAS DAQ
 - DRS4 based RO
 - Trigger based on FC7+GBT
- All successful operation and test, data under analysis
 - Preliminary data matches with prototype tests

CDC BG Rejection, Reconstruction

- Signal / BG hit discrimination using BDT
 - Signal efficiency = 0.99, when BG rejection = 0.95
 - 1/20 BG hit reduction : trigger rate = $1 \sim 2$ kHz
- Signal / BG event discrimination
 - Signal efficiency = 0.90, when BG rejection = 0.95
 - Hardware implementation on trigger system under development
- Offline track reconstruction with Kalman filter







M.J.Lee, COMET Phase-I, NUFACT2017



Physics sensitivity



- Net acceptance = 4.1%
 - Online efficiency ~0.99
 - Geometric acceptance
 + track quality ~0.18
 - 103.6 MeV
 - 700ns < t < 1170 ns : 0.3
- Background = 0.032
 - RPC ~ 0.003
 - DIO ~ 0.01
 - Cosmic < 0.01
- SES(Phase-I) ~ 3.1x10⁻¹⁵
 - SES(Phase-II) ~ 2.5x10⁻¹⁷



Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) Combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays [†]	< 0.01
Total		0.032
	† This estimate is currently limited by computing resource	es.

$\underbrace{\mathsf{DME}}_{e}^{\mu} \text{ LNV physics: } \mu^{-} - e^{+} \text{ Conversion}$ $\mu^{-} + N(A, Z) \rightarrow e^{+} + N(A, Z - 2)$





Nµ-stop = 10¹⁸, BR(µ⁻e⁺)=1.7×10⁻¹²

Atom	$E_{\mu^{-}e^{+}}$	$E_{\mu^{-}e^{-}}$	E_{RMC}^{end}	N.A.	f_{cap}	τ_{μ} –	A_T
	(MeV)	(MeV)	(MeV)	(%)	(%)	(ns)	
²⁷ Al	92.30	104.97	101.34	100	61.0	864	0.191
^{32}S	101.80	104.76	102.03	95.0	75.0	555	0.142
^{40}Ca	103.55	104.39	102.06	96.9	85.1	333	0.078
48 Ti	98.89	104.18	99.17	73.7	85.3	329	0.076
^{50}Cr	104.06	103.92	101.86	4.4	89.4	234	0.038
⁵⁴ Fe	103.30	103.65	101.93	5.9	90.9	206	0.027
⁵⁸ Ni	104.25	103.36	101.95	68.1	93.1	152	0.009
64 Zn	103.10	103.04	101.43	48.3	93.0	159	0.011
$^{70}\mathrm{Ge}$	100.67	102.70	100.02	20.8	92.7	167	0.013

Candidate for muon stopping target

- Similar process with $0\nu\beta\beta$ in eµ sector
 - Provides clues in LNV and Majorana ν
 - Another physics case with COMET Phase-I detector
- Experimentally simple but hard to achieve good sensitivity
 - By flipping charge
 - RMC background dominates
- Replacing Al target to other nuclei may allow O(10⁴) sensitivity improvement (arXiv:1705.07464)

OMET e

Schedules



- Highly recognized by KEK IPNS, stage-2 of COMET Phase-I approved (i.e. project full funded, beam will be delivered)
- Phase-I physics data taking in 2019
 - Depending on budget allocation
 - Cosmic run at 2018, 4 weeks of engineering run
 - 5 month data taking
- Phase-II R&D in parallel with Phase-I R&D and data taking
- Phase-II physics data taking in 2021~2022
 - 1 year data taking



