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A two-stage approach in the the search for $\mu - e$ conversion with COMET

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Abstract. The COMET experiment will search for the charged lepton flavour violating process $\mu^- + N(Z, A) \rightarrow e^- + N(Z, A)$ in Al with a single event sensitivity of 3×10^{-17} . This will be a four orders of magnitude improvement on the current limit set by SINDRUM-II in Au. The design, R&D and construction of COMET are all well underway and described here is an update on the current status of the experiment.

1. Introduction to Charged Lepton Flavour Violation

It has been known since the discovery of neutrino oscillations that lepton flavour is not a conserved quantity in nature [1]. However, although neutrino oscillations are evidence of lepton flavour violation in the neutral lepton sector, there has been no observation of this phenomenon among the charged leptons.

In fact, this is what would be expected from the Standard Model (SM) since it predicts these charged lepton flavour violation (CLFV) processes to have tiny branching ratios of $O(10^{-54})$. This is a result of large suppressions in Feynman diagrams such as the one shown in Figure 1, which arise from the fact that the neutrino is oscillating in a virtual loop.

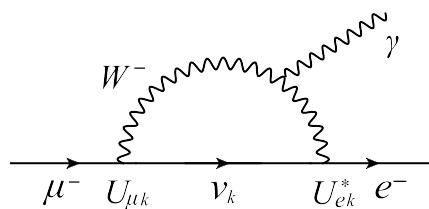


Figure 1. Standard Model Feynman Diagram for the $\mu \rightarrow e\gamma$ process.

Since the SM prediction is so small, any observation of a CLFV process would be clear evidence of beyond the Standard Model physics and so there are many experiments that are looking for such processes.

The CLFV processes that are searched for in the muon sector are given in Table 1 along with their current upper limits.



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Table 1. The current limits in muon CLFV searches.

CLFV Process	Current Limit at 90% CL	Experiment	Reference
$\mu^+ \rightarrow e^+ \gamma$	$< 5.7 \times 10^{-13}$	MEG	[2]
$\mu^+ \rightarrow e^+ e^- e^+$	$< 1.0 \times 10^{-12}$	SINDRUM	[3]
$\mu^- + \text{Au} \rightarrow e^- + \text{Au}$	$< 7 \times 10^{-13}$	SINDRUM-II	[4]

COMET will be searching for the $\mu^- + N(Z, A) \rightarrow e^- + N(Z, A)$ process (also known as $\mu - e$ conversion) in aluminium.

The $\mu - e$ conversion process occurs when a muon is stopped by an atom and falls down to the 1s state, forming a muonic atom. The muonic atom then decays with a certain lifetime (864 ns for aluminium [5]), with one of its possible decay processes being an interaction with the quarks in the nucleus to produce a single electron.

The muon's mass defines the energy of the initial state and so the electron in the final state will have a very well-defined energy approximately equal to it. The full equation for the energy of $\mu - e$ conversion electrons is $E_e = m_\mu - E_b - E_{rec}$ where E_b is the binding energy of the 1s state of the muonic atom and E_{rec} is the energy taken away by the recoiling nucleus. For aluminium, the electron energy is 104.9 MeV.

Another advantage of this process is that it remains a simple signal to search for at high muon rates since there is no need to determine coincidences like in $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$.

2. The COMET Experiment

The COMET experiment will be built in two phases. Phase-I will begin in 2016 and is seeking to achieve a single event sensitivity (S.E.S) of 3×10^{-15} and Phase-II will begin in 2019 with a S.E.S of 3×10^{-17} . The experimental layouts of Phase-I and Phase-II are shown in Figures 2 and 3 respectively.

As shown by the figures, COMET Phase-II has a distinctive S-shape and Phase-I is a smaller scale version that is identical up to the end of the first 90° bend. The advantage of taking a staged approach is that it will be possible to search for $\mu - e$ conversion at an intermediate sensitivity to the final design goal as well as allowing for the investigation of the backgrounds to be encountered in Phase-II with the actual beamline that will be used.

Searching for $\mu - e$ conversion with such a high sensitivity requires a very intense muon beam and this will be generated by firing protons at a production target and collecting the backwards travelling pions with a high solenoidal magnetic field. This will result in a muon beam intensity of $O(10^9)$ μ^- per second.

