PROCEEDINGS OF SCIENCE

Progress towards COMET Phase-I

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The COMET experiment is designed to search for flavour violation in the charged lepton sector, via the coherent neutrinoless process $\mu + A \rightarrow e + A$, which can probe a wide variety of BSM physics. Using the new high-power proton beam at J-PARC, the sensitivity of the final COMET experiment is substantially better than previous experiments. In order to better understand the beam and ordinary muon decay backgrounds that are relevant at this sensitivity, an initial Phase-I of the experiment will use just the upstream 90° bend of the final COMET beam transport. In addition to studying the beam characteristics, the Phase-I experiment will also search for $\mu - e$ conversions with sensitivity 2 orders of magnitude better than the current limit. The Phase-I experiment is in the final stages of design, and construction of the COMET facility has already begun.

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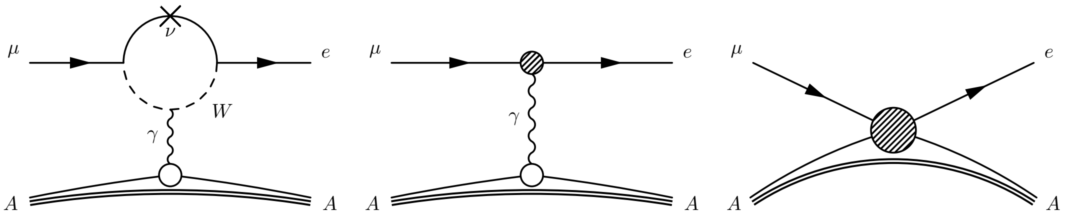
1. Introduction

1.1 Muon to electron conversion

Muon to electron conversion is the process $\mu A \to eA$, where a muon in orbit around an atomic nucleus converts into an electron, without any neutrinos. It is one of a class of processes that change the flavour of a charged lepton. In the Standard Model, these are mediated by loops containing a W boson and a neutrino (see Fig. 1a), and are easily related to the now-established phenomenon of neutrino oscillations. However, because the neutrino is much less massive than the W boson, the process is alternately suppressed by the large W mass (at low loop q^2) or by the low neutrino mass (at large loop q^2). This results in a Standard Model branching ratio that, at around 10^{-54}, is orders of magnitude below any currently conceivable experiment.

But without any explanation of particle masses, this is considered to be an accidental suppression which may not apply to any new physics. Indeed the process is ‘natural’ (in the sense that it will occur if not explicitly tuned out) in many theoretical extensions to the Standard Model, and at rates that are much closer to current experimental limits. Therefore experimental channels for observing charged lepton flavour violation offer a excellent opportunity to look for new physics, and are essentially free from any Standard Model background.



(a) (b) (c)

Figure 1: **(a)** The leading-order contribution to $\mu - e$ conversion in the Standard Model. Many new physics extensions can cause similar transitions, and (because the new particles are typically heavy) they can be described by effective field theories at low energy. This results two classes of terms: **(b)** Dipole effective operator and **(c)** four-fermion effective operator. The photon-radiating diagrams are a subset of all possible processes, which include other experimentally useful channels, such as $\mu \to e\gamma$.

COMET [1] is a new experiment currently under construction in Japan, which will take advantage of the high intensity pulsed proton beam available from the J-PARC main ring. The full COMET design has a sensitivity that is four orders of magnitude better than the current limit [3], which was set by the SINDRUM-II experiment at PSI. This is a significant improvement, and some aspects of the Monte Carlo (MC) simulations have never been validated to this precison. Although the experiment is designed so that a direct comparison with MC is not required, a better understanding of the process involved would allow it to be further optimised. This motivates a smaller experimental configuration that would be intermediate in sensitivity between SINDRUM-II and the full COMET. Such an experiment would still have a factor of 100 improvement in sensitivity, and allow the final COMET design to be refined.

This intermediate configuration will re-use (or rather, *pre*-use) elements and expertise, and is referred to as COMET Phase-I.[1] Figure 2 shows a comparison of the physics reach of the two

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[1] The full COMET experiment is correspondingly referred to as Phase-II.

