Invited paper

A search for muon-to-electron conversion at J-PARC: the COMET experiment

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A new experimental search for the charged-lepton-flavor-violating process of neutrinoless muon-to-electron conversion by J-PARC E21 (the COMET experiment), which aims at a factor of 10 000 improvement over the current limit, is described, together with the physics motivation of charged lepton flavor violation. The first-stage approach of the COMET experiment (COMET Phase-I), which has recently been taken for earlier realization of the measurement, is also mentioned.

Subject Index C10, C12, C14, C31

1. Introduction

The origin of the flavors of elementary particles is a puzzling enigma. Their properties and structure should reflect the nature of the physics beyond the Standard Model (SM). Flavor physics is thereby believed to provide a path to new physics. Flavor changing neutral current (FCNC) processes are of particular interest since they are expected to include the effect of new physics that is observable in high-precision experiments. Among the FCNC processes, the processes of charged lepton flavor violation (CLFV) have recently attracted much attention from both the theoretical and experimental points of view [1].

CLFV has yet to be observed and is known to be sensitive to new physics beyond the SM. The J-PARC E21 experiment is an experiment to search for a CLFV process of neutrinoless muon-to-electron conversion ($\mu^-\rightarrow e^-$ conversion) in a muonic atom,

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

at a single-event sensitivity (SES) of $2.6 \times 10^{-17}$ (or $< 6 \times 10^{-17}$ 90% confidence level (C.L.) upper limit) at the Japanese Proton Accelerator Research Complex (J-PARC). Here, the SES is an experimental sensitivity to observe one event. This experiment is called COherent Muon to Electron Transition (COMET) [2]. This anticipated sensitivity goal of the COMET experiment is a factor of 10 000 better than that of the current experimental limit, which is $B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$ from SINDRUM-II at PSI [3].

Recently, a two-stage approach in order to realize the COMET experiment in a timely manner has been taken. COMET Phase-I aims at an intermediate SES of $3 \times 10^{-15}$ or better, an improvement of about a factor of 100 or better [4]. In addition, the COMET Phase-I is intended to take measurements
of potential background sources for the COMET Phase-II, i.e. the original full-sized COMET experiment aiming at an ultimate sensitivity of $2.6 \times 10^{-17}$. Construction of COMET Phase-I is planned to start in 2013 and measurements are expected to start around 2016.

2. Physics motivation of CLFV

Up to now, a Higgs-like boson particle has been observed but no other new particles expected in physics beyond the SM have so far been found at the Large Hadron Collider (LHC). Therefore, the search for CLFV is crucial to find any clues of physics beyond the SM.

Figure 1 shows a past history of searches for CLFV in muon and kaon decays. The current status of various LFV searches is summarized in Table 1. The search for CLFV processes has notable advantages, including the following. (1) CLFV can have sizable contributions from new physics and thus can manifest itself in future experiments. (2) CLFV makes no sizable contribution in the SM, unlike the FCNC process of quarks; such contributions give serious background events and limit the sensitivity to new physics.

Although CLFV has never been observed, lepton flavor violation among neutrino species has been experimentally confirmed with the discovery of neutrino oscillations [18,19], and hence lepton flavor conservation is now known to be violated. The phenomenon of oscillation means that neutrinos are massive and hence the SM must be modified so that CLFV can occur. Furthermore, there are other reasons that compel us to modify the SM, including the existence of dark matter [20], and stability of the weak scale against quantum corrections [21–25]. These indicate that new physics beyond the SM will reveal itself at the TeV scale. This scale is within the scope of the LHC and expected CLFV experiments, including COMET.

![Fig. 1. History of searches for CLFV in muon and kaon decays. Reprinted figure from Ref. [1]. Copyright 2001 by the American Physical Society.](image-url)
Table 1. Present limits of CLFV of the muon, tau, pion, kaon, and Z boson.

| Reaction                  | Present limit | Reference |
|---------------------------|---------------|-----------|
| $\mu^+ \rightarrow e^+ \gamma$ | $< 2.4 \times 10^{-12}$ | [5]       |
| $\mu^+ \rightarrow e^+ e^- e^-$ | $< 1.0 \times 10^{-12}$ | [6]       |
| $\mu^- Ti \rightarrow e^- Ti$ | $< 6.1 \times 10^{-13}$ | [7]       |
| $\mu^- Au \rightarrow e^- Au$ | $7 \times 10^{-13}$ | [3]       |
| $\mu^+ e^- \rightarrow \mu^- e^+$ | $8.3 \times 10^{-11}$ | [8]       |
| $\tau \rightarrow e\gamma$ | $< 3.9 \times 10^{-7}$ | [9]       |
| $\tau \rightarrow \mu \nu \gamma$ | $< 3.1 \times 10^{-7}$ | [10]      |
| $\tau \rightarrow \mu \mu \mu$ | $< 1.9 \times 10^{-7}$ | [11]      |
| $\tau \rightarrow e e e$ | $< 2.0 \times 10^{-7}$ | [11]      |
| $\pi^0 \rightarrow e \mu$ | $< 8.6 \times 10^{-9}$ | [12]      |
| $K^+ \rightarrow e \mu$ | $< 4.7 \times 10^{-12}$ | [13]      |
| $K^0 \rightarrow \pi^+ e^- e^-$ | $< 2.1 \times 10^{-10}$ | [14]      |
| $K^0 \rightarrow \pi^0 \mu^+ e^-$ | $< 3.1 \times 10^{-9}$ | [15]      |
| $Z^0 \rightarrow e \mu$ | $< 1.7 \times 10^{-6}$ | [16]      |
| $Z^0 \rightarrow \tau e$ | $< 9.8 \times 10^{-6}$ | [16]      |
| $Z^0 \rightarrow \tau \mu$ | $< 1.2 \times 10^{-5}$ | [17]      |

Fig. 2. One of the diagrams showing massive neutrino contributions to a $\mu \rightarrow e$ transition ($\mu \rightarrow e \gamma$).

2.1. SM contribution to CLFV

It is well known that in the minimally extended SM, which includes vanishingly small neutrino masses to account for neutrino oscillations, the predicted rate for CLFV is too small to be observed. For example, the prediction for $B(\mu \rightarrow e \gamma)$ is given by the graph in Fig. 2 [26–29],

$$B(\mu \rightarrow e \gamma) = \frac{\alpha}{2\pi} \sum_k U_{ek} U_{\mu k}^* \frac{m_{\nu k}^2}{m_W^2} \left| \frac{m_{\nu k}}{m_W} \right|^2 < 10^{-54}.$$  \hspace{1cm} (2)

Here $U_{\beta i}$ is the Maki–Nakagawa–Sakata matrix [30] with $\beta$ denoting a charged lepton flavor eigenstate and $i$ a neutrino mass eigenstate with mass $m_{\nu i}$, $m_W$ is the $W$ boson mass, and $\alpha$ is the fine-structure constant. Note that the Glashow–Iliopoulos–Maiani (GIM) mechanism [31] leads to a prediction dependent on differences in the masses of the neutrinos. For the $\mu^+ \rightarrow e^+ \gamma$ process, a similar suppression arises due to gauge symmetry.

Therefore, the discovery of CLFV would imply new physics not only beyond the SM but also beyond neutrino oscillations.

2.2. New physics and CLFV

Most new physics or interactions beyond the SM predict CLFV at some level. Examples of such new physics models include supersymmetric (SUSY) models, extra-dimension models, little Higgs
models, models with new gauge $Z'$ bosons, models with new heavy leptons, leptoquark models, etc. Each gives a prediction for FCNC including CLFV [1].

**Supersymmetric models**

Supersymmetric extensions to the SM are the leading candidates for physics beyond the SM. In this class of models, a form of parity, called R-parity, is often imposed to suppress FCNC, rapid proton decays, and other phenomena. In this case, the source for CLFV is the mass matrix ($m_{\tilde{l}}^2$) for sleptons, the scalar partners of the leptons. In principle, this can be arbitrary and a large FCNC can be introduced. However, strong constraints are imposed on these parameters. For example, the branching ratio of $\mu^+ \rightarrow e^+ \gamma$ is given similarly to Eq. (2) by

$$B(\mu \rightarrow e\gamma) = \frac{\alpha}{2\pi} \left| \sum_k \tilde{U}_{ek} \tilde{U}_{\mu k}^* \frac{\Delta m_{\tilde{l}k}^2}{m_S^2} \right|^2 \left( \frac{m_W}{m_S} \right)^4,$$

where $m_S$ is the typical scale of scalar masses, $\tilde{U}$ denotes the mixing matrix between sleptons and leptons, and $\Delta m_{\tilde{l}k}^2$ is the mass-squared difference between the $k$th and the 1st sleptons. To suppress this, the conditions that, by some mechanism, $\tilde{U}$ is almost diagonal and/or $\Delta m_{\tilde{l}k}^2$ is small enough compared with $m_S^2$ have to be assumed. To implement these conditions at the weak scale, it is often assumed that at a certain scale $M_G$,

$$\tilde{U} = 1 \quad \text{and} \quad \Delta m_{k}^2 = 0,$$

and an observable effect arises as a radiative correction. As a result, $\tilde{U} \simeq 1$ and $\Delta m_{k}^2 \simeq 0$ are maintained at the weak scale.

Under this condition, the SUSY contribution to a muon-to-electron transition ($\mu \rightarrow e \ "\gamma"$), where "$\gamma$" is a virtual photon) is given by Fig. 3, where the mixing between a smuon ($\tilde{\mu}$) and a selectron ($\tilde{e}$) is denoted by $\Delta m_{\tilde{\mu}e}$, and plays a key role.

This slepton mixing parameter, $\Delta m_{\tilde{\mu}e}$ (or similarly $\Delta m_{\tilde{e}\mu}$) is given by the off-diagonal element of the slepton mass matrix ($m_{\tilde{l}}^2$) that is given by

$$m_{\tilde{l}}^2 = \begin{pmatrix}
m_{\tilde{e}\tilde{e}}, & \Delta m_{\tilde{e}\tilde{e}}, & \Delta m_{\tilde{e}\tilde{\mu}} \\
\Delta m_{\tilde{e}\tilde{e}}, & m_{\tilde{e}\tilde{e}}, & \Delta m_{\tilde{e}\tilde{\mu}} \\
\Delta m_{\tilde{\mu}\tilde{e}}, & \Delta m_{\tilde{\mu}\tilde{\mu}}, & m_{\tilde{\mu}\tilde{\mu}}
\end{pmatrix}.$$

Therefore, the determination of these SUSY contributions would enable us to study the structure of the slepton mass matrix, and then more importantly the “SUSY soft breaking” that is the origin of
SUSY particle masses. It should be noted that slepton mixing is difficult to study as precisely as in CLFV studies in high-energy collider experiments such as the LHC. Hence, studies of CLFV would provide a unique opportunity to study slepton mixing. In the following, the SUSY contributions to CLFV are presented in more detail.

There are several mechanisms that give the conditions in Eq. (4). Among these, gravity-mediated soft breaking is most often employed. It gives the conditions in Eq. (4) at the gravity scale (=Planck, $\sim 10^{19}$ GeV) or the grand unified scale ($\sim 10^{16}$ GeV). Non-zero off-diagonal matrix elements can then be induced by radiative corrections from $M_G$ to the weak scale ($\sim 10^2$ GeV).

To reproduce lepton mixing and the neutrino masses, the seesaw mechanism [32,33] has been studied most extensively. In this mechanism, three right-handed neutrinos $N_i$ are introduced. Mass terms for the neutrinos are given by the Yukawa coupling between the lepton doublets ($L_\alpha$) and the right-handed neutrinos and the Majorana mass term for the right-handed neutrinos:

$$W = \bar{N}_i f^\alpha \nu L_\alpha H_u + \frac{1}{2} \bar{N}_i M_R \bar{N}_j.$$ 

This leads Eq. (5) [35] to be

$$(\Delta m^2_L)_{\alpha\beta} \simeq -\frac{6 + a_0^2}{16\pi^2} m_0^2 (f_v^\alpha f_v^\beta) \log \frac{M_G}{M_R}.$$ 

Here $m_0$ denotes the SUSY breaking scale and $a_0$, a parameter for $A$ term breaking, is an $O(1)$ parameter.