After the beam is produced, it will travel around the first C-section, designed to be long enough so that the majority of the pions decay into muons and to select the low momentum particles. There are two reasons for this selection. First, it is only low momentum muons that will stop in the aluminium stopping target and also, any high momentum muons above 77 MeV/c could decay in flight and produce electrons of the same energy as the $\mu - e$ conversion signal which would be a major background to the experiment.

Once the muon beam gets around the first C-section, it will then enter the muon stopping target section where it will be stopped in the stopping target. Muonic atoms will then be formed and, after decaying, the emitted electrons will be guided through the final C-section which acts as an electron spectrometer to select 104.9 MeV/c electrons that will be evidence of the $\mu - e$ conversion process. The momentum and energy of the electrons will then be measured by the detector.

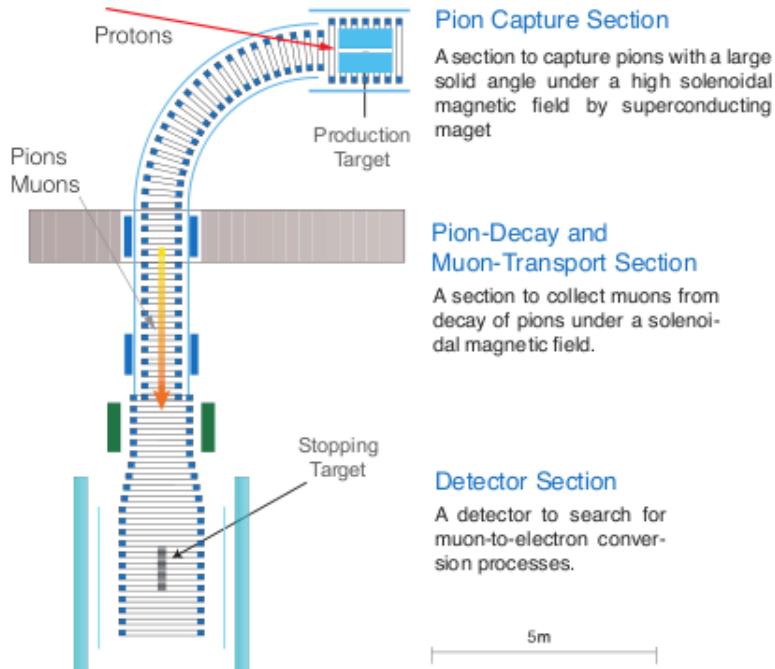


Figure 2. Experimental Layout for COMET Phase-I.

The detector will consist of a straw tube tracker with excellent momentum resolution and an electromagnetic calorimeter (ECAL) that will add both redundancy to the measurement and also act as a trigger for the DAQ. Together these two parts are known as the StrECAL.

For Phase-I, only the first 90° of the experiment will be built and, in order to reach the desired sensitivity, a cylindrical detector (named CyDet) will be used for the $\mu - e$ conversion search instead. This gives an increased geometrical acceptance but is affected more by any other particles emitted from the stopping target such as protons which consequently impact the data rates. In addition to the CyDet, there will also be a prototype StrECAL to be used for background investigations.

3. Proton Beam

COMET will use an 8 GeV, 3.2 kW (Phase-I) or 56 kW (Phase-II), pulsed proton beam at J-PARC. By using a pulsed beam we can utilise a delayed-timing window for our measurement in order to remove prompt backgrounds.

A diagram of the proton time structure is given in Figure 4 and shows the proton pulses (black, diagonal stripes) will have a $1.1 \mu\text{s}$ separation in time. Once the muon beam reaches the stopping target, there will be an immediate flash of prompt backgrounds (light grey, diagonal stripes) which mostly arise from pion contamination in the beam. The stopped muons then decay slowly (dark grey, vertical stripes) and a time window (dark grey, horizontal stripes) is opened sufficiently long after the prompt backgrounds have passed through the experiment that the search for a signal event (solid black) can start.

