Search for Muon to Electron Conversion at J-PARC

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Abstract

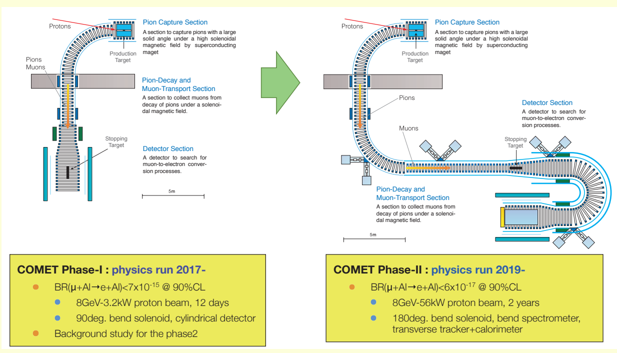
The COMET experiment at J-PARC is an experiment to search for muon to electron conversion at a single event sensitivity of 3x10[-17]. This process is charged-lepton flavor violating. We are planning to stage the COMET experiment. The staging approach is endorsed by J-PARC PAC and KEK. We will present the details of COMET Phase-I.

Introduction

Searches for the **charged lepton flavor violating (cLFV)** processes are very important to study the physics beyond the standard model of the elementary particle physics. Among the cLFV processes, a coherent neutrino-less conversion of muons to electrons (μ-e conversion), in the presence of a nucleus, **$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$**, is much attractive due to their upgradability with powerful proton divers such as J-PARC main ring and the Project-X in FNAL. Two experimental searches for the μ-e conversion have been proposed: COMET for the J-PARC and Mu2e for the FNAL. The both experiments are in their design phase, therefore a lot of simulation studies and R&D programs are underway. The COMET stands for COherent Muon to Electron Transition. It was approved as a stage-1 experiment by the J-PARC PAC in July 2009, and given the experiment number J-PARC E21.

Staging Approach of COMET

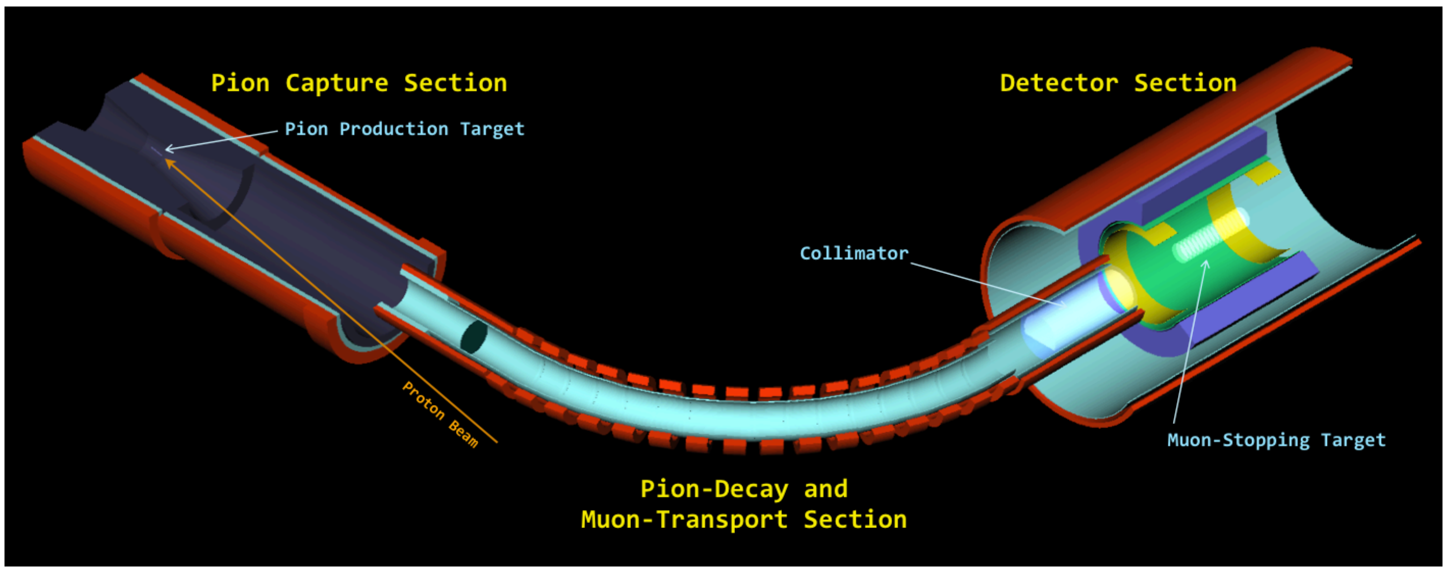
The proposed J-PARC mid-term plan includes the construction of the COMET beamline. This will provide the proton beamline for COMET and part of the muon beamline in the south area of the J-PARC Hadron Experimental Hall. We consider a staged approach for COMET: **"COMET Phase-I"** and **"COMET Phase-II"**.