Thus, in the SUSY model with the seesaw mechanism, slepton mixing can be induced from neutrino mixing. CLFV processes in muon decays are then also expected to occur [36–38]. An example of the branching ratio is shown in Fig. 4.
The most important result here is a possible relation between the branching ratio of $\mu^+ \rightarrow e^+ \gamma$ and that of $\mu^- \rightarrow e^- \gamma$ conversion. In this model, $\mu^- \rightarrow e^- \gamma$ conversion is dominated by a photonic dipole operator similar to Fig. 3, with a quark line attached at the other end of the photon line. Therefore the important relation \cite{39}

$$\frac{\text{Br}(\mu^+ N \rightarrow e^+ N)}{\text{Br}(\mu^- \rightarrow e^- \gamma)} \sim \alpha$$

is achieved. The details of this ratio depend on the nucleus, as can be seen in Fig. 5. For other types of SUSY models, the relation given in Eq. (8) may not hold and might depend strongly on the SUSY parameters.

**Little Higgs models**

In little Higgs models \cite{40,41}, the Higgs boson appears as a quasi-Nambu–Goldstone boson to ensure its stability against quantum corrections. There are several implementations of this idea. Among them, the model with T-parity \cite{42} is the most extensively studied. In this model, to prevent the hierarchy problem, mirror fields of the ordinary fields are introduced. These have odd T-parity, while ordinary fields are even under T-parity. This parity works similarly to R-parity in SUSY models.

The source of CLFV arises from the misalignment between the mirror fields and the ordinary fields \cite{43}. There is no principle forbidding large FCNC, and current limits on CLFV strongly constrain models. In Fig. 7, the predictions for $\mu^- \rightarrow e^- \gamma$ conversion and $\mu \rightarrow e \gamma$ are shown with an appropriate assumption taken for the misalignment.

The various contributions to $\mu^+ \rightarrow e^+ \gamma$ in these models are depicted in Fig. 6. In addition to the GIM suppression, the diagrams shown in Fig. 6 might cancel one another, making the overall photonic contribution small. Therefore, unlike the case of SUSY-seesaw models given in Eq. (8), the photonic diagrams do not give a leading contribution to $\mu^- \rightarrow e^- \gamma$ conversion, and the box and Z penguin diagrams dominate the amplitude for $\mu^- \rightarrow e^- \gamma$ conversion \cite{44–46}. Incidentally, due to T-parity conservation, there is no tree-level contribution to $\mu^- \rightarrow e^- \gamma$ conversion and hence both branching ratios are loop-suppressed. Thus the branching ratios in this model are almost equal, as shown in Fig. 7, namely,

$$\frac{\text{Br}(\mu^+ N \rightarrow e^+ N)}{\text{Br}(\mu \rightarrow e^+ \gamma)} \sim 1.$$
Extra-dimensional models

There are many kinds of models involving extra-dimensional space. Here we discuss the Randall–Sundrum model [47].

To explain the hierarchy among the Yukawa couplings, the SM fields are permitted to propagate in full 5D space [48,49]. In this scenario, the SM fields are localized at a different point of the 5th dimension. Yukawa couplings are quite sensitive to the position and this fact explains the hierarchy among the Yukawa couplings in effective 4D theory with $O(1)$ group 5D couplings. These $O(1)$ couplings indicate large mixing among the generations in full 5D theory. It manifests itself in the self-couplings of the 1st Kaluza–Klein (KK) gauge bosons and ordinary fermions as follows.

First we note that, in the interaction basis $(e_F, \mu_F, \tau_F)$, the gauge coupling “universality” among fermions is modified:

$$\begin{pmatrix}
\alpha_e & 0 & 0 \\
0 & \alpha_\mu & 0 \\
0 & 0 & \alpha_\tau
\end{pmatrix}
\begin{pmatrix}
e_F \\ \mu_F \\ \tau_F
\end{pmatrix}.$$  (10)
Here, $\alpha_{e,\mu,\tau}$ stand for the ratios of the couplings of the leptons ($e, \mu, \tau$) to the 1st KK gauge bosons to those of the corresponding SM couplings. They are not necessarily equal to one. In the mass eigenstate ($e, \mu, \tau$), therefore, there arise CLFV couplings as follows.

$$
\alpha_{e,0,0} \ 0 \\
0 \ \alpha_{\mu,0,0} \\
0 \ 0 \ \alpha_{\tau}
$$

$$
U_L^{\dagger} \ U_R \ 
\begin{pmatrix}
e \\
\mu \\
\tau
\end{pmatrix}, \quad \text{(11)}
$$

where $U_L(R)$ are the mixing matrices to diagonalize the mass matrix given in the basis of the interaction state. Note that since $\alpha_{e,\mu,\tau}$ are not equal, the effect of the mixing matrices remains. In principle, it causes a large CLFV effect. With the appropriate assumption, the prediction for CLFV is given in Fig. 8. There is not a strong correlation between $\mu^+ \to e^+ \gamma$ and $\mu^- \to e^- \gamma$ conversion. The branching ratios are predicted to be rather large and give a similar magnitude:

$$
\frac{\text{Br}(\mu + N \to e + N)}{\text{Br}(\mu \to e^+ \gamma)} \sim 1. \quad \text{(12)}
$$

2.3. $\mu^- \to e^- \gamma$ conversion vs. $\mu^+ \to e^+ \gamma$

There are considered to be two possible contributions in the $\mu^- \to e^- \gamma$ transition diagrams. One is a photonic contribution of dipole interaction, and the other is a non-photonic contribution of contact interaction [51]. For the photonic contribution, there is a definite relation between the $\mu^- \to e^- \gamma$ conversion process and $\mu^+ \to e^+ \gamma$ decay. Supposing that the photonic contribution is dominant, the branching ratio of the $\mu^-\to e^- \gamma$ conversion process is expected to be smaller than that of $\mu^+ \to e^+ \gamma$ decay by a factor of a few hundred due to electromagnetic interaction of a virtual photon, as shown in Eq. (8). This implies that the search for $\mu^- \to e^- \gamma$ conversion at the level of $10^{-16}$ is comparable to that for $\mu^+ \to e^+ \gamma$ at the level of $10^{-14}$.

If the non-photonic contribution dominates, the $\mu^+ \to e^+ \gamma$ decay would be small whereas the $\mu^- \to e^- \gamma$ conversion could be sufficiently large to be observed. It is worth noting the following. If a $\mu^+ \to e^+ \gamma$ signal is found, a $\mu^- \to e^- \gamma$ conversion signal should also be found. The ratio of the branching ratios between $\mu^+ \to e^+ \gamma$ decay and $\mu^- \to e^- \gamma$ conversion carries vital information on
the intrinsic physics process. If no $\mu^+ \to e^+ \gamma$ signal is found, there will still be an opportunity to find a $\mu^- \to e^- \gamma$ conversion signal because of the potential existence of non-photonic contributions.

The effective Lagrangian that includes both the photonic and non-photonic contributions is given by [51]

$$\mathcal{L} = \frac{1}{1 + \kappa} \frac{m_\mu}{\Lambda^2} \bar{\mu}_R \gamma^\mu \mu L F_{\mu\nu} + \frac{\kappa}{1 + \kappa} \frac{1}{\Lambda^2} (\bar{\mu}_L \gamma^\mu \mu L) (\bar{q}_L \gamma^\mu q_L),$$

where $\kappa$ determines the ratio between the photonic and non-photonic contributions and $\Lambda$ indicates the typical energy scale of new physics. Figure 9 shows the relation between the branching ratios of $\mu^+ \to e^+ \gamma$ and $\mu^- \to e^- \gamma$ conversion in terms of a function of a ratio of the photonic and non-photonic contributions. The current limits of CLFV [5-7] give a stringent limit on these effective energy scales as $\Lambda > 10^3$ TeV in tree diagrams. This means, e.g., that if these operators are loop-suppressed by a factor of $1/(16\pi^2)$, the scale explored by new CLFV experiments would be in the TeV range. The 90% C.L. upper limits expected from COMET Phase-I, COMET Phase-II, and PRISM (as a future prospect [52]) are also shown.

In general, the relation between the photonic and non-photonic contributions is model-dependent. For example, in SUSY models, they are both loop-suppressed and are related to each other tightly, while, in little Higgs models, they are both loop-suppressed but are not related so much. Therefore,
the relation between $\mu \to e\gamma$ and $\mu^- e^- \nu_e$ conversion shows a characteristic feature for each model. This demonstrates that the $\mu^- e^- \nu_e$ conversion search has outstanding physics motivation.

3. $\mu^- e^- \nu_e$ conversion phenomenology

3.1. What is $\mu^- e^- \nu_e$ conversion?

When a negative muon is stopped by some material, it is trapped by an atom, and a muonic atom is formed. After it cascades down energy levels in the muonic atom, the muon is bound in its $1s$ ground state. The fate of the muon is then to either decay in orbit ($\mu^- e^- \nu_e$) or be captured by a nucleus of mass number $A$ and atomic number $Z$, namely, $\mu^- + N(A, Z) \to \nu_\mu + N(A, Z - 1)$. However, in the context of physics beyond the Standard Model, the exotic process of neutrinoless muon capture, such as

$$\mu^- + N(A, Z) \to e^- + N(A, Z), \quad (14)$$

is also expected. This process is called $\mu^- e^- \nu_e$ conversion in a muonic atom. This process violates the conservation of lepton flavor numbers, $L_e$ and $L_\mu$, by one unit, but the total lepton number, $L$, is conserved. The branching ratio of $\mu^- e^- \nu_e$ conversion is determined to be the ratio of the rate of $\mu^- e^- \nu_e$ conversion to that of normal muon capture, namely,

$$B(\mu^- N \to e^- N) = \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- + N \to \nu_\mu + N')}. \quad (15)$$

The final state of the nucleus $(A, Z)$ could be either the ground state or one of the excited states. In general, the transition to the ground state, which is called coherent capture, is dominant. The rate of coherent capture over non-coherent capture is enhanced by a factor approximately equal to the number of nucleons in the nucleus, since all of the nucleons participate in the process.

3.2. Signal and background events for $\mu^- e^- \nu_e$ conversion

Event signature

The event signature of coherent $\mu^- e^- \nu_e$ conversion in a muonic atom is a mono-energetic single electron emitted from the conversion with an energy of

$$E_{\mu e} = m_\mu - B_\mu - E_{\text{rec}},$$

where $m_\mu$ and $m_e$ are the muon mass and the electron mass respectively, and $B_\mu$ and $E_{\text{rec}}$ are the binding energy of the $1s$ muonic atom and the nuclear recoil energy, respectively. The nuclear recoil energy is approximately given by

$$E_{\text{rec}} \sim \left( m_\mu - B_\mu \right)^2 / (2m_N),$$

where $m_N$ is the mass of the recoiling nucleus, and is very small.

From an experimental point of view, $\mu^- e^- \nu_e$ conversion is a very attractive process. Firstly, the $e^-$ energy of about 105 MeV is far above the end-point energy of the muon decay spectrum ($\sim 52.8$ MeV). Secondly, since the event signature is a mono-energetic electron, no coincidence measurement is required. The search for this process has the potential to improve sensitivity by using a high muon rate without suffering from accidental background events, which would be serious for $\mu^+ \to e^+ \gamma$ decay and other muon CLFV processes, such as $\mu^+ \to e^+ e^+ e^-$ decay.