COMET phases, SINDRUM-II, and the related MEG experiment [2], which is only sensitive to the dipole interaction. Phase-I of COMET should improve upon SINDRUM-II and be competitive with MEG (or better) across this parameter space.

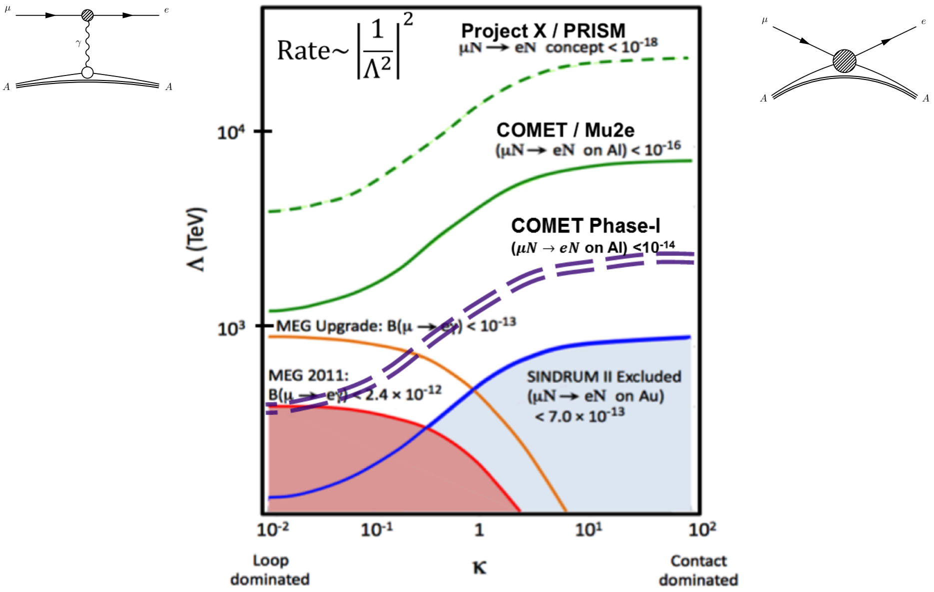

Figure 2: Current limits (filled) and future sensitivity (lines) to Charged Lepton Flavor Violating processes as a function of the parameter κ, which describes the relative strength of the dipole (loop) and four-fermion (contact) terms.

1.2 Decay of captured muons

To motivate the following sections, which describe the design of the experiment, it is worth reminding ourselves of the possible decays of a muon in an atomic orbit.

When a negative muon comes to rest in matter it will capture around the positive nucleus of an atom. From there it will quickly cascade down to the $1s$ orbital, and remain there until it decays, by whatever channel. The X-rays emitted during this cascade, in particular the final $2p-1s$ transition, are a useful tool for establishing the number of muon captures.

The signal process is $\mu A \to eA$, in which the nucleus recoils only slightly. The nuclear recoil carries almost no energy, and since this is effectively a 2-body process, the electron is mono-energetic at around 105 MeV. It is these 105 MeV electrons that COMET will look for.

The most obvious decay channel, and one that creates the most important background, is muon decay-in-orbit ($\mu N \to e\nu\bar{\nu}N$). This is very similar to the decay of a free muon, with one important difference. Because the nucleus can recoil, the usual kinematic constraints of a free muon decaying at rest do not apply and the electron can take almost all the decay energy, up to the 105 MeV of the conversion process. This is rare (since the neutrinos must get almost no energy) but still common enough to be the most important background. This is discussed, along with other backgrounds, in another talk [4].

The other significant mode is nuclear muon capture ($\mu N(Z) \to \nu N^*(Z-1)$). The excited nucleus in the final state will decay, ejecting protons, neutrons, and other light nuclear fragments.

