EPJ Web of Conferences **179**, 01011 (2018) https://doi.org/10.1051/epjconf/201817901011
FCCP2017

Status of the COMET experiment

R. P. Litchfield[1,a]

[1] *Imperial College, London*
On behalf of the COMET collaboration

Abstract. The COMET experiment, currently under construction at J-PARC, is designed to search for the the neutrinoless flavour-changing charged-lepton process $\mu^- + A \rightarrow e^- + A$, which is a promising channel to look for new physics. The experiment will make use of the high-power proton beam available at the J-PARC Main Ring to achieve a sensitivity orders of magnitude better than the current limits. The experiment will be staged, with 'Phase-I' scheduled to begin commissioning soon while the 'Phase-II' design is refined in parallel. A description the design of both Phases is presented, along with the latest developments.

1 Muon to electron conversion

Lepton flavour is conserved in the Standard Model without massive neutrinos, but it is not protected by any symmetry and is now known to be violated by non-zero neutrino masses with mixing. Neutrino mixing also gives rise to the charged lepton conversion process, but the rate of such processes can be calculated and is hugely suppressed, down to the level of 1 in 10^{54}, because the neutrino masses are very much smaller than the W boson mass. Thus the charged-lepton channel is an ideal place to look for new physics, as there is no known reason for it to be forbidden, it is only 'accidentally' (at least as far as we know) not present in the Standard Model. Physics scenarios enhancing leptonic flavour violation processes are a central theme of this workshop, so details are not repeated here. Suffice to say that the process is predicted in a wide range of new physics models, unless parameters are tuned specifically to suppress it.

The COMET (COherent Muon to Electron Transition) experiment is currently under construction at J-PARC in Tōkai, Japan. [1] It will search for evidence of the conversion of muons to electrons without the production of neutrinos, $\mu^- + A \rightarrow e^- + A$, a process that conserves total lepton number, but not lepton flavour.

As noted in the name, COMET will look specifically for the coherent conversion process: Muons that are stopped and bound in the $1s_\mu$ orbit of an atomic nucleus convert to electrons, and the 4-momentum transfer to the nucleus is no more than required to conserve energy and momentum. The electron is therefore mono-energetic at around 105 MeV, which is the muon rest mass minus the binding and nuclear recoil energies.

[a] e-mail: p.litchfield@ic.ac.uk

2 Experimental concept

The experimental signature that COMET will use is the single mono-energetic electron produced by conversion of stopped muons. The clean sample of stopped muons is provided by a delayed window technique, making use of the relatively long lifetime of bound muons to 'wait out' all the other activity associated with providing an intense muon source, as illustrated in Fig. 1. The delayed window technique requires that the primary beam for the muon source is pulsed, with a relatively large time gap between pulses. The lifetime of stopped muons decreases with increasing atomic number, as the muon is bound more tightly to the nucleus. So although the rate of the process is enhanced for heavier nuclei, the choice of stopping target is mostly driven by requiring a good match to the size of the gap between pulses provided by the accelerator. The J-PARC Main Ring will provide proton bunches at 1.2 μs intervals, and this makes aluminium the preferred stopping target, although titanium is also a good choice and could be used at a later date.

The ultimate goal of COMET is to discover (or constrain) the μ–e process with a sensitivity of four orders of magnitude better than the current (90% C.L.) limit of 7×10^{-13}, from the SINDRUM-II experiment [2]. Although there is no intrinsic background, this requires excellent control over accidental backgrounds that may give rise to electrons near the signal energy. It also requires an intense muon source: even with perfect efficiency, an experiment aiming for a 10^{-17} sensitivity would need to use 10^{17} muons. Since this is a new approach that provides a marked improvement in sensitvity, the experiment will be staged into two Phases, with Phase-I intended to provide input for the detailed design of Phase-II, as well as producing an intermediate result in a timely fashion.

Because of the delayed window, prompt backgrounds induced by the beam should be relatively easy to control,

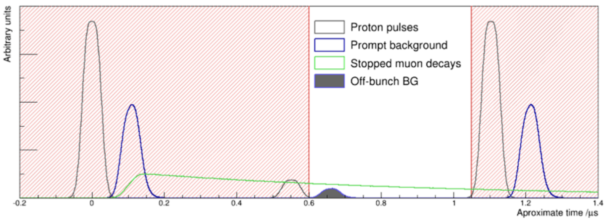

Figure 1. Cartoon of the delayed window technique. The prompt backgrounds (blue) should all occur a few hundred nanoseconds after the primary beam time, while the signal occurs according to the lifetime of the muonic atoms, which is matched to the bunch frequency. An important aspect is whether there are non-negligible off-time bunches (grey fill). In reality, such a background is not expected to be a problem, as described in the next section.

