Simulations of the cosmic-veto system for the COMET experiment

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Abstract. In the COMET experiment searching for the muon-electron conversion not conserving lepton numbers, a scintillator-strip-based veto system will be used to prohibit the COMET detector from fake signals initiated by cosmic muons. In order to verify the efficiency of the system, we have built its computer model and carried out various simulations. To tune the model, experimentally measured data are utilized. The simulations give the inefficiency of the cosmic-muon registration being below 0.0001, which meets requirements of the experiment. In addition, simulations of neutrons originating from muon captures and traversing a shield beneath the cosmic-veto system have been carried out using the Geant4 toolkit. A Geant4 application has been written with an appropriate detector design and possible spectrum of neutrons' energy. Design of the shield has been optimized to ensure the time loss concerned with fake veto signals caused by the background neutrons is tolerable. Materials of shield's layers are chosen, and optimum thicknesses of the layers are computed.

1. Introduction
The discoveries of recent years suggest the possibility of extending the Standard Model. Many of the extended models predict the charged lepton flavor violation (CLFV). The search for new physics through CLFV complements that being undertaken at LHC. One of the processes appropriate to experiments seeking for CLFV is the neutrinoless muon-electron conversion in the field of nuclei. When a negative muon is stopped by some material, it is trapped by an atom, forming a muonic atom. The fate of the muon is then to either decay in orbit or be captured by a nucleus. In the context of physics beyond the Standard Model, the exotic process of muon capture accompanied by neutrinoless electron emission is also expected, $\mu^- N \rightarrow e^- N$. The final state of the nucleus could be either the ground state or one of the excited states. In general, the transition to the ground state dominates, which is called coherent capture. The rate of the coherent capture is enhanced by a factor approximately equal to the number of nucleons in the nucleus.

The latest search for $\mu^- - e^-$ conversion was performed by the SINDRUM-II collaboration at the PSI. They set the current upper limit on the branching ratio of $\mu^- Au \rightarrow e^- Au$ at $7 \cdot 10^{-13}$. The COMET Phase-I experiment is seeking to measure the coherent neutrinoless muon-electron transition in aluminum nuclei with a single event sensitivity of $3.1 \cdot 10^{-15}$, assuming running period of 110 days. The experiment will utilize a dedicated 8 GeV proton beam extracted from J-PARC’s Main Ring via a new beamline. Muons will be produced in decays of pions.
produced in collisions of the proton beam with a graphite target. The yield of low momentum muons is enhanced using a pion capture solenoid. Muons are momentum- and charge-selected using a muon transport solenoid before being stopped in an aluminum target at the center of a Cylindrical Drift Chamber (CDC) in a 1 T magnetic field.

The COMET Phase-I detector will be augmented with prototypes of the Phase-II straw tracker and the electron calorimeter. As well as providing valuable experience with the detectors, they will be used to characterize the beam and measure backgrounds to the neutrinoless muon conversion signal to ensure that the Phase-II single event sensitivity of $2.6 \cdot 10^{-17}$ can be achieved. Another experiment that also searches for CLFV is the MEG experiment at PSI. This uses a final state different to that of the COMET, $\mu^+ \rightarrow e^+ + \gamma$, yet data of the two experiments can be combined to discriminate between different theoretical models.

The event signature of the coherent $\mu^- - e^- \rightarrow e^-$ conversion in a muonic atom is a mono-energetic single electron emitted from the conversion with an energy of $E_e \approx m_\mu - B_\mu$, where $m_\mu$ is the muon mass and $B_\mu$ is the binding energy of the muonic atom. From an experimental point of view, the $\mu^- - e^- \rightarrow e^-$ conversion is a very attractive process. Firstly, the electron energy is far above the end-point energy of the free muon decay spectrum. 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 other processes, such as $\mu^+ \rightarrow e^+ \gamma$ and $\mu^+ \rightarrow e^+ e^+ e^- \rightarrow e^-$ decays.

The energy of emitted electrons $E_e \approx m_\mu$ coincides with the endpoint of muon decay in orbit (DIO), which is the only relevant intrinsic physics background. Since the energy distribution of DIO falls steeply above $m_\mu/2$, this background can be suppressed using a good energy resolution of the COMET detector. There are several other potential sources of background events in the energy region around 100 MeV, involving beam particles or cosmic rays.

Beam-related background events may originate from muons, pions or electrons from the beam. Apart from DIO, muons can produce background events by decay in flight or radiative muon capture. The restriction on the muon momentum to be less than 70 MeV/c allows the background caused by in-flight decay of muons to be avoided. Pions can produce background events by radiative pion capture. Gamma rays from both captures produce electrons mostly through $e^+ e^- \rightarrow e^-$ pair production at the aluminum muon-stopping target. However, since the lifetime of muonic atoms is $\approx 1 \mu s$, a pulsed beam allows the prompt background events to be removed by performing measurements in a delayed time window.