Muon-related backgrounds

Muon decay in orbit (DIO) in a muonic atom would be one of the most important intrinsic physics background from muons. The endpoint of the DIO spectrum coincides with the energy of the signal electron ($E_{\mu e}$). The DIO spectrum above $m_\mu / 2$ occurs owing to the nuclear recoil momentum. Since the energy distribution of DIO falls steeply above $m_\mu / 2$, the experimental setup can have a large signal acceptance and the detectors can still be protected against the vast majority of decay and
capture background events. Energy distributions for DIO electrons have been calculated for a number of muonic atoms \cite{53-56} and energy resolutions of the order of 0.1% are sufficient to keep this background level below $10^{-18}$ in a branching ratio, namely with respect to the rate of the normal muon capture (in Eq. (15)).

**Beam-related backgrounds**

There are several other potential sources of electron background events in the energy region around 100 MeV, involving either beam particles or cosmic rays. Beam-related background events may originate from muons, pions, or electrons in the beam. Apart from DIO, muons may produce background events by muon decay in flight or radiative muon capture (RMC). Pions may produce the most serious background events by radiative pion capture (RPC). Gamma rays from RMC and RPC produce electrons mostly through $e^+e^-$ pair production inside the target.

There are three methods to suppress beam-related background events:

- **Beam pulsing**
  Since muonic atoms have lifetimes of the order of 1 $\mu$s, a pulsed beam with a width that is short compared with this lifetime would allow the removal of prompt background events by performing measurements in a delayed time window. As will be discussed below, there are stringent requirements on beam extinction during the measuring interval.

- **Beam momentum**
  The in-flight decay of muons in a beam produces 100 MeV/$c$ electrons by Lorentz boost, if the muon momentum is larger than 77 MeV/$c$. Beam electrons produced at the proton target would also be a source of 100 MeV/$c$ electron background. Thus, if the beam momentum is restricted to be lower than 77 MeV/$c$, these backgrounds can be suppressed.

- **Beam purity**
  Pions in a muon beam (beam pions) would be the most critical background source, since they produce background through radiative pion capture. They should thereby be reduced. The lifetime of the pion (26 ns) is much shorter than the lifetime of muon (2.2 \times 10^3 ns). Thus, if the length of the muon beam line is long enough, most beam pions will decay away as they are transported through the muon beam line. For the beam momentum range of interest for the $\mu^−e^−$ conversion search, e.g. of less than 77 MeV/$c$, the level of pion contamination will be decreased by an order of magnitude for each 10 m of beam line length. Next-generation experiments are planned to have a muon beam line of about 20 m.

3.3. Why is $\mu^-e^-$ conversion the next step?

Considering its marked importance to physics, it is highly desirable to consider a next-generation experiment to search for CLFV. There are three important processes to be considered; namely, $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^+e^−$, and $\mu^- \rightarrow e^−$ conversion.

The three processes have different experimental issues that need to be solved to realize improved experimental sensitivities. They are summarized in Table 2. The processes of $\mu^+ \rightarrow e^+\gamma$ and $\mu^+ \rightarrow e^+e^+e^-\gamma$ are detector-limited owing to accidental backgrounds. To consider and go beyond the present sensitivities, the resolutions of detection have to be improved, which requires innovative improvement of the detector technology. In particular, improving the photon energy resolution is difficult. On the other hand, for $\mu^- \rightarrow e^-\gamma$ conversion, there are no accidental background events, and an experiment with higher rates can be performed. If a new muon source with a higher beam intensity and better
beam quality for suppressing beam-associated background events can be constructed, measurements of the search for $\mu^-e^-$ conversion with a higher sensitivity can be performed.

Furthermore, it is known that, in comparison with $\mu^+\rightarrow e^+\gamma$, there are more physical processes that $\mu^-e^-$ conversion and $\mu^+\rightarrow e^+e^+e^-$ could contribute to. For instance, in SUSY models, photon-mediated diagrams can contribute to all three processes, but diagrams mediated by particles other than photons, such as Higgs-mediated diagrams, can contribute to only $\mu^-e^-$ conversion and $\mu^+\rightarrow e^+e^+e^-$ [57]. In summary, with all the above considerations from experimental and theoretical issues, we believe that a $\mu^-e^-$ conversion experiment would be the natural next step in the search for muon CLFV.

4. Present experimental status of $\mu^-e^-$ conversion

Table 3 summarizes the history of searches for $\mu^-e^-$ conversion. From Table 3, it is seen that over about 30 years the experimental upper limits have been improved by 5 orders of magnitude. In the following, the past and future experiments on the search for $\mu^-e^-$ conversion will be described.

### 4.1. SINDRUM-II

The latest search for $\mu^-e^-$ conversion was performed by the SINDRUM-II Collaboration at PSI. Figure 10 shows their results. The main spectrum, taken at 53 MeV/c in muon beam momentum, shows the steeply falling distribution expected from muon DIO. One event was found at higher momenta, but just outside the region of interest. The agreement between measured and simulated positron distributions from $\mu^+$ decay means that confidence can be high in the accuracy of the momentum calibration. At present there are no hints concerning the nature of the one high-momentum event: e.g., it might have been induced by RPC from pions in a beam or cosmic rays. They set the 90% C.L. upper limit on the branching ratio of $\mu^+e^-$ conversion in gold, of $B(\mu^-+Au\rightarrow e^-+Au)<7\times10^{-13}$ [3].

### 4.2. MECO at BNL

There was an experimental proposal at Brookhaven National Laboratory (BNL), the MECO experiment [64], aiming to search with a sensitivity of $10^{-16}$. Its design was based on the MELC...
Fig. 10. Momentum distributions of electrons and positrons for the two event classes. Measured distributions are compared with the results of simulations of muon decay in orbit and $\mu^{-}\pi^{+}$ conversion. Reproduced from [3] with kind permission from Springer Science and Business Media.

Fig. 11. A schematic layout of the Mu2e experiment.

The Mu2e experiment has been actively revived at the Fermi National Laboratory (FNAL) as the “Mu2e” experiment [66]. A schematic layout of the Mu2e experiment is shown in Fig. 11. The muon beam line and detector for the Mu2e experiment are similar to those of the MECO experiment. Their goal is a single-event sensitivity (SES) of $3 \times 10^{-17}$ with 3 years of $2 \times 10^7$ second running per year.
The Mu2e experiment will use the FNAL proton source, and the desired proton beam structure from their 8 GeV booster can be made by reusing the recycler and debuncher rings. A major challenge is the requirement for proton extinction in between the proton bursts. In order to maintain the pion stop rate in the “silent” interval, a beam extinction factor better than $10^{-10}$ is required. The experimental proposal was approved at FNAL in the fall of 2008 on its physics motivation and experimental feasibilities. They are under the US DOE (Department of Energy) critical decision (CD) process for their funding, and they received the CD-1 in spring, 2012. They are aiming at an experiment start around 2020. The Mu2e experiment would strongly compete with the COMET experiment at J-PARC.

5. Overview of COMET at J-PARC

The COMET experiment is designed to be carried out in the nuclear and particle experimental hall (NP hall) using a bunched proton beam that is slow-extracted from the J-PARC main ring (MR) [2]. The experimental set-up consists of a dedicated proton beam line section, a muon beam line section and a detector section. The muon beam line section is composed of pion capture solenoids with high magnetic fields, and the muon transport with curved and straight solenoids. The detector section is composed of a muon-stopping target, an electron transport for $\mu^-\rightarrow e^-$ conversion signals, followed by the detectors. A schematic drawing of the experimental set-up is shown in Fig. 12.

COMET aims to improve the sensitivity by a factor of 10 000 over the current limit, i.e., an SES of $3 \times 10^{-17}$. In order to achieve this, several important features have been considered, as highlighted below.

- **Highly intense muon source**: To achieve an experimental SES of $3 \times 10^{-17}$, a total number of muons stopped in the muon-stopping target of $2 \times 10^{18}$ is needed, and, therefore, a highly intense muon beam line has to be constructed. To increase the muon beam intensity, two methods are adopted. One is to use a proton beam of high beam power. The other is to use a system of collecting pions (“pion capture system”), which are parents of muons, with high efficiency. In the muon collider and neutrino factory R&D, superconducting solenoid magnets producing a high
magnetic field surrounding the proton target have been proposed and studied for pion capture over a large solid angle. With the pion capture system, about $8 \times 10^{20}$ protons of 8 GeV are needed to achieve a number of muons of the order of $10^{18}$. The concept of the pion capture system has been experimentally demonstrated by the MuSIC facility at the Research Center of Nuclear Physics (RCNP), Osaka University [67–70]. Figure 13 shows a picture of MuSIC at RCNP.

- **Pulsed proton beam**: There are several potential sources of electron background events in the energy region around 100 MeV, where the $\mu^--e^-$ conversion signal is expected. One of them is beam-related background events. To suppress the occurrence of beam-related background events, a pulsed proton beam utilizing “beam pulsing” is proposed. Since muons in muonic atoms have lifetimes of the order of 100 nsec, a pulsed beam with beam buckets that are short compared with these lifetimes would allow removal of prompt beam background events by allowing measurements to be performed in a delayed time window. As will be discussed below, there are stringent requirements on the beam extinction during the measuring interval. Tuning of a proton beam in the accelerator ring as well as extra extinction devices should be installed to achieve the required level of beam extinction.

- **Muon transport system with curved solenoids**: The captured pions decay to muons, which are transported with high efficiency through a superconducting solenoid magnet system. Beam particles with high momenta would produce electron background events in the energy region of 100 MeV, and, therefore, they must be eliminated with the use of curved solenoids where the centers of the helical motion of the electrons drift perpendicular to the plane in which their paths are curved, and the magnitude of the drift is proportional to their momentum. By using this effect and by placing suitable collimators at appropriate locations, beam particles of high momenta can be eliminated.

- **Spectrometer with curved solenoids**: To reject electron background events and reduce the probability of false-tracking owing to high counting rates, a curved solenoid spectrometer is considered to allow selection of electrons on the basis of their momenta. The principle of momentum selection is the same as that used in the muon transport system, but, in the spectrometer, electrons of low momenta, such as less than 80 MeV/c, which mostly come from muon decay in orbit (DIO) are removed. The detection hit rates for the COMET experiment would be sufficiently
small to handle, about 1000 tracks per second (1000 Hz), whereas the Mu2e experiment expects very high hit rates of about 500 kHz per single wire of the tracking device.

6. Proton beam for COMET

The J-PARC main ring (J-PARC MR) is used to supply a pulsed 8 GeV proton beam, which is slowly extracted, maintaining its bunch structure, into the J-PARC NP hall. The pulsed proton beam then hits the pion production target located inside the pion capture solenoid magnet to produce pions.

6.1. Proton beam power

The J-PARC MR will deliver a proton beam, as the design goal, with an intensity of \(3.3 \times 10^{14}\) protons per cycle and a cycle time of about 0.3 Hz. Protons from the J-PARC MR are extracted to the NP hall by slow extraction. When operated in slow extraction mode, the average beam current and duty factor are 15 μA and 0.2 respectively.

The number of pions (and therefore their daughter muons) produced by a proton beam is proportional to the proton beam power, which is given by the product of the beam energy and beam current. This is due to the fact that the pion cross-section increases linearly with proton beam energy.

The required beam energy is about 8 GeV. The reasons for the relatively low proton beam energy, i.e. 8 GeV, are twofold. One is to suppress production of antiprotons, and the other is to ease the requirements of the beam extinction system if needed, where a lower beam energy is easier to deflect, as described in the next subsection. The cross section of antiproton production, \(p + p \rightarrow p + p + p + \bar{p}\) whose threshold is at 5.6 GeV, rapidly increases above a proton beam energy of 10 GeV. Thus a proton beam energy of 8 GeV is used in the current design. At this energy, even if antiprotons are produced, most of them can be eliminated by inserting a stopping foil in the muon transport line. The aluminum foil separating the vacuum between the areas of the COMET muon beam line and the primary beam line can be used for this purpose.