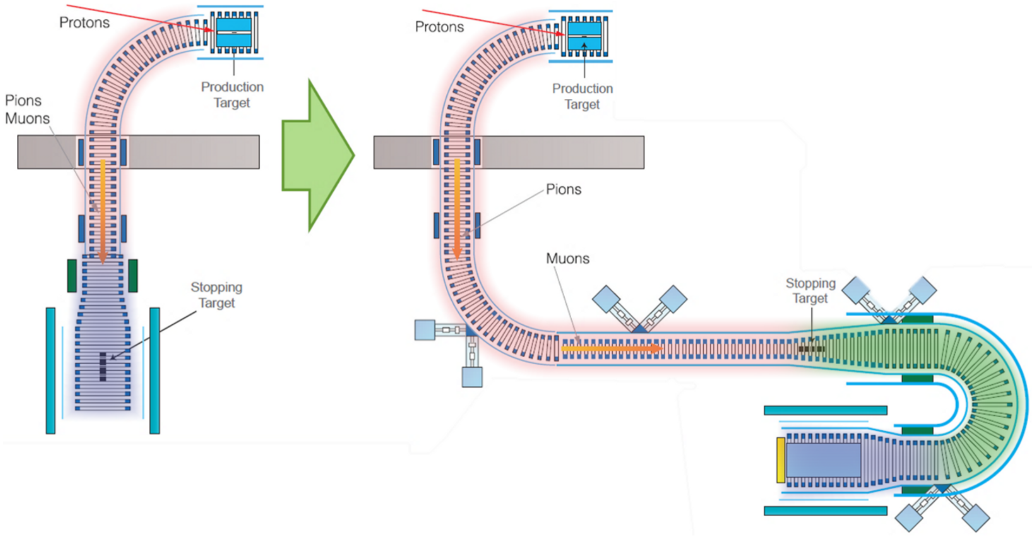

Figure 3: The two phases of COMET. Both phases are entirely contained in snaking solenoids, although the purpose (and therefore bore and field strength) varies along the path. On the left, Phase-I has a short muon transport solenoid (red) with one 90° bend and a detector section (blue) that contains the muon capture target inside a cylindrical detector. On the right, Phase-II has a longer muon transport with a total bend of 180°. After the target there is an electron spectrometer (green) leading to the detectors, which are mounted in a planar orientation. Both phases will use the essentially the same production section (top, not tinted).

These do not constitute any real problem for analysis but impact on the experiment design, contributing to the radiation levels and increasing the noise rate in the detectors.

2. Comparison with Phase-II

A comparison of Phase-I and Phase-II of the COMET experiment can be seen in Figure 3. In both phases, the entire experiment from production target to detector sits inside a solenoidal channel. Different sections of solenoid serve different purposes, but in all cases charged particles below a transverse momentum cut-off will trace helical paths inside the central bore.

The most visually distinctive sections are the curved transport solenoids. By deflecting the beam in the horizontal plane, an additional vertical dispersion is produced that is proportional to the particle charge. By adding compensating dipoles, the horizontal channel can be made to select only negative-sign particles within a particular momentum range. Phase-I has a single 90° section, but Phase-II makes much greater use of these elements, with two 90° bends in the muon transport, and a similar curved spectrometer to select the conversion electrons. The properties of these curved sections are described in more detail in another presentation [5].

The other main difference between Phase-I and Phase-II relates to the existence of the spectrometer section. The spectrometer will filter out backgrounds meaning that the Phase-II detector can be made up of perpendicular planes downstream of the target. In Phase-I, similar detectors will exist, but will not be optimal for conversion searches because the background from beam particles and other decays is vastly higher. As such the Phase-I incarnations of these detectors serve two