Also in this diagram is an illustration of what happens if there is insufficient extinction of the proton beam between pulses (small, striped black pulse in the centre of the plot). Having residual protons between the main pulses means that the corresponding muons arrive at the

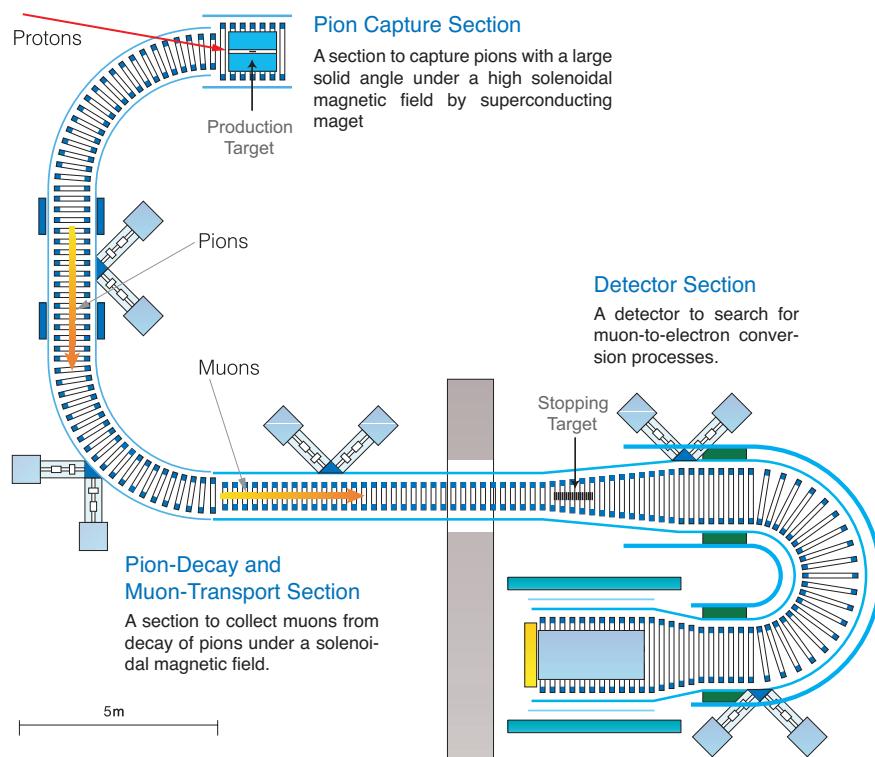


Figure 3. Experimental Layout for COMET Phase-II.

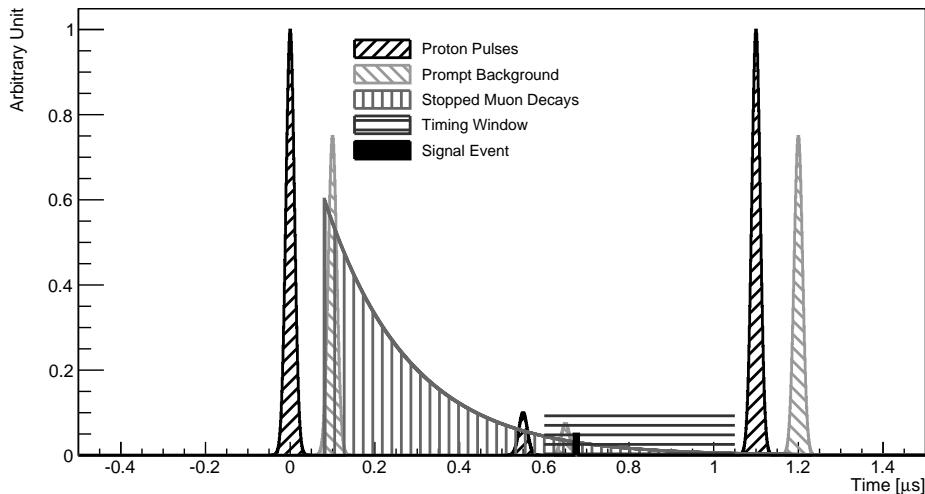


Figure 4. The time structure of the COMET proton beam and associated backgrounds.

stopping target later than they should. This means that a smaller prompt background flash occurs which arrives in the measurement window and so will obscure any search for the $\mu - e$ conversion process. An extinction factor of 3×10^{-11} is necessary to overcome this problem and, in order to get it down to the required level, a novel injection method has been developed and

has been successfully demonstrated at J-PARC in May 2014.

4. Background Estimates

As for any rare search measurement, it is very important to know the background processes that could mimic the signal and to estimate how much impact they will have. For COMET Phase-I, 0.03 background events are expected per signal event for a branching ratio of 1×10^{-15} and 30 days running. The important backgrounds are muon decay-in-orbit, which contributes 0.01 background events per signal event and radiative pion capture which also contributes 0.01 background events per signal event.