6.2. Proton time structure

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 signal electrons emitted from the stopping target and entering the detector during the interval between proton pulses are measured. Figure 14 shows a typical time structure for the pulsed proton beam suitable for the COMET experiments. In addition to this, the proton beam has to be transported to the pion production target whilst keeping its pulse

![Fig. 14. Bunched proton beam in slow extraction mode.](image-url)
structure. This can be realized using the bunched slow extraction technique. The requirements on the time structure are satisfied by operating the J-PARC MR by filling only three (four) out of nine buckets in the case when the ring is operated at a harmonic number of nine. The three (four) filled buckets are distributed along the ring in such a way that two (one) empty buckets exist between two filled buckets. Since the time difference between two consecutive buckets is 585 ns, as determined by the acceleration RF frequency, the bunch–bunch spacing will then be 1.751 (1.17) μs. This satisfies the COMET proton pulse separation requirement.

This will be realized by filling every third (second) bucket, which gives a total of three (four) out of nine buckets filled in the MR. The schemes are illustrated in Figs. 15 and 16 for the cases of three and four buckets filled, respectively.

Once the proton beam is accelerated to 3 GeV in the J-PARC 3 GeV rapid cycle synchrotron (RCS), it is injected to the J-PARC MR. As in the case for normal operations, a single injection transfers a total of two beam buckets from the RCS to the MR, and this is repeated four times in one MR cycle. The bunch configuration of the RCS needs to be arranged as shown in Table 4 to realize the necessary MR bunch configurations.

Fig. 15. An example of COMET beam acceleration bunch configuration. This figure shows the case for 3 buckets filled out of 9 acceleration buckets.

Fig. 16. An example of COMET beam acceleration bunch configuration. This figure shows the case for 4 buckets filled out of 9 acceleration buckets.
Table 4. RCS bunch configuration for COMET acceleration.

| Injection | Three buckets filled | Four buckets filled |
|-----------|----------------------|---------------------|
|           | Bucket A | Bucket B | Bucket A | Bucket B |
| 1st       | filled   | empty    | filled   | empty    |
| 2nd       | empty    | filled   | filled   | empty    |
| 3rd       | empty    | empty    | filled   | empty    |
| 4th       | filled   | empty    | filled   | empty    |

Fig. 17. Excitation timing of the kicker magnets after the injected beam bunches make a single turn in the MR (double injection kicking).

6.3. Proton extinction factor

The beam-related background events come within a few hundred ns after the proton pulse since these are mostly prompt processes. This timing information is very important for distinguishing signal events from background events. It is also very important to reduce the number of residual protons between pulses as these produce beam-related background in the signal timing window. The relative number of residual protons between pulses needs to be $10^9$ times smaller than the number of protons in the main pulse. This ratio is called the “proton extinction factor”.

A series of kicker magnets in the RCS kicks the beam bunches in the RCS ring towards the beam transfer line to the J-PARC MR. Another series of kicker magnets in the MR accepts them on the MR accelerator orbit. For the COMET beam, these kicker magnets can be excited in different ways from the normal operation in order to remove the remaining protons in empty buckets to improve the proton extinction factor. There are currently two kinds of injection methods being considered. One is called “double injection kicking mode” and the other “single bunch kicking mode”. The sources for the remaining protons between the proton pulse are considered to come from an inefficiency in the linac chopper.

Double injection kicking mode can be conducted as follows. In normal operation mode, the kicker magnets in the MR are excited only once to get the beam bunches from the RCS. However, in the double injection kicking mode, the kicker magnets in the MR are excited twice after one beam turn with its phase shifted by half a cycle so that the remaining protons in empty buckets are swept away as shown in Fig. 17. A preliminary test of this new injection scheme was conducted in 2010 and has proved to improve the proton extinction significantly.

Single bunch kicking mode can be realized by shifting the excitation timing of the injection-kicker magnets in the MR by 600 ns with respect to that of the extraction-kicker magnets in the RCS, as illustrated in Fig. 18. In this method, protons remaining in empty buckets can never be injected or
accelerated. A preliminary test of this method was performed in 2012; it has also proved to improve the proton extinction factor significantly. It was measured to be in the order of $O(10^{-11})$.

Moreover, it was found that the extinction does not deteriorate while the beam is circulating along the J-PARC MR after acceleration until it is extracted, if we keep the RF voltage for acceleration above a certain level. We need further investigation to optimize the operating condition of the acceleration RF, taking into account the heat load of the RF modules and possible particle leakage during beam circulation.

7. Muon beam for COMET

7.1. Proton target

Experiments on the search for $\mu^- - e^-$ conversion would use low-energy muons that can be stopped in a target. Therefore, capture of low-energy pions is of interest. At the same time, high-energy pions, which could potentially cause background events, should be eliminated. For these reasons, it has been decided to collect pions emitted backward with respect to the proton beam direction. To study pion capture, a simulation was performed using both MARS [71] and GEANT4 [72] with FLUKA [73].

Figure 19 shows the momentum spectra of $\pi^-$ produced from a graphite target. It can be seen that the maximum of transverse momentum ($p_T$) is around 100 MeV/c for a longitudinal momentum ($p_L$) of $0 < p_L < 200$ MeV/c for both forward- and backward-scattered pions. The maximum of the total momentum for backward-scattered pions is about 120 MeV/c, whereas that for forward-scattered pions is about 200–400 MeV/c. It can also be seen that high-energy pions are suppressed in the backward direction.

7.2. Pion capture

To collect as many pions of low energy as possible, the pions are captured using a high solenoidal magnetic field. In this case, pions emitted into a half hemisphere can be captured within the transverse momentum threshold ($p_T^{\text{max}}$). $p_T^{\text{max}}$ is given by the magnetic field strength ($B$) and the radius of the inner bore of the solenoid magnet ($R$) as

$$p_T^{\text{max}}(\text{GeV}/c) = 0.3 \times B(\text{T}) \times R(\text{m})/2.$$  \hspace{1cm} (16)

In the current design, we employ conservative design values, namely $B = 5$ T, $R = 15$ cm, and a length of 1.4 m.

Figure 20 shows a schematic view of the pion capture system and the superconductors used in the solenoid magnets in the pion capture system. It consists of a proton target, a surrounding radiation
Fig. 19. Pion production in a graphite target. (Top) Correlation between $p_L$ and $p_T$. (Middle) Total momentum distributions for forward and backward $\pi^-$'s. (Bottom) $p_T$ distributions for $0 < p_L < 0.2$ GeV/c, $0.2 < p_L < 0.4$ GeV/c, and $0.4 < p_L < 0.6$ GeV/c.

Fig. 20. (Top) Cross section of the superconducting coil for the capture solenoid. (Bottom) Schematic layout of the capture solenoid system. Shaded areas represent radiation shields made of tungsten. Gray regions represent superconducting coils. A proton beam is injected from the lower-left region of the figure, and captured pions are transported towards the left. Dimensions are in mm.

shield, a superconducting solenoid magnet for pion capture with a 5 T magnetic field, and a matching section connected to the transport solenoid system with a 3 T field. The 30-cm-thick radiation shield, which is necessary to achieve a heat load below 100 W for the superconducting magnets, is inserted between the pion production target and the superconducting coils. The inner bore of the shield is
tapered to keep it away from beam protons and high-energy pions, which are scattered forward. To collect backward-scattered pions, the proton beam should be injected through the barrel of the solenoid, and should be tilted with respect to the solenoid axis by about 10°.

7.3. **Muon transport system**

Pions and muons are transported to a muon-stopping target through the muon beam line, which consists of curved and straight solenoids. The key requirement for the muon beam line is that it should be possible to select the electric charge and the momentum of beam particles. In addition, it is required to provide high-efficiency transportation of muons with the momentum of interest, about 40 MeV/c. At the same time, it is necessary to eliminate energetic muons with a momentum larger than 77 MeV/c, since their decays in flight would produce spurious signals of ∼105 MeV electrons.

Tracking simulation studies were performed using a single-particle tracking code based on GEANT4. The magnetic field of the solenoids can be computed using a realistic configuration of coils and their current settings.

The selection of the electric charge and momentum of beam particles can be performed by using curved solenoids. It is known that, in curved solenoids, the center of the helical trajectory of a charged particle is shifted, and the drift ($D_{[m]}$) is given by

$$ D = \frac{q}{0.3 \times B} \times \frac{s}{R} \times \frac{p_L^2 + \frac{1}{2} p_T^2}{p_L}, $$

(17)

where $q$ is the electric charge of the particle (with its sign), $B$ (T) is the magnetic field at the axis, and $s$ (m) and $R$ (m) are the path length and the radius of curvature of the curved solenoid, respectively.

There are two ways of compensating for the drift of the particles with the momentum of interest; one way is to install an additional curved solenoid bent in the opposite direction, and the second way is to apply a transverse magnetic field (with respect to the solenoid axis) of

$$ B_{\text{comp}} = \frac{1}{q R} \frac{p_0}{2} \left( \cos \theta_0 + \frac{1}{\cos \theta_0} \right), $$

(18)

where the trajectories of charged particles with momentum $p_0$ and pitch angle $\theta_0$ are corrected to be on-axis.

The present design of the COMET muon beam line in Fig. 12 utilizes two curved solenoids with a bending angle of 90° in the same bend direction, with the compensation magnetic fields of $B_{\text{comp}}$, whereas the Mu2e experiments in Fig. 11 use the second 90° curved solenoid in the opposite bend direction. As a result, the net bending angle of 180° for COMET would provide better momentum separation than the 90° bending angle for Mu2e.

The solenoids in the COMET muon beam line would have a magnetic field of 3 T and a radius of curvature of 3 m. Compensation magnetic fields of $B_{\text{comp}} = 0.03$ T for the first 90° bend and $B_{\text{comp}} = 0.05$ T for the second 90° bend are applied. A muon yield coming to the muon-stopping target region of about 0.0035 $\mu$/proton is obtained.

8. **The detector system for COMET**

The sole role of the detector system is to identify genuine $\mu^- \rightarrow e^-$ conversion events from a huge number of background events. A schematic layout of the COMET detector system is shown in Fig. 21.

The signature of a $\mu^- \rightarrow e^-$ conversion event is a mono-energetic (∼105 MeV) electron emitted from a muon stopped in the target. In contrast, background events have various origins. They can
be rejected using various combinations of different methods associated with the muon beam line and the detector. The parameters that can be measured from the signals are momentum, energy, and timing only. Therefore, to enable signal events to be distinguished from those of background events, the events should be measured as precisely as possible. The background event rejection will be explained in detail in Sects. 9.2 and 12.

The detector system being considered in Fig. 21 is quite different from that planned in the Mu2e experiment. The detector system consists of three sections. The first is a section where a muon-stopping target is placed in a graded magnetic field to increase the solid angle. The second is a section in which transport of electrons of interest (∼105 MeV/c) through curved solenoids with compensation magnetic fields is performed, and electrons and other particles of low energy (<80 MeV/c) are eliminated to reduce the occurrence of background events as well as the counting rate of the detector. The third is a section where the momenta and energies of surviving electrons are measured in a uniform solenoidal magnetic field.

8.1. Muon-stopping target

In the COMET experiment, to eliminate background events arising from both prompt and late-arriving beam particles, a detection window opens about 700 ns after the prompt. Therefore, it is not suitable to use heavy materials for which the lifetime of muonic atoms is short. It was decided to use aluminum for the muon-stopping target. The lifetime of negative muons in a muonic atom of aluminum is 865 ns [74]. It should be noted that the branching ratio for aluminum (Z = 13) is smaller than that for titanium (Z = 22) by only a factor of 1.7 for the case of dipole interaction responsible for $\mu^- - e^-$ conversion. In the preliminary target configuration, the target is composed of 17 aluminum disks, each being 100 mm in radius and 200 μm in thickness, which are arranged with a disk spacing of 50 mm. A graded magnetic field is applied at the target location. The graded magnetic field would reflect electrons emitting backward toward the forward direction due to mirroring effects, and at the same time make the directions in which electrons are emitted more parallel to the axis, by reducing their polar angles. Figure 22 shows the baseline configuration of a graded magnetic field in the stopping target region. Monte Carlo simulations were carried out to study the stopping efficiency of muons for this configuration. Figure 23 shows the momentum distributions of the muons approaching the target (open histogram) and those stopped by the target disks (histogram in green). A muon-stopping efficiency of 0.66 was obtained. Downstream of the muon-stopping target, a beam blocker 30 cm in diameter is placed to stop beam particles passing through the muon-stopping target.