_	S. Mihara, T. Nakamoto, H. Nishiguchi, T. Ogitsu, C. Omori, M. Sugano, Y. Takubo, M. Tanaka, M. Tomizawa, T. Uchic	Institute for Chem	Y. Iwashita ical Research, Kyoto University, Kyoto, Japan	University Technology Malaysia T. Numao			
The COMET Collaboration	M. Yamanaka, M. Yoshida, Y. Yoshii, K. Yoshi High Energy Accelerator Research Organization (KEK),	Institute for .	V.V. Thuan Nuclear Science and Technology, Vietnam	TRIUMF, Canada			
R. Akhmetshin, A. Bondar, L. Epshteyn, G. Fedotovich, D.	Yu. Bagaturia Ilia State University (ISU), Tbilisi, Georgi	Institute o	HB. Li, C. Wu, Y. Yuan of High Energy Physics (IHEP), China	Contact Person			
Budker Institute of Nuclear Physics (BINP), Novos	P. Dauncey, P. Dornan, B. Krikler, A. Kurup, J. Nash, J. Pa Imperial College London, UK	A. Liparteliani, N. M Institute of High Energy Physi	Iosulishvili, Yu. Tevzadze, I. Trekov, N. Tsverava cs of I.Javakhishvili State University (HEPI TSU), Tbilisi,	L	* *		
K. Palmer Department of Physics, Brookhaven National Labo	P. Sarin, S. Umasankar Indian Institute of Technology Bonbay, India	S. Dymoy, P. Evtouki	Georgia ovich. V. Kalinnikov, A. Khvedelidze, A. Kulikov.	Now momboro oro	117 0		
Y. Arimoto, K. Hasegawa, Y. Igarashi, M. Ikeno, S. Ishimoto S. Mihara, T. Nakamoto, H. Nishiguchi, T. Ogitsu, C. Omor M. Suzano, Y. Takuko, M. Tanaka, M. Tamirawa, T. Uch	Y. Iwashita Institute for Chemical Research, Kuoto University, K	G. Macharashvili, A. Moiseen Joint Institute f	ko, B. Sabirov, V. Shmakova, Z. Tsmalaidze, E. Velicheva or Nuclear Research (JINR), Dubna, Russia	Inew members are			
M. Sugano, T. Takubo, M. Tahasa, M. Tokha, Y. Yoshi, K. Yos M. Yamanaka, M. Yoshida, Y. Yoshii, K. Yos High Energy Accelerator Research Organization (KEK)	V.V. Thuan Institute for Nuclear Science and Technology V	M. Danilov, A. Drutskoy, V. Rusinov, E. Tarkovsky Institute for Theoretical and Experimental Physics (ITEP), Russia		LPNHE, France	27		
Yu. Bagaturia Ilia State University (ISU), Tbilisi, Geor	H-B. Li, C. Wu, Y. Yuan Institute of High Energy Physics (IHEP), Ch	Max-Planck-Institute for Ph	T. Ota ysics (Werner-Heisenberg-Institute), Munchen, Germany	Kyushu University, Japa	an 12		
P. Dauncey, P. Dornan, B. Krikler, A. Kurup, J. Nash, J. 1 Imperial College London, UK	A. Liparteliani, N. Mosulishvili, Yu. Tevzadze, I. Trekov Institute of High Energy Physics of I. Javakhishvili State Universit	Y. M	Iori, Y. Kuriyama, J.B. Lagrange				
P. Sarin, S. Umasankar Indian Institute of Technology Bonbay, Ir	Georgia S Dymoy P Extoukhovich V Kalinnikov A Khyedelict		S.Mihara, J-	PARC PAC Meeting, 16/Mar/201	.2		
Y. Iwashita Institute for Chemical Research, Kyoto University,	G. Macharashvili, A. Moiseenko, B. Sabirov, V. Shmakova, Z. Tsmala Joint Institute for Nuclear Research (JINR), Dubna, Ru	aidze, E. Velicheva ussia	New members are		1		
V.V. Thuan Institute for Nuclear Science and Technology,	M. Danilov, A. Drutskoy, V. Rusinov, E. Tarkovsky Institute for Theoretical and Experimental Physics (ITEP),	, Russia	LPNHE, France	27 institutes	21		