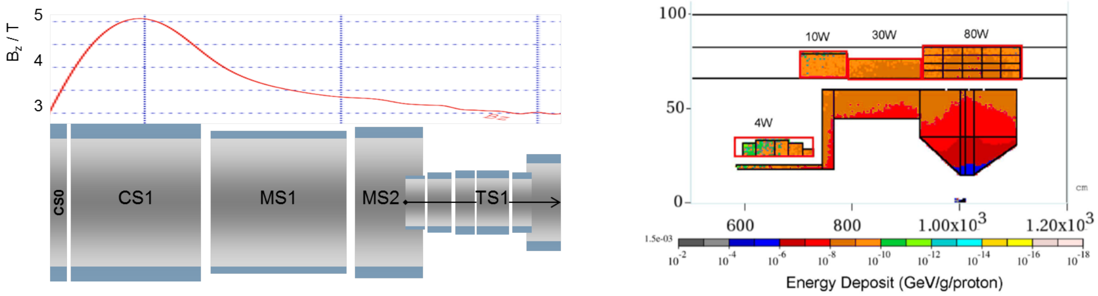

Figure 4: (Left) Axial magnetic field strength in the pion capture section. Below the axis is shown the locations of the various individual solenoids. The proton beam travels at a small angle to the solenoid axis, travelling in the direction of MS2 to CS0. **(Right)** Energy deposition in the capture section solenoids. (Note that orientation is mirrored w.r.t. to left-hand figure.)

main purposes: as prototypes for the Phase-II detectors; and to characterise the backgrounds in the region of the target.

To perform a $\mu - e$ conversion search in Phase-I, another detector will be used. In order to stay clear of the beam backgrounds it has a cylindrical geometry and is hence referred to as the *CyDet*. This is discussed in Section 4.

The part of the experiment that is most similar between the two phases is the production section for the secondary pion beam. This is almost by necessity, since the higher radiation levels in this area means that access will be restricted after it has been exposed to beam.

3. Front-end components

The heart of the front-end is the pion production target. In Phase-I, COMET will use a graphite target, 60 cm long by 2 cm in diameter. The exact material is IG-43 graphite, which is chosen because it has been use in J-PARC's T2K experiment (which uses an even more destructive fast-extracted beam that operates at over 200 kW). In the Phase-I beam, a graphite target can be maintained purely with radiative cooling, and will have lower residual radioactivity than higher-Z materials, making it easier to replace in the case that a new design is favoured for Phase-II.

Surrounding the target is a capture solenoid, and this is joined to transport line using matching solenoids that reduce the field strength down smoothly. Because COMET requires low energy pions in order have stopping muons at the conversion target, the pions are collected from the *backward* hemisphere (w.r.t. the proton beam) of the target. The axial B-field in the capture section is shown in Fig 4. At the target location this field peaks at 5 Tesla. By using a strong field that adiabatically weakens along the matching section, particles emitted at high angles to the solenoid axis are deflected to smaller angles, effectively increasing the solid angle aperture of the transport line.

The coils for this powerful capture solenoid are wound from superconducting wire and must be kept at cryogenic temperatures. This presents a technical issue as the proton interactions will heat the target and surrounding material quite substantially. Detailed simulations have been made to understand this heating. In Phase-I the total thermal power is expected to be around 30 kW, and to counteract this the inner bore of the capture section is shielded with water-cooled elements of

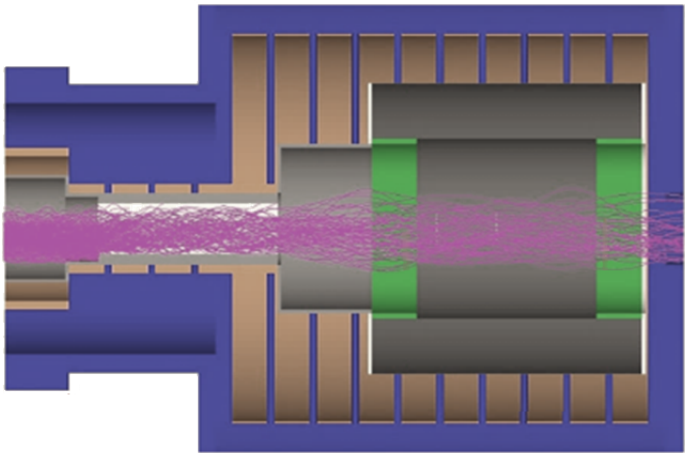

Figure 5: Cut away of the Phase-I CyDet section, showing the coils (brown), CDC (dark grey), and Čerenkov Hodoscopes. Particle tracks are shown in purple to give an indication of the width of the beam pulse, which drives the design to include a wide inner bore for the detector.

copper and tungsten. In Phase-II the heating is even higher, totalling about 120 kW. A map of the simulated energy deposit in Phase-II is shown in Fig 4. Further evaluation will be done based on data from Phase-I, since in Phase-II the shielding will also be heavily irradiated.