![Fig. 21. Layout of the COMET detector system. It consists of muon-stopping target, curved electron transport, and electron detection sections.](image-url)
Fig. 22. Distribution of a graded magnetic field over the target region.

Fig. 23. Momentum distributions of muons approaching the target (open histogram) and those stopped by the muon-stopping target (in green).

8.2. Electron transport through curved solenoids

As in the COMET muon beam line, the electron transport section uses curved solenoids to remove protons from muon nuclear capture and electrons of low momentum (<80 MeV/c), which would otherwise dominate the detector counting rate and produce enormously high hit rates. The transmission efficiencies for signal electrons and DIO electrons are estimated by GEANT4. Curved solenoids with a bend angle of 180°, a magnetic field of 1 T, and a magnetic field gradient from 3 T to 1 T at the muon-stopping target region are considered. These would give a geometrical acceptance of signal events at the target region of about 0.73 and a transmission efficiency of signal events through curved solenoids of about 0.47, resulting in a net acceptance of signals of μ⁻ → e⁻ conversion of about 0.32. This configuration would also give survival rates for DIO electrons of 10⁻⁷ – 10⁻⁸, resulting in a detector hit rate of the order of 1 kHz for 10¹¹ stopped muons per second.

8.3. Detection of electrons

The main purpose of the electron detector is to distinguish electrons from other particles and to measure their energies, momenta, and timings. The electron detector consists of an electron tracking detector with straw-tube gas chambers for measuring momenta of electrons, an electromagnetic calorimeter for measuring their energies, and fast trigger counters. The detector is placed under a uniform solenoidal magnetic field for momentum tracking. Furthermore, to reduce multiple scattering
in momentum measurements, the entire system is placed under vacuum. A candidate layout of the electron detector is shown in Fig. 24.

The required momentum resolution is less than 350 keV/c for an SES of $3 \times 10^{-17}$. The electron tracking detector consists of five stations of straw-tube gas chambers, where each station is composed of two views ($x$ and $y$), and one view has two staggered layers of straw-tubes. Each of the straw-tubes is 5 mm in diameter and 25 $\mu$m in thickness. From a GEANT4 Monte Carlo simulation with 250 $\mu$m position resolution, a momentum resolution of 350 keV/c is obtained. The DIO background events in the signal region are estimated by using tracking with track quality cuts, which requires the probability of good tracks being more than 5%. The DIO background of 0.15 events at an SES of $3 \times 10^{-13}$ is estimated, and it is smaller than one event.

The electron calorimeter, which is located downstream from the tracking detector, would serve three purposes. One is to measure the energy of electrons. High energy resolution is required. The second is to provide a timing signal for the electron events, and at the same time give a trigger signal that could be used to select events to be recorded for further analysis. On this regard, fast response and high efficiency are needed. The third is to provide additional data on hit positions of the electron tracks at the calorimeter location. This would be useful in eliminating false tracking. Candidate inorganic crystals, such as cerium-doped Gd$_2$SiO$_5$ (GSO) crystals or LYSO crystals, have been considered.

Cosmic-ray-induced electrons (or other particles misidentified as electrons) may cause background events. Therefore, passive and active shielding against cosmic rays covering the entirety of the detector is considered.

### 8.4. Detector acceptance

The acceptance is determined by the geometrical acceptance, which has been discussed before, and the efficiencies of the analysis requirements. They are discussed in the following.

- **Total momentum requirement:**
  
  To determine the energy region for the $\mu^- - e^-$ conversion signals, they were generated in simulation studies inside the muon-stopping target and reconstructed using a tracking program. Figure 25 shows the distribution of the reconstructed momentum (without correction for energy loss in the target), where the lower-momentum tail comes from energy loss of electrons in the muon-stopping target and an intrinsic momentum resolution of about 350 keV/c is seen in the high-momentum side of the signal peak. The signal region is determined to be 103.5 MeV/c
Fig. 25. Reconstructed momentum distribution of 105 MeV electrons (green line). This is not corrected for average energy loss of electrons (of about 0.4 MeV/c). The energy region for the signal is set to 103.5 MeV/c to 105.2 MeV/c for an uncorrected energy scale. The DIO background is shown by the red line.

Fig. 26. Timing window of detection.

to 105.2 MeV/c, which corresponds to about a two-sigma width of momentum spread. In this signal region, about 0.72 of the total signal events is contained.

• Transverse momentum requirement:
To eliminate background events, such as those from beam electrons and muon decay in flight, a requirement on the transverse momentum (which is a momentum component transverse to the beam axis) of electrons greater than 52 MeV/c \( (p_T > 52 \text{ MeV/c}) \) at the detector position is placed.

• Timing requirement:
Measurement starts about 700 ns after the prompt to avoid beam-related prompt background events. A schematic timing chart is shown in Fig. 26. The acceptance in the detection window is about 0.39 for aluminum.

Table 5 summarizes the acceptances. The total signal acceptance for the spectrometer and the detector is 0.031.

9. Signal sensitivity and background estimation

9.1. Signal sensitivity
We estimate the signal sensitivity of our search for \( \mu^- \rightarrow e^- \) conversion. The SES is defined by the number of muons stopping in the muon target \( (N_{\mu \text{stop}}) \), the fraction of captured muons \( (f_{\text{cap}}) \), and the
Table 5. Summary of signal acceptance.

| Acceptance                              | 0.73 |
|-----------------------------------------|------|
| Geometrical solid angle with mirroring  |      |
| Acceptance loss due to beam blocker     | 0.57 |
| Curved solenoid acceptance              | 0.47 |
| Track reconstruction efficiency         | 0.88 |
| Track quality cut efficiency            | 0.89 |
| Transverse momentum cut efficiency      | 0.83 |
| $E/\rho$ cut efficiency                 | 0.99 |
| Helix pitch cut efficiency              | 0.99 |
| Momentum selection efficiency           | 0.72 |
| Timing window selection efficiency      | 0.39 |
| Trigger acceptance                      | 0.9  |
| Total                                   | 0.031|

Table 6. Total number of muons delivered to the muon-stopping target.

| Proton intensity (\$/s) | $4.4 \times 10^{13}$ |
|------------------------|-----------------------|
| Running time (s)        | $2 \times 10^7$       |
| Muons per proton transported to the target | 0.0035 |
| Muon stopping efficiency| 0.66                  |
| Total stopped muons    | $2 \times 10^{18}$    |

detector acceptance ($A_e$), as follows:

$$B(\mu^- + Al \rightarrow e^- + Al) = \frac{1}{N_{\mu}^{\text{stop}} \cdot f_{\text{cap}} \cdot A_e}. \quad (19)$$

The total number of muons that are stopped in the muon-stopping target ($N_{\mu}^{\text{stop}}$) of about $2 \times 10^{18}$ for $2 \times 10^7$ sec is estimated as shown in Table 6. For aluminum, the fraction of muons captured is about $f_{\text{cap}} = 0.6$. The total acceptance for the signal is 0.031 as shown in Table 5.

By using $N_{\mu}^{\text{stop}}$, $f_{\text{cap}}$, and $A_e$, the single-event sensitivity is obtained by

$$B(\mu^- + Al \rightarrow e^- + Al) = \frac{1}{2 \times 10^{18} \times 0.6 \times 0.031} = 2.6 \times 10^{-17}. \quad (20)$$

Since a 90% confidence level (C.L.) upper limit is given by $2.3/(N_{\mu} \cdot f_{\text{cap}} \cdot A_e)$, the upper limit is obtained as

$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% \text{ C.L.}), \quad (21)$$

which is about 10,000 times better than the current published limit of $<4.3 \times 10^{-12}$ (90% C.L.) obtained by SINDRUM II at PSI [62].

9.2. Background events and their rejection

Potential sources of background events for $\mu^- - e^-$ conversion are categorized into three different types. They are

1. Intrinsic physics background events:
   Intrinsic physics background events originate mostly from muons stopped in the muon-stopping target. They arise from muon decays in orbit, radiative muon capture, and particle emission (such as protons and neutrons) after muon capture.
Table 7. Summary of background event rates at an SES of $3 \times 10^{-17}$. Background events marked with an asterisk are proportional to the beam extinction, and the rates in the table assume $10^{-9}$ beam extinction.

| Background                          | Events   |
|-------------------------------------|----------|
| Radiative pion capture*            | 0.05     |
| Beam electrons*                    | <0.1     |
| Muon decay in flight*              | <0.0002  |
| Pion decay in flight*              | <0.0001  |
| Neutron-induced                    | 0.024    |
| Delayed pion radiative capture     | 0.002    |
| Antiproton-induced                 | 0.007    |
| Muon decay in orbit (DIO)          | 0.15     |
| Radiative muon capture             | <0.001   |
| $\mu^-$ capture with neutron emission | <0.001   |
| $\mu^-$ capture with charged particle emission | <0.001 |
| Cosmic ray muons                   | 0.002    |
| Electron cosmic ray muons          | 0.002    |
| Total                               | 0.34     |

(2) Beam-related background events:
This type of background event is caused by particles in a beam, such as electrons, pions, muons, and antiprotons. There are two different types; one is a prompt background event and the other is a late-arriving background event. For the former, beam pulsing with high beam extinction is a very effective way of rejecting the background events, and the proton extinction factor is required to be good.

(3) Cosmic-ray background events:
This type of background event is caused by cosmic-ray muons that interact with the beam line and the detector to produce $\sim$100 MeV electrons.

The expected background rates at an SES of $3 \times 10^{-17}$ are summarized in Table 7.

10. Overview of COMET Phase-I

In this section, we would like to describe the staged approach of the COMET experiment, in particular, COMET Phase-I [4].

10.1. Staged approach and the J-PARC mid-term plan

The proposed J-PARC 5-year mid-term plan from 2013 includes the construction of the COMET beam line. This will provide the proton beam line for COMET and part of the muon beam line in the south area of the J-PARC NP hall. We, the COMET Collaboration, consider a staged approach for COMET to carry out the measurements in a timely manner. To realize this staged approach, it is planned to construct the COMET muon beam line up to the end of the first $90^\circ$ bend so that a muon beam can be extracted to the experimental area. This stage is called “COMET Phase-I”. Figure 27 shows the part of the muon beam line that will be constructed in COMET Phase-I.

COMET Phase-I has two major goals. One is direct measurement of the proton beam extinction factor and other potential background sources for the full-sized COMET experiment (COMET Phase-II), and the second is a search for $\mu^- \rightarrow e^-$ conversion with an intermediate SES of better than the current limit.
Direct background measurements at COMET Phase-I

The direct measurement of potential background sources will be vital for COMET Phase-II. The current background estimates are made by extrapolating existing measurements over four orders of magnitude, and uncertainties are therefore difficult to quantify and are potentially large. However, once the partial muon beam line is completed, it will become possible to make realistic background estimations from direct measurements. Potential backgrounds that can be measured are pions, neutrons, antiprotons, gammas, and electrons in the beam, the electron spectrum of muon DIO, and so on. To carry out these direct measurements, a dedicated detector with charged particle tracking and an electromagnetic calorimeter will be prepared. Based on these, the final design of the COMET beam line and detectors will be optimized and uncertainties on the background estimations minimized. This will significantly enhance the ultimate sensitivity of COMET Phase-II.