For the COMET Phase-I, we will construct the first 90 degrees of the muon beamline so that a muon beam can be extracted to the experimental area. Then, we will:

1) make a direct measurement of the proton beam extinction and other potential background sources for the COMET Phase-II experiment, using the actual COMET beamline, and
2) carry out a search for μ−e conversion with a singe-event sensitivity (S.E.S.) of **3×10^{-15}**, which is better than achieved by SINDRUM-II.

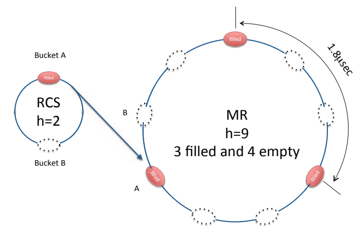
After these measurements, the muon transport will be extended up to 180 degrees for the COMET Phase-II. We will start the μ−e conversion search with S.E.S. of **3×10^{-17}** sensitivity with an electron spectrometer and detectors.



Proton Beam for the COMET Phase-I

The J-PARC main ring (MR) is used to supply a pulsed 8 GeV proton beam, which is slow extracted, maintaining its bunch structure, into the J-PARC Nuclear and Particle Experimental Hall (NP Hall). The pulsed proton beam then hits the pion production target located inside the pion capture solenoid magnet. The produced pions decay to muons as they are transported from the pion production target to the muon stopping target. These muons are momentum selected by the curved solenoid transport channel.

The required proton beam power is 8 GeV × (0.1–1) μA ((0.63–6.3) × 10^{12} protons/s), which will provide enough muons at COMET Phase-I to allow the beam properties to be studied and the physics goals to be achieved. For the beam property study, a normal slow-extraction beam is best for reducing the instantaneous detector hit rate. For the μ−e conversion search, as in the case of that using the full COMET experiment, the proton beam needs to be pulsed with a time separation of about 1 μs, which corresponds to the lifetime of a muon in a muonic atom. The proton beam in the main ring is extracted and delivered to the pion production target whilst maintaining the pulse structure of the beam. For COMET Phase-I to achieve its expected sensitivity, the relative number of residual protons between pulses needs to be as small as the requirement for the full COMET experiment, namely 10^9 times smaller than the number of protons in the main pulse, because of the shorter length of the muon transport line, which leads to a larger survival rate for the pions.



Beam Power	8 kW
Energy	8 GeV
Average Current	1 μA
Beam Emittance	$10\,\pi$ mm·mrad
Protons per Bunch	$< 10^{10}$
Extinction	10^{-9}
Bunch Separation	1~2 μs
Bunch Length	100 ns

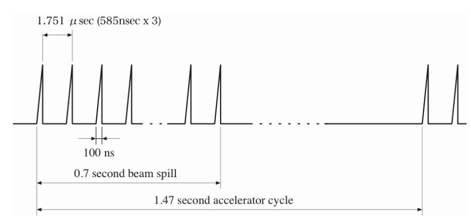
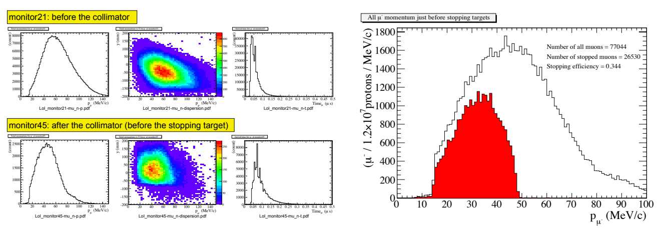


Figure 1: Up: COMET beam acceleration bunch configuration in the RCS and the main ring with requirements on the pulsed proton beam for the COMET experiment. Bottom: Timing structure of the bunched proton beam in a slow extraction mode.

Muon Beam

The muon beam line of COMET Phase-I will include the pion capture section and the muon transport section up to the end of first 90◦ bend of the COMET experiment. The design of the muon beam line of COMET Phase-I is identical to that of the full COMET experiment. COMET Phase-I uses negatively-charged low-energy muons, which can be easily stopped in a muon-stopping target. The low-energy muons are mostly produced by the decay in flight of low-energy pions. Therefore, the production of low-energy pions is of major interest. At the same time, high-energy pions and muons, which could potentially cause background events, should be eliminated as well as possible.