but provide the main constraint on the how soon the delayed window can be used after the beam pulse[1]. More problematic are backgrounds originating from the long-lived muons. The most obvious is from decay-in-orbit, $\mu^- + A \rightarrow e^- + \nu + \overline{\nu} + A$, which is the fate of around 39% of muons bound on aluminium. This process is very similar to free muon decay, but since the leptonic system can recoil against the heavy nucleus is is possible for the the decay energy to be carried almost entirely by the electron. The theoretical maximum energy is therefore very close to that of the mono-energetic line of the conversion signal. This is heavily suppressed, and the vast majority of electrons have much lower energies, but the fraction is large enough to makes it necessary for the experiment to have good (100 keV-scale) momentum resolution. In COMET this will be provided by using large magnetic fields and low-mass tracking detectors.

Another muon-related background is from decay-in-flight. If the muon has momentum of at least 77 MeV$/c$, it is possible, depending on the decay angle, for the electron to end up in the 105 MeV signal region. Thus while collection of lower energy muons is a priority, it is also important to avoid allowing higher-energy muons into the vicinity of the stopping target. This drives the design of the muon collection system.

The three key design points of the experiment are then:

- An intense *pulsed* muon source, emphasising less-energetic muons that will stop in a thin aluminium target.
- A muon beamline that can efficiently collect and transport low-energy negative muons (and their parent pions) from the point of production to the stopping target, but filter out high-energy and positive muons and pions.
- Detectors that can make accurate momentum measurements of 105 MeV electrons originating in the stopping target.

[1] A very cautious window—starting later than naively expected—should be used because of the possibility of stragglers, and to allow for the detector readout to go quiet.

3 COMET Design

The protons of the COMET primary beam will be resonant slow extracted from the J-PARC Main Ring at a beam momentum of 8 GeV$/c$. In order to get a longer delayed window between bunches only four of the nine accelerator buckets will filled in each cycle. In order to eliminate 'off-pulse' prompt backgrounds the ratio of protons in 'empty' to filled buckets should be no higher than 10^{-9}. Initial tests indicate that levels of 10^{-11} and lower are already achievable. The experiment will monitor the primary beam using highly radiation-tolerant diamond-based detectors.

The beam is directed towards a graphite production target that sits in a 5 T solenoid field. Secondary particles produced at the target travel in helical paths in the solenoid field, and are thus captured in the secondary beamline. A peculiarity of the set-up it that the solenoid system is designed to collect pions emerging in the *backward* direction, as forward going secondaries are more energetic (so will not produce muons that can be stopped) and contain a larger fraction of other undesirable hadrons, such as anti-protons.

The field of this *Capture* Solenoid decreases smoothly from 5 T at the target position down to 3 T at the rear section. As secondaries travel through this gradient field, their helix angle decreases, effectively increasing the angular acceptance of the secondary beamline around the target.

The lower field at the exit of the capture solenoid is matched to a *Transport* solenoid which serves several purposes: The first and simplest is that it provides propagation space in which the pions can decay to produce the muons required by the experiment. The transport solenoid is also curved, which results in the helical trajectories drifting either up or down depending on the charge and momentum of the particle. Since the aperture of the transport solenoid is finite, this acts as a filter of high-momentum and wrong-sign particles, an effect which is enhanced by including a collimator at the end of the transport section. A dipole field is applied and tuned so that pions and muons with appropriate momenta (between about 20 and 50 MeV$/c$) are transmitted with high efficiency, and others are removed.

The subsequent sections of the experiment differ significantly between Phase-I and Phase-II, so are described separately. Both Phases are illustrated and compared in Fig. 2.

3.1 Phase-I

In Phase-I, the transport solenoid is around 4 m long and bends through 90°, with a collimator (again inside a solenoid) at the end, to provide a narrower band of selected momenta. After the collimator solenoid sits a much larger (1.07 m radius) *Detector* solenoid, inside which is the aluminium stopping target, which consists of a number of thin aluminium foils on solenoid axis. In Phase-I the outer part of the detector solenoid will be instrumented with a Cylindrical Drift Chamber (CDC). The drift chamber uses an all-stereo-wire design with 18 layers of sense wires. The chamber was completed in 2016 and is currently (at time

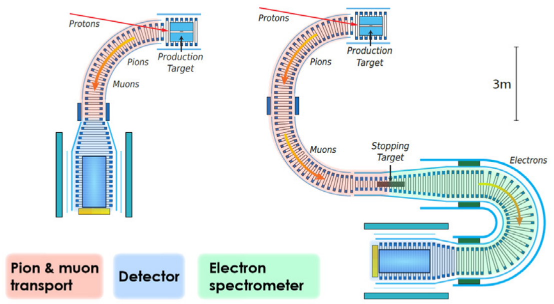

Figure 2. Plan view of Phase-I [left] and Phase-II [right] of COMET. The Capture section and first 90° are common to both Phases.