Search for $\mu^- - e^-$ conversion at COMET Phase-I

A search for $\mu^- - e^-$ conversion with an SES beyond that achieved to date can be performed. To carry out a search for $\mu^- - e^-$ conversion, two types of detector systems are being considered. One is a reuse of the detector for the background measurements, and the other is a detector dedicated to searching for $\mu^- - e^-$ conversion, based on a cylindrical drift chamber (CDC).

The dedicated detector is based on a cylindrical drift chamber (CDC) that surrounds a muon-stopping target. The anticipated SES is a factor of about 100 or more better than the current limit by SINDRUM-II, namely an SES of $3.1 \times 10^{-15}$ or better.

In addition to the $\mu^- - e^-$ conversion search, the special features of the COMET Phase-I detector allow for further possibilities:

- This detector can detect both positive and negative particles, whereas the full-sized COMET detector can detect only negatively charged particles owing to the electron transport system that uses curved solenoids. This allows for a search for the lepton-number-violating process $\mu^- + N \rightarrow e^+ + N'$ ($\mu^- - e^+$ conversion) concurrently with the $\mu^- - e^-$ conversion search. The anticipated experimental sensitivity for $\mu^- - e^+$ conversion could be similar to $\mu^- - e^-$ conversion.

- This detector can have a large geometrical coverage, and thereby a coincidence measurement with a large solid angle is achievable. Also, the J-PARC MR can provide a DC proton beam with a duty factor of about 0.2. These facts indicate that a search for $\mu^- + e^- \rightarrow e^- + e^-$ conversion in a muonic atom is possible [75]. This is a previously-unmeasured process. With a beam of less than $10^7$ muons/s in intensity, a measurement of $\mu^- + e^- \rightarrow e^- + e^-$ can be carried out.

In the following, some details for COMET Phase-I will be described.
10.2. Proton beam for COMET Phase-I

The required proton beam power is about $8 \text{ GeV} \times 0.4 \mu\text{A} \sim 3.2\text{ kW}$ ($\sim 2.5 \times 10^{12}$ 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. We start at lower intensities, which are also suitable for performing the accelerator studies that are needed to realize 8 GeV beam extraction from the J-PARC MR.

10.3. Muon beam for COMET Phase-I

The muon beam line of COMET Phase-I will include the pion capture system section and the muon transport section up to the end of the first $90^\circ$ bend of the COMET experiment. The design of the muon beam line of COMET Phase-I is identical to that of COMET Phase-II. At the end of the muon beam line, a beam collimator is placed to reduce beam backgrounds. Figure 27 shows the schematic layout of the muon beam line and the detector for COMET Phase-I.

10.4. Detector for background measurements

The setup is composed of a solenoid magnet with 0.85–1 T field strength, 5 tracker layers, and crystal calorimeters. Detectors are located in a vacuum vessel functioning as a cryostat for the spectrometer magnet. The same detector technology as the COMET Phase-II detector will be employed. The tracker will be constructed using straw gas chambers being developed for the COMET Phase-II tracker. The crystal calorimeter will be composed of GSO or LYSO crystals. This setup will be regarded as a final prototype of the COMET Phase-II detector.

The detector is required to provide sufficient information to identify particles in the beam and measure their momenta. When charge selection is not performed in the Phase-I beam transport setup, all kinds of particles are contained in the beam: $p$, $\bar{p}$, $e^\pm$, $\mu^\pm$, and $\pi^\pm$, $K^\pm$. These particles are identified mainly using $dE/dx$ information in the tracker and the ratio of energy and momentum ($E/p$). The momentum measurement is carried out by reconstructing the tracks using the tracker hits. Shower shape information in the calorimeter will be utilized for $\bar{p}$ identification. The possibility of measuring the direction of photons contained in the beam is under consideration. We expect that this can be carried out by inserting a converter between the tracker layers. The configuration will be optimized with Monte Carlo simulation.

We need to reduce the primary proton intensity far below 1 kW to ensure safe detector operation. In addition, a continuous proton beam in the normal slow beam extraction mode from the J-PARC MR will be used. This will help to reduce the detector occupancy rate, realizing reliable and stable measurements.

10.5. Detectors to search for $\mu^- - e^- \text{ conversion}$

The search for $\mu^- - e^- \text{ conversion}$ with a sensitivity beyond the current limits can be made. The pion contamination per proton in the muon beam at COMET Phase-I will be high due to the shorter muon beam line than that of Phase-II. However, since the muon intensity per proton will be almost the same as that of Phase-II and the muon beam intensity could be the highest in the world, we will be able to probe beyond the current limit and set the world’s best limit should no signal be observed. As mentioned in Sect. 10.1, two types of detector configurations are considered for the $\mu^- - e^- \text{ conversion}$ search in COMET Phase-I. Both of them can concurrently run at the same time. In the following, the CDC detector dedicated to $\mu^- - e^- \text{ conversion}$ will be mentioned.
10.5.1. Overview of cylindrical drift chamber. The baseline detector to search for $\mu^− − e^−$ conversion is a CDC. Figure 28 shows a schematic view of the detector setup, where the CDC surrounds the muon-stopping target located at its center. The CDC is placed inside a superconducting solenoid magnet that produces a magnetic field of 1–1.5 T. The reason for the use of a CDC is as follows. In COMET Phase-I, the curved electron transport system (included in COMET Phase-II) will not be available and it was therefore decided that the CDC geometry, where the detector is placed at 90° to the beam axis, would be used, to avoid direct hits of beam particles on the detectors.

The cylindrical detector has several features as follows:

- Most beam particles that do not stop in the muon-stopping target continue going downstream and escape the detector. The background rate is therefore reduced, as well as the hit rate in the detector that is to be read out.
- To reduce background events and detector rates, such as from DIO electrons and protons emitted from nuclear muon capture, the momentum selection of charged particles should be made. This can be easily done by adjusting the radial size of the CDC and a solenoidal magnetic field. In the current design, the momentum threshold is set to be about 70 MeV/$c$.

Segmented trigger hodoscope counters are placed at both the upstream and downstream ends of the CDC. Using Cherenkov detectors for these trigger counters will allow positive electron identification. The solenoid magnet has an iron yoke that acts as passive shielding for cosmic rays. In addition, an active cosmic-ray shield is installed outside the detector. To monitor the number of negative muons stopped in the muon-stopping target, a detector to measure muonic X-rays from muonic atoms of aluminum is employed. Muonic X-rays are useful for counting the number of muons stopped, since they are emitted when a negative muon is captured by an atom in its excited states and then goes down to the ground state.

10.5.2. CDC structure. The role of the CDC is to reconstruct charged particle tracks and measure their momenta precisely. The main parameters for the CDC are listed in Tables 8 and 9. The drift chamber covers the region from 540 mm to 840 mm in the radial direction. The length of the drift chamber is 1500 mm. It has 5 super-layers. The 1st, 3rd, and 5th super-layers are in the axial direction, and the 2nd and 4th super-layers are stereo layers with a stereo angle of about 60 mrad (or 3.5°).
A sense wire is surrounded by field wires, forming a drift cell of 1 cm$^2$. The drift chamber gas is He:C$_2$H$_6$ = 50:50. The inner wall of the drift chamber is CFRP of 400 $\mu$m in thickness.

We have a super-layer wire configuration. Having 5 layers in each super-layer allows track segments to be formed reliably. An additional 2 layers are located in the innermost and outermost super-layers. These have active guard wires, since high hit rates are expected because of proton backgrounds and the wall effect. Even if the first two layers cannot provide good performance, the other five layers will provide sufficient performance to allow track segments to be formed as in the other super-layers. Super-layers alternate between axial and stereo configurations. The total number of layers is thus 29.

We have semi-square cells and the radial cell size is 10 mm. The number of cells in each layer is chosen considering the following: multiples of 32 simplify the mapping of electronics channels and trigger segments. Better azimuthal granularity would guard against large rates from background hits, but the size of the cells is constrained by the physical dimensions of the feedthroughs. A larger stereo angle provides for better resolution in $z$, but larger variations of the radial cell size along the $z$-direction occur at the boundary region between the axial and stereo super-layers, and therefore a stereo angle of about 60 mrad is chosen. It should be noted that the stereo angles in each layer are slightly different, given the cell structure.

The numbers of sense and field wires are 9684 and 28 352, respectively. These numbers are not too large compared to large cylindrical drift chambers that have been constructed recently (e.g. 14 336 sense wires for the BELL-II CDC).

### Table 8. Parameters for COMET Phase-I central drift chamber.

| Parameter                        | Value     |
|----------------------------------|-----------|
| Radius of inner cylinder         | 540 mm    |
| Radius of outer cylinder         | 840 mm    |
| Radius of innermost sense wire   | 550 mm    |
| Radius of outermost sense wire   | 830 mm    |
| # of layers                      | 25        |
| Gas                              | He:C$_2$H$_6$ = (50:50) |
| Length                           | 1500 mm   |

### Table 9. Material and thickness of the CDC wires.

| Sense wire | Field wire |
|------------|------------|
| Material   | Plating    | Diameter ($\mu$m) | Tension (g) | Number of wires |
| tungsten   | gold       | 30                | 50          | 9684           |
| aluminum   | no         | 126               | 80          | 28 352         |

10.5.3. **CDC hit rates.** The maximum usable muon beam intensity will be limited by the detector hit occupancy. As described before, charged particles with transverse momentum ($P_T$) greater than 70 MeV/c are expected to reach the CDC. There are several sources of such charged particles: (1) electrons from muon decays in orbit (DIO), (2) electrons and positrons from high-energy photon conversion, and (3) protons emitted after nuclear muon capture, namely $\mu^- + N \rightarrow N' + p + \nu_\mu$.

The hit rate due to proton emission dominates. Although there are no experimental data available for the rate of protons emitted after muon capture in aluminum, we can estimate using the measured energy spectrum of charged particles emitted from muon capture in $^{28}$Si [76]. In our estimation, it
is assumed that the proton emission probability per muon capture in aluminum is 0.15, as for the measurement for $^{28}$Si. It should be noted that the theoretical estimation is 0.04 proton emissions per muon capture in aluminum [77], and thus our assumption is conservative. Figure 29 shows the energy spectrum of protons emitted after nuclear muon capture on $^{28}$Si [76].

To estimate the detector hit rates by proton emission, the energy spectrum of protons emitted after muon capture is fitted to an empirical function as follows:

$$P(T) = A \left( 1 - \frac{T_{th}}{T} \right)^{\alpha} \exp \left( -\frac{T}{T_0} \right),$$

(22)

where $T$ is the kinetic energy with fitted parameters $T_{th} = 1.4$ MeV, $\alpha = 1.328$, and $T_0 = 3.1$ MeV, and $A$ is a normalization factor. In our Monte Carlo simulation, protons are generated isotropically based on Eq. (22). From the simulation, it is found that $3.9 \times 10^{-3}$ protons per muon capture reach the CDC.

If we assume that the number of muons stopped in the muon-stopping target is $5.8 \times 10^9$/s, the number of muon captures on aluminum is about $3.5 \times 10^9$/s, since the fraction of muon captures in aluminum is $f_{cap} = 0.61$. Therefore, the total number of hits in all the cells in the first layer is estimated to be $1.4 \times 10^9$/s ($= (3.9 \times 10^{-3}) \times (3.5 \times 10^9)$). The total number of cells in the first layer of the CDC is 332. Therefore, the hit rate per drift chamber wire will be about 40 kHz. This rate is well below the limit of the region of stable operation of a gaseous detector. Also, since the rate of proton emission follows the muon lifetime in a muonic atom, this single rate becomes lower in the time window of the measurement. In addition, the inner supporting frame also helps to reduce the number of protons reaching the CDC. Thus the detector operating condition will be safe enough for physics measurement at COMET Phase-I.