HB. Li, C. Wu, Y. Yuan Institute of High Energy Physics (IHEP), (T. Ota Max-Planck-Institute for Physics (Werner-Heisenberg-Institute), Mu	unchen, Germany Kyl	ushu University, Jap	oan 12 countries	⁵ B.I. Step		
A. Liparteliani, N. Mosulishvili, Yu. Tevzadze, I. Trek Institute of High Energy Physics of I.Javakhishvili State Univer	Y. Mori, Y. Kuriyama, J.B. Lagrange				uchi ¹⁹ , A. Yamamoto ¹⁵ , P		
Georgia S. Dymov, P. Evtoukhovich, V. Kalinnikov, A. Khvede	S.Mi	ihara, J-PARC	PAC Meeting, 16/Mar/20	12	⁵ , T. Yoshioka ¹⁹ , Y. Yuar		
G. Macharashvili, A. Moiseenko, B. Sabirov, V. Shmakova, Z. Tsm. Joint Institute for Nuclear Research (JINR), Dubna,	Alaidze, E. Velicheva			¹ North China Electric Power University,	, Beijing, People's Republic		
M. Danilov, A. Drutskoy, V. Rusinov, E. Tarkovs Institute for Theoretical and Experimental Physics (ITEL	^{ky} LPNHE, Fr	rance	27 institutes	² Institute of High Energy Physics (IHEP) ³ Peking University, Beijing, I ⁴ Relations Cht. Universit), Beijing, People's Republi People's Republic of China (BSU) Minch Belanus		
T. Ota Max-Planck-Institute for Physics (Werner-Heisenberg-Institute), 1	Munchen, Germany Kyushu Univers	sity, Japan	12 countries	⁵ B.I. Stepanov Institute of Physics, National Aca ⁶ Budker Institute of Nuclear Physic	ademy of Sciences of Belaru ics (BINP), Novosibirsk, Ru		
Y. Mori, Y. Kuriyama, J.B. Lagrange				⁷ Charles University, Pro S The Cocker of Institute Daresbu	ague, Czech Republic y Laboratory, Warri		
S.A	lihara, J-PARC PAC Meeting, 1	.6/Mar/2012		Creek Technical University,	Prague, Czech Repu nology, Bombay, Ind		
Halt vear da	ata taking for	1		¹² Institute for Theoretical and Exper- ¹³ Institute for Theoretical and Exper-	d Technology, Hanoi. timental Physics (IT		
				¹⁴ Joint Institute for Nuclear Research Or 1 ¹⁵ High Energy Accelerator Research Or	earch (JINR), Dubme reganization (KEK), 1		
– Muon conv	version			² King Mediaeric June ⁵ Invefine for Chemical Research Research Research Research ⁶¹⁰ Ryushu University,	ersity, Saudi Arabia Ryoto University, Ky oto Eniversity, Kyot 2. Fukuoka, Japan		
measurem	ent	The second se	COMET Collaboration	n meeting@KEK 26-30 Jan 2015	(LPNHE), CNRS-IN MC), Paris, France versiti Malava, Kual-		
			176.0	ollaboratore			
— Beam measurement			I/O CONADULATORS,				
			22 institu	Ites 15 countries			
			33 11300				

• ... and the Future?



$ME_{e}^{\#}$... and the Future up to O(10⁻¹⁹)





- x(1/2) from reduced beam acceptance from solenoid to FFAG
- x3 from removing detection time window (no pion)
- x3 from pion capture improvement
 - x20 from 56 kW \rightarrow 1MW
- Multi GW beam
- PRISM (Phase Rotated Intense Slow Muon source)







Cosmic ray / Neutron

- To suppress Cosmic Ray muon to factor of 10⁻⁴
 - Decay in flight, interaction with detector material
 - Note: CDC can full-reconstruct CR
- Neutron issue
 - SiPM weak to neutron irradiation, generates noise at Strip sensor
 - Internal Neutron Shield reduces neutron from stopping target
 - Similar neutron flux expected from proton target, shielding around beamline under study











M.J.Lee, COMET Phase-I, NUFACT2017