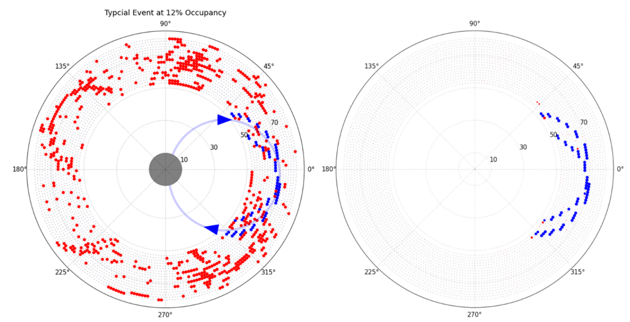

Figure 3. Reconstruction of simulated tracks. In the first step [left] hits are classified as signal-like (blue) or background-like (red). In the second step [right], a Hough transform based on the signal-like hits is used to select hits belonging to a track, which can be reconstructed in 3D using the two stereo projections.

of the workshop) taking cosmic ray data using an external scintillator trigger at KEK. The fully installed detector will trigger from scintillator and Cherenkov hodoscope rings place near the upstream and downstream ends of the CDC.

Reconstruction of events recorded by the CDC is under development using Monte-Carlo simulations. Even with the filtering afforded by the transport solenoid, the number of particles passing through the centre of the Detector Solenoid would make it impossible to operate a drift chamber at small radius. The 50 cm minimum radius of the CDC means that it escapes this direct beam flash, and the majority of decay-in-orbit electrons. But there is still expected to be a lot of activity causing many hits unrelated to the triggering track. Reconstruction first focusses on identifying noise hits based on local features, then finds tracks hits based on the global pattern of the signal-like hits. These tracks are then fit to obtain the transverse and longitudinal components of the track momentum (using the two stereo projections) and indicate whether the tracked particle originated in the target foils. Figure 3 illustrates the high detector occupancy, and how effective this this two-step track finding algorithm is.

3.2 Phase-II

In Phase-II, the transport solenoid will be extended with a second 90° section to provide better momentum filtering, which will be necessary at higher primary beam power. The stopping target will sit in a straight solenoid section, and downstream of this there will be a second (180°) set of curved *Spectrometer* Solenoids. This second set of curved solenoids will have a much larger inner radius and are designed to collect electrons near 105 MeV/c. In this way they act a filter for signal electrons, reducing backgrounds and enabling the use of higher beam intensities. The COMET software framework is designed to be used by both phases, so detailed simulation of Phase-II is ongoing in parallel with preparations for Phase-I. This commonality also allows for rapid inclusion of tuned simulations from Phase-I into the Phase-II design optimisation.

Because the majority of decay-in-orbit electrons are removed by this curved electron spectrometer, the detector solenoid (which is reused and sits after the spectrometer) can be instrumented with full-plane detectors. The baseline design uses several planes of straw tubes as a tracker to reconstruct the helical trajectory, followed by a LYSO-crystal EM calorimeter. The design is being evaluated in Phase-I with a partial plane of crystals and 5 tracking stations, each containing of 4 planes of straws in an YYXX configuration. During Phase-I, this detector can be exchanged with the CDC, and will be used for evaluation of the detector technology and to characterise the secondary beam that reaches the detector solenoid. This can be used to check the simulations for both Phase-I and Phase-II, and to optimise collimator designs for the Phase-II spectrometer.

A small ($\sim 10 \times 10\,\mathrm{cm}^2$) prototype using straws arranged as a single station of the Straw Tube Tracker and an 8×8 crystal section of the Calorimeter was taken to a electron test-beam at ELPH in Sendai in March 2017 (see Fig. 4). This was a fully integrated test of the system, and included the front-end readout cards for both detectors and a DAQ using the same MIDAS framework planned for the real experiment. The test was very successful, meeting all of the planned goals with spare time to try out some extra configurations and trial the trigger system. Analysis of the data is currently (as of Sept '17) ongoing.