### 10.5.4. CDC trigger counters and trigger rates.

Segmented trigger counters, placed at both the upstream and downstream ends of the CDC, are a layer of concentric segmented Cherenkov counters that are not sensitive to protons. The trigger rate is dominated by the DIO electrons that impinge on the trigger counter. Figure 30 shows the energy spectrum of DIO electrons from muonic aluminum with the fraction of DIO events hitting the trigger counters shown in green. The rate is about
Fig. 30. Energy spectrum of the DIO electrons hitting the trigger counters (shown in green) for aluminum.

Fig. 31. Calculated energy spectrum of electrons above 70 MeV from muon DIO from muonic aluminum.

1.2 × 10⁻⁷ per muon decay. Since the number of muons stopped in the stopping target is estimated to be 5.8 × 10⁹ muons/s, the trigger rate is estimated to be 270 Hz (=5.8 × 10⁹ × 0.39 × (1.2 × 10⁻⁷)).

10.5.5. CDC momentum resolution. The momentum resolution of the CDC is critical to allow the discrimination of μ⁻ → e⁻ conversion signal electrons from electrons originating from DIO. The end point of the DIO spectrum approaches the energy of the μ⁻ → e⁻ conversion signal, although it falls off quickly, being proportional to (ΔE)⁵, where ΔE = E_{μe} − E_{DIO} is the difference between the energy of the μ⁻N → e⁻N conversion electron (E_{μe}) and the energy of the DIO electron (E_{DIO}). For aluminum, E_{μe} is 104.9 MeV. The DIO electron energy spectrum has been calculated for muonic aluminum [56]. Figure 31 shows the DIO electron spectrum for muonic aluminum. The energy difference of ΔE = 1 MeV is seen at a DIO branching ratio of 10⁻¹⁶.
The tracking performance was studied by using a GEANT4 Monte Carlo simulation. In this simulation, electrons of 105 MeV/c leaving the stopping target were generated isotropically from 17 disks of aluminum of 200 μm thickness. The drift chamber wall is modeled correctly and a gas mixture of He:C₂H₆ = 50:50 is simulated in the chamber volume.

Hit information generated in the simulation is smeared by the expected position resolutions of the drift chamber, \( \Delta x = \Delta y = 100 \mu m \) and \( \Delta z = 2 \) mm. The hit positions thus obtained with smearing are used for track reconstruction.

The fitted momentum can be lower than the true momentum of 105 MeV/c, since electrons can lose energy in the muon-stopping target and the inner supporting frame. This energy loss reduces the peak of the momentum distribution and also produces a low-energy tail and broadens the core peak width owing to energy straggling.

11. Signal sensitivity for COMET Phase-I

In this section, the estimation of signal sensitivity and background events for the CDC system is described.

11.1. Signal acceptance for the COMET Phase-I CDC

The acceptance for \( \mu^- - e^- \) conversion signals is determined by several factors. They are

- geometrical acceptance including a solid angle of the CDC
- requirement of hits at the CDC trigger counters
- efficiency of track reconstruction with track quality cuts
- efficiency of momentum selection (a momentum window cut)
- efficiency of timing selection (a timing window cut)
- efficiency of event trigger and a DAQ live time.

The geometrical acceptance depends on the detector configuration, such as the sizes of the CDC and of the trigger counters, and a magnetic field. Figure 32 shows the distributions of transverse momenta \( (P_T) \) and longitudinal momenta \( (P_L) \) for the generated events (in black), reconstructed events (in blue), and those reconstructed events hitting the trigger counters (in magenta) of 105 MeV/c electrons, in forward and backward directions. From this, it is found that electron tracks with \( P_T \) of more than 80 MeV/c can be reconstructed. The geometrical acceptance of tracks of about 24%, with the requirements of the trigger counter hits, is obtained. It can be seen that the tracks with a large pitch (with large \( P_L \)) angle would miss the trigger counters.

A momentum cut can be used to reduce background events from DIO electrons. Figure 33 shows the reconstructed momentum spectrum of \( \mu^- - e^- \) conversion signal events that were generated using Monte Carlo simulations and the DIO electron spectrum. In Fig. 33, the vertical scale is normalized so that the integrated area of the signal event curve is one event, assuming a branching ratio of \( B(\mu N \rightarrow e N) = 3 \times 10^{-15} \). A detailed description of the estimation of contamination from DIO electrons is presented in Sect. 12.1. In this study, the momentum cut of 104.1 MeV/c \( < P_e < 106 \) MeV/c, where \( P_e \) is the electron momentum, is determined in such a way that contamination from DIO electrons of 0.01 events is expected for a single-event sensitivity of \( \mu^- - e^- \) conversion of \( 3 \times 10^{-15} \).

The efficiencies of the timing selection and the trigger and DAQ are assumed to be the same as those in the COMET Phase-II experiment, as shown in Table 5. From these, the net acceptance for the \( \mu^- - e^- \) conversion signal, \( A_e = 0.062 \), is obtained for the CDC in COMET Phase-I. The breakdown of the acceptance is shown in Table 10.
Fig. 32. Distributions of $P_T$ (top) and $P_L$ (bottom) for all generated events (in black), reconstructed events (in blue), and those reconstructed events hitting the trigger counters (in magenta) of 105 MeV/c electrons, in forward (right) and backward (left) directions.

Fig. 33. Distributions of reconstructed $\mu^-\rightarrow e^-$ conversion signals (in red) and reconstructed DIO events (in black). The vertical scale is normalized so that the integrated area of the signal is equal to one event with its branching ratio of $B(\mu N \rightarrow eN) = 3 \times 10^{-15}$. A momentum cut of $104.1 \text{ MeV}/c < P_e < 106 \text{ MeV}/c$, where $P_e$ is the electron momentum, is applied.
The SES for $\mu^- - e^-$ conversion is given by Eq. (19). For COMET Phase-I, $N^{\text{stop}}_\mu$, which is the number of muons stopped in the muon-stopping target, can be estimated as follows. A proton current of 0.4 $\mu$A corresponds to $2.5 \times 10^{12}$ protons/s. With a running period of $1.5 \times 10^6$ s (about 18 days), the total number of protons on target is about $3.8 \times 10^{18}$. The number of muons stopped at the muon-stopping target is estimated to be 0.0023 per proton from the COMET_G4 simulation program. From these, a total number of muons stopped of $N^{\text{stop}}_\mu = 8.7 \times 10^{15}$ ($=0.0023 \times 3.8 \times 10^{18}$) is obtained. This corresponds to $5.8 \times 10^9$ muons stopped/s. It should be noted again that the signal acceptance for the CDC in COMET Phase-I is $A_e = 0.062$, and the fraction of muon capture for aluminum is $f_{\text{cap}} = 0.61$.

By using the numbers thus obtained, from Eq. (19), the single-event sensitivity is given by

$$B(\mu^- + \text{Al} \rightarrow e^- + \text{Al}) = \frac{1}{8.7 \times 10^{15} \times 0.062 \times 0.61} = 3.1 \times 10^{-15}. \quad (23)$$

The 90% confidence upper limit with zero background events is given by

$$B(\mu^- + \text{Al} \rightarrow e^- + \text{Al}) < 7.2 \times 10^{-15}. \quad (24)$$

12. Background estimation for COMET Phase-I

The background events for the COMET Phase-I CDC are evaluated. Some of the background estimations that are different from COMET Phase-II are selected and shown as follows.

12.1. Muon decays in orbit (DIO)

The predicted momentum spectrum of DIO electrons for aluminum[56] is shown in Fig. 31. Based on the spectrum, DIO electrons are generated in a Monte Carlo simulation and their tracks are reconstructed with a tracking program. Figure 33 shows the reconstructed momentum spectrum of DIO electrons, together with the $\mu^- - e^-$ conversion signals.

These momentum distributions are integrated above a momentum threshold ($P_{\text{th}}$). Figure 34 shows the integrated fractions of the $\mu^- - e^-$ signal events and the DIO events as a function of $P_{\text{th}}$. Then, $P_{\text{th}}$ for the signal region is determined in such a way that the fraction of DIO electrons in the signal region is 0.01 events. From this, the momentum signal region of $104.1 \text{ MeV}/c < P_e < 106 \text{ MeV}/c$ is determined.

12.2. Beam-related prompt backgrounds

The beam-related prompt backgrounds arise from protons between the beam pulses. These backgrounds are suppressed by the proton beam extinction factor. The proton beam extinction factor, $R_{\text{extinction}}$ of $3 \times 10^{-11}$, which is based on our recent experimental measurements at the J-PARC MR, is used in the following background estimation.

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**Table 10.** Breakdown of the $\mu^- - e^-$ conversion signal acceptance per stopped muon.

| Event selection       | Value    | Comments                        |
|-----------------------|----------|---------------------------------|
| Geometrical acceptance| 0.24     | tracking efficiency included    |
| Momentum selection    | 0.74     | $104.1 \text{ MeV}/c < P_e < 106 \text{ MeV}/c$ |
| Timing selection      | 0.39     | same as COMET                   |
| Trigger and DAQ       | 0.9      | same as COMET                   |
| Total                 | 0.062    |                                 |
Fig. 34. Integrated event fractions for $\mu^- - e^-$ conversion events (in red) and DIO electron events (in blue) as a function of the lower momentum threshold of the signal region. It is normalized to one $\mu^- - e^-$ conversion event at $\text{SES} = 3 \times 10^{-15}$.

Table 11. Experimentally measured branching ratios of radiative pion capture in the unit of %. The numbers in this table were compiled from Table 4 in Ref. [78].

| Element | BR (Z) |
|---------|--------|
| $^{12}$C | $1.84 \pm 0.08, 1.92 \pm 0.91, 1.6 \pm 0.1$ |
| $^{16}$O | $2.27 \pm 0.24, 2.24 \pm 0.48$ |
| $^{40}$Ca | $1.82 \pm 0.05$ |

12.2.1. Radiative pion capture. The radiative pion capture (RPC) background is caused by pions contaminated in the muon beam. These pions are stopped in the muon-stopping target, and are captured by an aluminum nucleus immediately to form an excited state of the daughter nucleus.

There are two processes, one of which directly produces a $\gamma$ ray of high energy (direct process) and the other produces $\gamma$ rays as a de-excitation process of the excited daughter nucleus to their ground state. Some of these emitted $\gamma$ rays convert into an $e^- - e^+$ pair in the target or in material outside the target. When the $e^+ - e^-$ pair creation occurs in an asymmetric energy distribution and $e^-$ has high energy, it would mimic $\mu^- - e^-$ conversion signals. This is external conversion of a photon from RPC. Also, there is internal conversion of RPC, which contributes to almost the same rate.

The probability of $\gamma$ emission and the energy spectrum of $\gamma$s were extensively studied experimentally and theoretically more than 20 years ago. The probability of $\gamma$ emission has very small $Z$ dependence. It is almost 2% for C, O, and Ca, as shown in Table 11 [78]. The energy of $\gamma$ from RPC ranges from 50 MeV to 140 MeV, as shown in Fig. 35. The overall shapes of the spectra are very similar for C, O, and Ca. Therefore, we implemented the experimentally obtained spectrum for Ca in our Monte Carlo code for this study.

The number of RPC backgrounds is expressed as

$$N_{\text{RPC}} = N_{\text{proton}} \times R_{\text{extinction}} \times R_{\pi^- - \text{stop}/p} \times P_{\text{RPC}} \times P_{\gamma - e^-} \times A_{\text{geometry}} \times A_{\text{tracking}},$$  \hspace{1cm} (25)
Fig. 35. Momentum distribution of γs from RPC. This figure is reprinted from ‘Radiative pion capture in nuclei: a continuum shell-model approach’. Reprinted from Ref. [78], with permission from Elsevier. The histogram shows experimental data, and the lines are from some theoretical models.

where \( N_{\text{proton}} \) is the total number of protons on the pion production target, \( R_{\text{extinction}} \) is the proton beam extinction factor, \( R_{\pi^{-}\text{stop}}/p \) is the number of \( \pi^{-} \)s coming to the muon-stopping target per proton, \( P_{\text{RPC}} \) is the branching ratio of radiative muon capture, \( P_{\gamma^{-}\mu^{-}} \) is the probability of conversion of the RPC photon to an electron of 105 MeV/c, \( A_{\text{geometry}} \) is the detector acceptance of the RPC-originated electrons of 105 MeV/c, and \( A_{\text{tracking}} \) is the efficiency of tracking.