4. Phase-I detector

Although Phase-I will include elements of the planar straw tube trackers and EM calorimeter planned for use in Phase-II, the main detector for physics will be a cylindrical drift chamber (CDC) which forms the main part of the CyDet. This sits inside a detector solenoid that provides a field of 1 Tesla, and surrounds the muon stopping target. The target itself is composed of a succession of 17 thin (200 µm) aluminium foils. Aluminium is used because the muon decay time is well matched to the planned bunch structure of the beam.

The drift chamber itself is under construction. Once completed it will have an annular shape, with an inner (outer) radius of 50 cm (84 cm) and a length of 150 cm. The sense wires are arranged into 19 concentric rings, and use stereo layers to provide a measurement along the axial direction. Using a Helium-based gas mixture, simulation predicts the design will have a momentum resolution of 200 keV/c.

To trigger the readout of the drift chamber, and provide exact timing to use in reconstruction, two trigger hodoscopes sit inside the CDC inner radius at the upstream and downstream ends. The trigger hodoscopes will be composed of over-leaving segments each made up of a scintillator paddle and a lucite Čerenkov detector. Figure 5 is a cut-away of the CyDet, showing the trigger hodoscopes in relation to the CDC and detector solenoid coils.

5. J-PARC preparations

The COMET experiment will have its own experimental hall to the side of J-PARC's Hadron experimental area. The below-ground area of the hall houses the experiment itself. As of the end

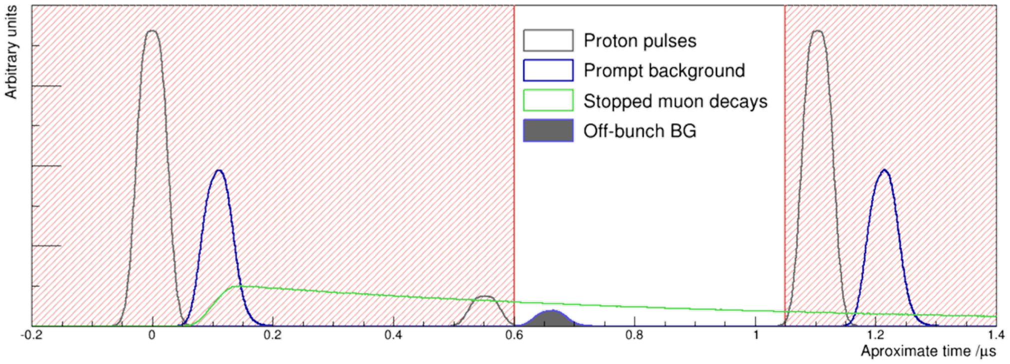

Figure 6: Cartoon of the delayed analysis window used to avoid prompt beam backgrounds in COMET. The elements are for illustration only, in particular note that the vertical scales are completely arbitrary.

of August 2014, fixed concrete shielding for this area has already been poured, and construction is advancing towards the external building, which will house the assembly area and operations room.

To route the 8 GeV beam to the new hall a new branch will be created near the start of the the slow extraction line. As well as COMET branch, a new "high momentum" branch will be installed. The current status of this switch yard area is that most of the magnets are in place, but have not yet been aligned to the design beam path.

5.1 Analysis window and extinction measurement

In parallel with the construction, it is possible to do studies with the existing accelerator to ensure that the beam quality meets our experimental requirements. One particularly strict requirement is what is known as the *extinction*.