Since the magnetic field at the detector (of 1 Tesla) is smaller than that at the muon beamline, the beam would spread when it enters the detector. The beam collimator is placed just after the end of the first 90◦ bend to determine a beam size so that muons that are not stopped in the muon stopping target are eliminated before entering the detector. And at the same time, it would eliminate high momentum muons. Figure 2 shows momentum distribution of negative muons coming to the muon stop- ping target and a faction of muons stopped in the muon stopping target.



Sensitivity and Background

By assuming a proton beam of 8 GeV with 0.4 μA, with a running period of 10^6 s, a total number of muon stopped is $N_{stop} = 5.8 \times 10^{15}$ (= 0.0023 × 2.5 × 10^{18}). The single event sensitivity is

$B(\mu + Al \rightarrow e + Al) = 3.1 \times 10^{-15}$.

The 90 % confidence upper limit is

$B(\mu + Al \rightarrow e + Al) < 7.2 \times 10^{-15}$.

Table 6.4 shows a summary of the estimated backgrounds. The total estimated back- ground is about 0.11 events for a single event sensitivity of 3.1 × 10^{-15} with a proton extinction factor of 10−9. If the proton extinction factor is increased, the expected background events are further reduced.

Table 6.2: Breakdown of the $\mu^- - e^-$ conversion signal acceptance per stopped muon for the case of trigger counters of 5 mm thickness.

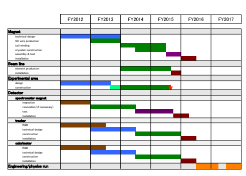
Event selection	Value	Comments
Geometrical acceptance	0.40	tracking efficiency included
Momentum selection	0.66	$P_e > 101.9$ MeV/c
Timing selection	0.39	same as COMET
Trigger and DAQ	0.9	same as COMET
Total	0.09	

Table 6.4: Summary of estimated background events for a single-event sensitivity of 3×10^{-15} with a proton extinction factor of 10^{-9}

Background	estimated events
Muon decay in orbit	0.05
Radiative muon capture	< 0.001
Neutron emission after muon capture	< 0.001
Charged particle emission after muon capture	< 0.001
Radiative pion capture	0.024
Beam electrons	< 01
Muon decay in flight	0.0004
Pion decay in flight	< 0.0001
Neutron induced background	0.024
Delayed radiative pion capture	0.002
Anti-proton induced backgrounds	0.007
Cosmic ray muons	0.0001
Electrons from cosmic ray muons	0.0001
Total	0.11

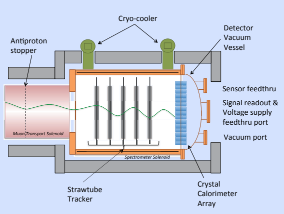
Schedule

The technically-driven schedule for COMET Phase-I is shown in Table 8.1. We are hoping to start construction in 2013 and carry out measurements in 2016.



Detectors for the COMET Phase-I

For Background Study



This figure shows a schematic view of the setup for background measurement. Mea- surement of the proton beam extinction ratio will be done by using segmented hodoscope counters as used in previous studies. The setup composed of a solenoid magnet with 0.85–1 T magnetic field strength, 5 layers of tracker, and crystal calorimeter. Detectors are located in a vacuum vessel functioning as a cryostat of the spectrometer magnet. The same detector technology as the COMET detector will be employed. The tracker will be constructed using straw chambers being developed for the COMET tracker. The crystal calorimeter will be composed of GSO or LYSO crystals; R&D is in progress and produc- tion will be ready in time for COMET Phase-I. We will make a decision which crystal to use according to the result of R&D. Performance of these detectors will be investigated in this measurement and upgraded for the COMET experiment if necessary. It is also possible to test readout electronics and the data acquisition scheme. In this sense this setup will be a real prototype of the COMET detector.

For μ-e conversion search

Two types of detector configuration are considered for the μ−e− conversion search in COMET Phase-I. One is a cylindrical detector option, and the other is a transverse tracker detector option, in which the detector for background measurements mentioned before is reused. The former is a detector dedicated for COMET Phase-I to maximize an experimental sensitivity for μ−e− conversion search, and the latter is a prototype detector for the full COMET experiment.The baseline option for the detector to search for μ−e conversion is a cylindrical detector.