The cosmic-ray background should be carefully eliminated because of the tiny number of signal events expected in the experiment. Cosmic-ray muons may decay in flight or interact with the materials around the area of the muon-stopping target, producing signal-like electrons in the detector region. For the Phase-I, only the area of the CDC has to be protected against cosmic muons to prevent the muon-induced background. Both passive and active shielding should be used to protect the region around this detector. The passive shielding consists of a thick concrete ceiling as the experiment is underground. Beneath the ceiling, Cosmic Veto Counters (CVC) will be located, whose inefficiency should as small as 0.0001 [1]. In our studies, we develop design and optimize parameters of the system using computer simulations.

2. The cosmic-veto system

Veto on cosmic muon propagation can be effectively organized using scintillator strip modules surrounding the COMET Phase-I detector [1]. Similar strip modules are used in the Belle II detector where the scintillator light is collected through Kuraray WLS fibers to Hamamatsu silicon photodetectors MPPC. To date properties of such a detecting system as well as the radiation hardness of MPPC are studied well enough [2].

The CVC system consists of eight super-modules, two above the CDC, two on either side and
one for the front and rear ends. The super-modules will be assembled from modules that are formed from 15 strips made of polystyrene-based scintillator and placed in parallel. Each strip have the same profile and a length of about 220 cm (110 cm for vertical modules). To provide a high registration efficiency, a super-module comprises four layers of modules. We have shown that the desirable value of the inefficiency can be achieved using a coincident signal in any two of the four strip layers, which allows us to reject fake signals caused by the MPPC noise as these rarely coincide within a short resolution time window [3].

3. Efficiency of scintillator counters

First we have carried out computer simulations of inefficiency of the CVC. In these simulations, we only model a horizontal slab of the COMET veto counter, expecting lower inefficiency for vertical slabs due to longer average muon range. The ionization produced by muons in a scintillator strip is proportional to their range in the strip, so the signal of a muon depends on its entrance position and direction as well as on the sizes of inactive zones in the detector. A layer of the CVC consists of scintillator strips of 40 mm width and 7 mm thickness. Surfaces of strips are chemically processed to provide a diffuse reflection of the scintillator light. Processing adds 0.2 mm to the strip width on average. Besides, we assume additional 0.1 mm separation of strips because of their imperfect geometry, so two neighboring strips are separated by a 0.3 mm inactive zone.

Similar to the Belle II KLM detector design, two neighboring modules are separated by an aluminum holder of 5 mm width, which also represent an inactive zone. This wide zone is particularly harmful for muon registration because its width is comparable with the average cosmic muon range in 7 mm thick strips, so that muon signals can vanish. To keep an appreciable muon signal, both inter-strip and inter-module inactive zones of different layers should be shifted w.r.t. each other.

Our simulations are done for both a single layer and a stack of four layers for three configurations described below. In the first one, each subsequent layer is moved w.r.t. the previous one the chosen distance in the same transverse direction. In the second configuration, the second and the fourth layers are moved w.r.t. others the same distance doubled. Finally in the third configuration, the third and the fourth layers are moved w.r.t. others the same distance doubled. Thus, in the latter two configurations an offset of layers equals to an average offset in the the first configuration, see figure 1.

![Figure 1. Strip layouts implemented in the simulation.](image)

On its way from a muon entrance point to an MPPC, the collected scintillator light is significantly attenuated. To take into account the attenuation, we use experimentally measured...
Muon signals in a 220 cm long strip. Our simulation show that in a single layer, about one third of unregistered muons goes through inter-module inactive zones. Others are not registered due to occasionally small signals, predominantly at inter-strip inactive zones in the rear part of strips where the attenuation of light is higher. Because of inactive zones in layers, an average range of muons contributing to signal amounts 10 mm contrary to 10.5 mm in a continuous layer of scintillator. This takes place under the condition that only the largest of two range parts contributes to the signal in the case when a muon crosses an inactive zone.

As for the complete stack of four layers, in the second and the third configurations at the offset of 40 mm, positions of inter-strip inactive zones of all layers coincide. At the offset about 43 mm the inter-strip inactive zones of two layers appear below (or above) of inter-module inactive zones of other layers, right on the symmetry line of the zones. Such offsets abruptly increase the inefficiency. Apparently, the first configuration is preferable because (i) positions of its inter-strip inactive zones do not coincide and (ii) they can only be crossed by a muon trajectory at large polar angle where the muon flux is lower.

The simulations have demonstrated that the inefficiency of the first configuration at the readout threshold of eleven photo-detector’s pixels is less than 0.0001 when the average offset of layers exceeds about 20 mm. In addition to the 11-pixel threshold that is a possible level of noise signals’ amplitudes after a long exposition of MPPCs to a neutron background of the experiment [2], separate simulations have been done for the readout thresholds equal to 10, 9, 8, and 7 pixels. These have shown the muon registration inefficiency decreases by an order of magnitude when the threshold value is reduced by two pixels.

4. Noise signals

The noise signals of MPPC above the readout threshold can fake muon passing through the counters, which results in wasted time of data taking. This is a result of random coincidences of the noise signals that appear in two strips of two layers within resolution time and could not be distinguished from signals of a real muon in those layers. Veto time windows should be formed around such noise signals, and data from the veto windows should be excluded from the physics analysis, while in fact there was no cosmic muon.