The decay-in-orbit (DIO) background is the only intrinsic physics background in the experiment and occurs when the stopped muon decays normally into an electron and two neutrinos. The electron energy spectrum for this process is a rapidly falling distribution above 52.8 MeV but, if the neutrinos take very little energy, the electron can have energies very close to the signal region. Although the end-point of this spectrum is below the signal energy, in reality, the signal and background could be smeared into each other due to detector resolution effects.

The radiative pion capture (RPC) background occurs when pion contamination in the beam is captured by the aluminium nucleus in the stopping target. This leaves the nucleus in an excited state and, as it decays back to the ground state, it emits high energy gamma rays that can pair-produce electrons with an energy in the signal region. This is a prompt process and so is suppressed by the extinction factor described in section 3.

5. Cylindrical Detector - CyDet

For COMET Phase-I, a cylindrical detector (CyDet) will be installed to search for the $\mu - e$ conversion process. This increases the geometrical acceptance of the detector but also increases the rate of hits since any particles emitted from the stopping target will enter the detector. The emitted particles mostly consist of protons from nuclear muon capture and so, for Phase-II, this will not be a problem since there will be a final C-section that will charge select the protons away.

The CyDet will be composed of two parts. A cylindrical drift chamber (CDC) to measure the momentum of the electrons and a pair of Cherenkov counters to act as a trigger.

The requirements of the CDC are that it needs to have a gas gain of $> 10^5$, a position resolution in the transverse plane of $< 250 \mu\text{m}$, a position resolution in the z direction of $< 2 \text{ mm}$ and the gas needs to reduce the amount of multiple scattering in order to minimise the amount of energy loss and achieve the best possible momentum resolution.

The current design for the CDC is based on the design of the CDC that has been built for Belle-II. This was constructed at KEK and so allows the exploitation of tooling and expertise that already exists in the community. The specific parameters of the CyDet geometry are given in Table 2.

There are two important parameters that help in the reduction of the backgrounds. First, the inner radius of the CDC is large enough so that the large flux of low p_T electrons that occur from DIO do not enter the detector and, second, the inner wall is thick enough to remove protons that are emitted from the target but not so thick that any electrons that pass through it lose too much energy and so any signal electrons lose enough energy to be smeared into the background.

Currently, there is a small-scale prototype of the CDC that has undergone cosmic ray tests at both KEK and Osaka and the procurement of the final CyDet is underway.

Table 2. Geometry parameters of the CyDet for COMET Phase-I.

Parameter	Value
CDC Inner Radius	55 cm
CDC Outer Radius	84 cm
CDC Length	150 cm
CDC Drift Gas	He:iC ₄ H ₁₀ (90:10)
Trigger Counter Material	Scintillator and Cherenkov Counter
Trigger Counter Length	300 mm
Trigger Counter Thickness	35 mm
Magnetic Field	1 T

6. Straw Tube Tracker and ECAL - StrECAL

The StrECAL detector will be the main detector for Phase-II but a prototype will also exist for Phase-I to measure backgrounds in preparation for Phase-II. It will consist of a straw tube tracker with five stations (4 layers of straws in each station) and an electromagnetic calorimeter.

The straw tube tracker will be based on the design of the tracker built at JINR for NA62 and so a collaboration has been set up between KEK and JINR to undertake design and R&D work. Currently, a 1:1 scale prototype of a tracker station has been built with fewer channels and is undergoing various tests at KEK.

The requirements for the ECAL are that it needs a resolution of $< 5\%$ at 105 MeV, a low trigger rate, a spatial resolution of $< 1.5\text{ cm}$ and a quick response of $< 100\text{ ns}$ so that it can be used as the trigger.

At present, there are two candidate crystals under consideration: GSO and LYSO. Both of these have been tested in a beam test at Tohoku University in March 2014 and a decision on which crystal will be used will be made in the immediate future.

7. Conclusion

COMET will be searching for the charged lepton flavour violating process $\mu^- + N(Z, A) \rightarrow e^- + N(Z, A)$. COMET will have a single event sensitivity of 3×10^{-15} in Phase-I which will run in 2016 and a single event sensitivity of 3×10^{-17} in Phase-II which will begin in 2019.

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