For COMET Phase-I, \( R_{\pi^{-}\text{stop}}/p = 6.9 \times 10^{-5} \) is obtained from the beam simulation. This can be compared with that in COMET Phase-II, \( R_{\pi^{-}\text{stop}}/p = 3.5 \times 10^{-7} \). The simulation was started from the RPC photons generated uniformly inside the muon-stopping target and isotropically emitted, based on the photon spectrum in Fig. 35. A total number of \( 10^7 \) RPC photon events were generated. Electrons and positions were created by pair production from the RPC photons, and electrons were also generated by Compton scattering. As a result, there are 336 electron events in the signal region. In the end, these would give \( P_{\gamma^{-}\mu^{-}} \times A_{\text{geometry}} \times A_{\text{tracking}} = 3.4 \times 10^{-5} \). With \( N_{\text{proton}} = 3.8 \times 10^{18} \) protons on target, a total of 0.0018 background events from the external conversion of radiative pion capture is obtained. The contribution of internal conversion is about the same as that of external conversion. Therefore, \( N_{\text{RPC}} = 0.0036 \) events is estimated with a proton beam extinction factor of \( 3 \times 10^{-11} \).

12.2.2. Beam electrons, and electrons from muon and pion decays in flight. Beam electron background is caused by electrons contaminating the muon beam. The electrons in the muon beam mostly originate from decays of \( \pi^0 \)s produced by proton bombardment. Electrons will scatter off the muon-stopping target and falsely appear as signal electrons if the electron momentum is in the signal region.

Similarly, decays of muons in flight during the muon transport system can produce energetic electrons that have sufficient total momentum. For the decay electrons to have \( p_{\text{total}} > 102 \) MeV/c, the muon momentum must exceed 77 MeV/c (\( p_{\mu} > 77 \) MeV/c). Furthermore, \( \pi \rightarrow e\nu \) decay of pions in flight is also a potential source of background. The \( \pi \) momentum must exceed 60 MeV/c to cause this background process. It is noted that the branching ratio of \( \pi \rightarrow e\nu \) is about \( 1.2 \times 10^{-4} \).

The number of this type of beam background events is given by

\[
N_{\text{e-scatt}} = N_{\text{proton}} \times R_{\text{extinction}} \times R_{\text{e-beam/}p} \times P_{\text{e-det}} \times P_{\text{e-signal}},
\]

(26)
where $R_{e\text{-beam}/p}$, $P_{e\text{-det}}$, and $P_{e\text{-signal}}$ are the number of $e^-$s coming to the muon-stopping target per proton, the probability of $e^-$ coming to the CDC, and the probability of $e^-$ appearing in the signal region, respectively. GEANT4 simulations were made to estimate energetic electrons in the muon beam, including the beam electrons and electrons from muon and pion decays in flight. After the beam collimator, the number of all electrons with momenta greater than 80 MeV/c is $R_{e\text{-beam}/p} = 1.7 \times 10^{-5}$ per proton. The electrons thus obtained were injected into the COMET Phase-I CDC simulation to examine the probability of them reaching the CDC. Out of 40 000 electrons, none of them reach the CDC, and thereby the upper limit of the product of the probabilities of $R_{e\text{-det}} \times P_{e\text{-signal}} < 2.5 \times 10^{-5}$ is obtained. Therefore, from Eq. (26), the estimated background is less than 0.00016.

12.2.3. Background induced by beam neutrons. Background events induced by neutrons in the muon beam line are estimated. These neutrons could pass through the curved muon beam line by continuously reflecting from the inner sides of the beam duct. By using GEANT4 Monte Carlo simulation, the average transit time of these neutrons arriving at the muon-stopping target is estimated to be about 300 ns, and less than the time of 700 ns before the measurement time window opens. Therefore, it is regarded as a prompt background.

From simulation work, it turns out that the most probable process producing a 100 MeV electron is $\pi^0$ production from energetic neutrons (more than 180 MeV in kinetic energy), followed by $\pi^0$ decays with photon conversion. The prompt neutron background rate $N_{\text{neutron}}$ can be estimated by

$$N_{\text{neutron}} = N_{\text{proton}} \times R_{\text{extinction}} \times R_{n/p} \times R_{\pi^0/n} \times R_{e/\pi^0},$$

where $R_{n/p}$, $R_{\pi^0/n}$, and $R_{e/\pi^0}$ are rates of neutrons of kinetic energy more than 180 MeV per proton, of $\pi^0$s per neutron, and of $e^-$s per $\pi^0$, respectively. In our simulation studies, neutrons were produced and transported through the COMET Phase-I beam line. $R_{n/p}$ of $10^{-5}$ neutrons per proton is obtained at the end of the first 90° bend. Then, by using GEANT4 simulation, $R_{\pi^0/n} = 7 \times 10^{-8}$ is obtained from neutron interaction at the muon-stopping target. By producing $10^6 \pi^0$s following the above kinetic distributions, about 16 electrons fall into the signal region. From this, a rate of $R_{e/\pi^0} = 1.6 \times 10^{-6}$ is obtained. These give about $N_{\text{neutron}} \sim 4 \times 10^{-10}$. The neutron-induced background through $\pi^0$ production can be seen as negligible.

12.3. Cosmic-ray-induced backgrounds

The background events induced by cosmic rays are proportional to the total running time. The running time of COMET Phase-I is short, at $1.5 \times 10^6$ sec, in comparison to that of the full-sized COMET of $2 \times 10^7$ sec. Therefore, the estimated background events are about a factor of 10 less than that of the full-sized COMET experiment of 0.002 in Table 7, namely 0.0002.

12.4. Summary of background estimations

Table 12 shows a summary of the estimated backgrounds. The total estimated background is about 0.03 events for a single-event sensitivity of $3 \times 10^{-15}$ with a proton extinction factor of $3 \times 10^{-11}$. If this small number of the background estimation is correct, we could run for a longer time to improve the SES further.
Table 12. Summary of estimated background events for a single-event sensitivity of $3 \times 10^{-15}$ with a proton extinction factor of $3 \times 10^{-11}$. The numbers with $\ast$ are directly proportional to the proton extinction factor.

| Background                                      | Estimated events |
|------------------------------------------------|------------------|
| Muon decay in orbit                            | 0.01             |
| Radiative muon capture                         | <0.001           |
| Neutron emission after muon capture            | <0.001           |
| Charged particle emission after muon capture   | <0.001           |
| Radiative pion capture                         | 0.0096$\ast$     |
| Beam electrons                                 |                  |
| Muon decay in flight                           | <0.000.48$\ast$  |
| Pion decay in flight                           |                  |
| Neutron-induced background                     | ~0$\ast$         |
| Delayed radiative pion capture                 | 0.002            |
| Antiproton-induced backgrounds                 | 0.007            |
| Electrons from cosmic ray muons                | 0.0002           |
| Total                                          | 0.03             |

13. Towards the full-sized COMET Experiment (COMET Phase-II)

The proposed staged approach will produce valuable scientific outcomes at each phase and the physics impact of our CLFV search in COMET Phase-I will be significant. The addition of the full-sized muon beam line as planned in Phase-II will give the ultimate SES for the COMET experiment of $3 \times 10^{-17}$, as described in Sect. 9.

14. Summary

In this paper, we have presented an experiment, COMET (COherent Muon to Electron Transition), to search for the CLFV process of coherent neutrinoless conversion of muons to electrons ($\mu^- \rightarrow e^-$ conversion) in the presence of a nucleus, $\mu^- + N(A, Z) \rightarrow e^- + N(A, Z)$, with a single-event sensitivity of $3 \times 10^{-17}$, at J-PARC.

CLFV has great potential to reveal new physics phenomena beyond the SM. Within the SM that is modified to take account of neutrino oscillation, the expected rate is less than $10^{-54}$ and so any observation of a $\mu^- \rightarrow e^-$ conversion would be a clear signal of physics beyond the SM. Many models of new physics, such as those based on supersymmetric grand unification (SUSY-GUT), supersymmetric seesaws (SUSY-seesaw), and extra dimensions, require the existence of CLFV to be accessible, to realizable future experiments.

Muons would provide the best laboratory to study CLFV as they can be produced in substantial numbers and have a sufficiently long lifetime for precise measurements of their decays. Present accelerators can produce about $10^{15}$ muons/year, and it is anticipated that it will be possible to produce $10^{18} \sim 10^{19}$ muons/year with a new high-intensity source that is proposed (pion capture system) in conjunction with the J-PARC main proton synchrotron ring.

The main processes that are accessible for CLFV are the decays $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^+e^-$ and $\mu^- \rightarrow e^-$ conversion. Of these, $\mu^- \rightarrow e^-$ conversion would provide the best sensitivity to new physics, as the potentially measurable sensitivity of $O(10^{-17})$ is significantly better than the limits expected with current technology for the $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^+e^-$ processes.

We have described the COMET experiment on the search for $\mu^- \rightarrow e^-$ conversion in a muonic atom of aluminum, $\mu^- + \text{Al} \rightarrow e^- + \text{Al}$, at a single-event sensitivity of $B(\mu^-\text{Al} \rightarrow e^-\text{Al}) \sim 3 \times 10^{-17}$ at J-PARC. This is a factor of 10 000 better than that of current experiments.
COMET will use a bunched proton beam, slow-extracted from the J-PARC MR. Beam bunching will be necessary to reject beam-related backgrounds. The experimental setup consists of high magnetic-field solenoids for pion capture, C-shaped curved solenoids with momentum selection, and a C-shaped curved solenoid electron spectrometer. The experiment will require about $2 \times 10^{18}$ stopping muons, which, with the expected transmission of muons in our muon beam line, will require about $8.5 \times 10^{20}$ protons of 8 GeV on target.

Recently, a new initiative of a two-stage approach has been undertaken to achieve an early and timely start to the series of searches for $\mu^- - e^-$ conversion. This staged experimental proposal for COMET Phase-I presents the first part of the staged construction of the COMET experiment. To realize this staged approach, we would like to construct the COMET proton beam line and the COMET muon beam line up to the end of the first 90° bend so that a muon beam can be extracted to the experimental area of the J-PARC NP experimental hall.

Firstly, with COMET Phase-I we would like to make a direct measurement of the proton beam extinction and other potential background sources for the full-sized COMET experiment (COMET Phase-II), using the actual COMET beam line. The direct measurement of potential background sources will be vital for the COMET experiment.

Secondly, we would like to carry out a search for $\mu^- - e^-$ conversion with a single-event sensitivity of better than $3.1 \times 10^{-15}$, which is a factor of 100 or more better than that achieved by SINDRUM-II. Since the curved electron transport system in COMET Phase-II will not be included, another type of a dedicated detector is being considered. The present baseline detector for a $\mu^- - e^-$ conversion search at COMET Phase-I is a cylindrical drift chamber, which turns out to be capable of achieving the aimed goals.

Ultimately, with the completion of the rest of the COMET beam line and the detector, we intend to carry out COMET Phase-II to achieve an SES of $3 \times 10^{-17}$. The proposed staged approach will produce valuable scientific outcomes at each phase and the physics impact of our CLFV search will be significant.

In summary, we have shown that the physics case made by the COMET experiment and its staged approach is extremely strong, and that it is aligned with the proposed J-PARC mid-term plan for the construction of the COMET beam line. We are hoping to start construction of COMET Phase-I in 2013 and perform measurements in 2016; then we can carry out COMET Phase-II in 2021. We are confident that the COMET experiment would have significant opportunities for great discoveries and J-PARC is the best proton facility to carry out this important experiment.

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