The operation mode for COMET is based on resonant slow extraction. Normally the accelerator RF is turned off before extraction begins, resulting in a continuous beam over the extraction period. For COMET we will not turn off the accelerator RF, so that extracted beam preserves the accelerator bunch structure. The reason for this is shown in a cartoon in Fig. 6. The proton beam bunches are nominally spaced at 1.2 μs, which corresponds to every second accelerator bucket Around 100 ns after the beam pulse at the pion targets, the detectors see a beam flash of secondary beam particles that would overwhelm any signal. To avoid this, a window cut is used, only analysing events that come well after the beam flash. This drives the material choice for the muon stopping target: the lifetime of the stopped μ^- (which decreases for higher-Z nuclei) must be similar to the bunch spacing. If it is too short, the muons will mostly decay before the analysis window is opened. Contrarily, the $\mu - e$ conversion branching fraction increases for heavier nuclei. Therefore the ideal nucleus is light enough that the muon lifetime is comparable to the bunch spacing but no lighter. Aluminium ($Z = 13$) fits the specification well, and is easy to work with.

Th use of a delayed analysis window eliminates the background from beam flash, but one contribution may remain. The 'empty' buckets in the accelerator still provide stable accelerated orbits and can collect protons that have been disturbed too far from their intended orbits. This is rare, but even a small beam flash will swamp the signal if it is not properly accounted for. The number of protons in supposedly empty buckets is parametrised as a fraction of the number in the

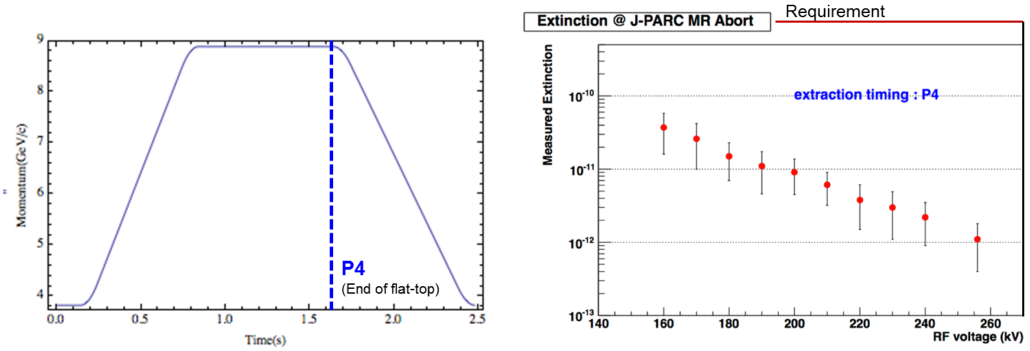

Figure 7: Results of the 2014 extinction test at J-PARC MR. The beam was accelerated to 8 GeV, then maintained at flat-top with a range of RF voltages. The extinction was measured at the fast-extraction abort line, and shows a clear dependence on the maintained RF voltage.

filled buckets, and this ratio is called the extinction. The accelerator design goal for COMET is an extinction of below 10^{-9}. In 2014, this was tested in 8 GeV extraction. The results are shown in Figure 7, and comfortably exceeds the design requirements even for quite modest applied RF voltages. This result is encouraging, and hopefully a sign of things to come for COMET.

6. Timeline and developments

Since the talk was written the facility construction has proceeded even further. The building structure is nearly complete and expected to be finished in March of 2015. Phase-I is projected to be ready in JFY2016, and is projected to reach a single event sensitivity of 3×10^{-15} in a run of around 3 months.

References

[1] Many documents available at `http://comet.kek.jp/`

[2] F. Tenchini, "*The search for CLF violation in the MEG & MEG II experiments*", also presented at NUFACT2014

[3] W. H. Bertl *et al.*, [SINDRUM-II Collaboration], Eur. Phys. J. C **47**, 337 (2006)

[4] A. Sato and C. Wu, "*Backgrounds studies for the COMET Phase-I and Phase-II*", also presented at NUFACT2014

[5] A. Kurup, "*COMET Phase II*", also presented at NUFACT2014