4 Sensitivity projections and timeline

The quantity measured by a μ–e conversion experiment is usually expressed as ratio

$$R = \frac{N\,(\mu A \rightarrow eA)}{N\,(\mu A \rightarrow \nu A')} \tag{1}$$

which is to say the relative rates of the conversion process and the (flavour-conserving) weak Nuclear Muon Capture (NMC) process. Because of the short range of the weak interaction, the rate of NMC depends on how tightly the muon is bound to the nucleus. Thus as well as the lifetime of the bound muon, the relative rates of NMC and decay-in-orbit depend on the nucleus. For ^{27}Al the NMC

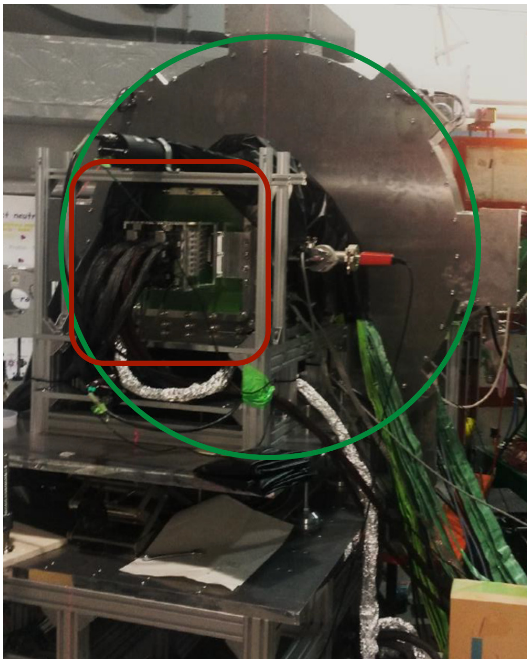

Figure 4. The test-beam prototype Phase-II detector, during the run at ELPH. The Straw Tube Tracker and Calorimeter pieces are indicated in green and red respectively.

fraction (f) is 61%. The ratio R is easier to calculate theoretically than the fraction of muons converting to all those captured, and it makes it easier to compare measurements using different nuclei.

Experimental sensitivity is expressed using the a quantity called Single Event Sensitivity (SES). This is the value of R such that the number of events seen by an experiment has an expectation value of one, and is essentially just the reciprocal of the number of events that would be expected if $R = 1$. This can therefore be expressed using the total number of stopped muons produced and the various efficiencies:

$$\mathrm{SES} = \frac{1}{N_\mu \cdot g \cdot f \cdot A}, \qquad (2)$$

where $g = 0.9$ is the probability for the nucleus to remain in the ground state after the conversion. There are two experiment-dependent quantities: N_μ, the number of stopped muons; and A the experimental acceptance. In Phase-I, the latter is dominated by the geometric acceptance of the detector around the target (18%), and time acceptance of the delayed window (30%). Overall, for COMET Phase-I, with a selection tuned for a background expectation of 0.03 events, projections from simulations give $A = 4.1\%$ and $N_\mu = 1.5 \times 10^{16}$, assuming a goal of 5 months of running. This gives a single event sensitivity of 3×10^{-15}. For COMET Phase-II, which is designed to run at a primary beam power of 56 kW (c.f. 3.2 kW for Phase-I) with better acceptance, the projected single event sensitivity is 2.6×10^{-17} after one year of running.

The schedule for operation of Phase-I is dependent on progress of facility construction, which (since J-PARC is a running facility) must take into account operation of the J-PARC accelerators for existing experiments. The most recent assessment projects that commissioning of the Phase-I configuration could begin as early as the end of Japanese Financial Year (April~March) 2018, with physics data-taking primarily in JFY 2019 and 2020. Fabrication of the extended solenoids and final development of detectors for Phase-II would precede in parallel, so that it could commence relatively soon after the completion of Phase-I.

Acknowledgements

On behalf of the COMET collaboration, I thank KEK and J-PARC, Japan for hosting the COMET experiment and providing the necessary infrastructure.

Additionally, the work is supported in part by: Japan Society of the Promotion of Science (JSPS) KAKENHI Grant No. 25000004; JSPS KAKENHI Grant No.JP17H06135; National Natural Science Foundation of China (NSFC) under Contracts No. 11335009 and 11475208; Research program of the Institute of High Energy Physics (IHEP) under Contract No. Y3545111U2; the State Key Laboratory of Particle Detection and Electronics of IHEP, China, under Contract No.H929420BTD; IN2P3-CNRS, France; Shota Rustaveli National Science Fund (SRNSF), Georgia; Institute for Basic Science of the Republic of Korea, Project No. IBS-R017-D1-2017-a00; Russian Foundation for Basic Research Grant No. RFBR-17-02-01073; Science and Technology Facilities Council, United Kingdom; JSPS London Short Term Predoctoral Fellowship program; Daiwa Anglo-Japanese Foundation Small Grant; and Royal Society International Joint Projects Grant. Crucial computing support from all partners is gratefully acknowledged, in particular from CC-IN2P3, France.

References

[1] COMET Review Document (TDR), and other documents available at `https://comet.kek.jp`

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