During data taking, the frequency of noise signals grows with irradiation of photo-detectors by background neutrons that damage the p-n conjunction of silicon photo-detectors [2]. We have shown that operating at the threshold above seven pixels keeps the fraction of the lost time at the level of few percents throughout full time of data taking. A disadvantage of working at high thresholds is lower muon registration efficiency. However, our simulations of the efficiency value have demonstrated that it still meets COMET requirements even at the 11-pixel threshold [3].

5. Signals of background neutrons

Neutrons emitted from the muon-stopping target can also cause fake veto signals in the CVC. Besides, they could damage silicon photo-detectors being used in the CVC [3]. On average, neutrons appear in six of ten muon captures by atomic nuclei of a target made of aluminum, which results in \( \sim 10^9 \) neutrons per second for the COMET Phase-I.

There are two major ways in which neutrons affect the CVC: through gammas from neutron captures by materials of the detector and kicking protons and ions out directly in the CVC. We have studied the latter way in detail. Since there is a threshold for signal amplitudes of the CVC photo-detectors, signals of low-energy neutrons are being rejected. Affordable values of the threshold lie from one tenth to one fifth of the average MIP signal in CVC [3], so the threshold corresponds to 0.2–0.4 MeV of energy deposited in scintillator by ionization. We perform simulations of neutron signals using the Geant4 toolkit, version 10.0, with the FTFP_BERT_HP physics list.
First of all, the simulations have shown that the stopping power of charged projectiles created by fast and medium-energy neutrons in polystyrene is much higher than that for MIP [4]. As a result of the Birks’ law, for neutron’s energy below 1 MeV, light yield of the projectiles lies below the readout threshold values quoted above. Therefore, such neutrons are not typically seen by the CVC. Furthermore, the sub-millimeter range of the charged projectiles in strips makes coincident signals in two strips extremely unlikely.

Then, we have carried out simulations of a shield between the CDC and CVC. The most convenient shielding material by far is concrete, this is comparatively chip, strong, available in bricks, and allows pouring, which simplifies the construction of complicate profiles. It shields quite effectively against low-energy and fast neutrons, moderating and then capturing them. However, the spectrum of neutrons from muon captures stretches up to tens of MeV. It takes more elastic collisions to moderate energetic neutrons, hence a longer free path, i.e., higher penetration ability, and this trend persists at higher energies. Furthermore, energetic neutrons interact inelastically and cause spallation, giving birth to high-energy projectiles.

For these reasons, a more sophisticated structure should be designed for COMET inner shielding as follows. Iron is not that good in construction of such a heavy self-supporting structure as the COMET inner shield. Iron still makes a much better job in moderating medium-energy neutrons, though at the cost of a sea of fast neutrons. The fast neutrons can be effectively moderated through elastic scattering in polyethylene, which can, however, result in neutron captures on hydrogen accompanied by emission of 2.2 MeV gammas undesirable for the CVC. Gammas emitted in the neutron captures should be shielded by such a high-Z material as lead.

Thus, the three layers of different materials represent a better choice for the shield.

In order to optimize the thickness of each layer, we have simulated neutrons impinging on a three-layer slab of 4 × 4 m² area, using an experimentally known energy spectrum [5]. Materials of layers are iron in the first, polyethylene in the second and lead in the third one. Behind the slab, there are a 10 mm thick air gap and then four 7 mm thick scintillator layers interleaved with 3 mm thick polystyrene pads. We vary thickness of the three shield’s layers, keeping the total shield’s thickness equal to 45 cm and recording spectra of neutrons and gammas in the air gap as well as the response of each of the four scintillator layers.

For instance, for a combination of 25 cm of iron, 10 cm of polyethylene, and 10 cm of lead, the number of coincident signals above 5 pixels is equal to 240, which is 2.4 · 10⁻⁴ of the number of incident neutrons. As the expected rate of muon-capture neutrons at the shield slab is about 1.7 · 10⁸ per second, one gets about 4 · 10⁴ coincident signals per second in the scintillator layers behind the shield. These signals fake cosmic-muon signals. Then, for the whole CVC with four side half-slabs, the rate of the fake signals is about 120 kHz. Thus, if we apply a 50 ns veto window, we have as little as 0.6% of date-taking time lost due to neutrons from muon captures.

Iron shields against medium- and high-energy neutrons more effectively than concrete, but it is less convenient from the point of view of engineering. A good compromise is the use of reinforced concrete containing scrap iron. Therefore, reinforced concrete as a material of the first shield layer has been implemented in the next simulations, volume fractions of iron and concrete being about 0.33 and 0.66 respectively. Additionally, a 10 cm thick return yoke of solenoid has been placed in front of the inner shield in the simulation. For several combinations of thicknesses of the three shield materials, table 1 shows the number of fake signals as well as neutrons and gammas behind the shield. These simulations have shown that the shield should be comprised of 25 to 30 cm of the iron-concrete mix, 10 cm of polyethylene and 5 cm of lead.

Such a shield reduces the flux of fast and more energetic neutrons at photo-detectors of the CVC by two orders of magnitude, so that no substantial radiation damages of photo-detectors is expected throughout full period of data taking. The optimal configuration of the shield is of an arched shape, which accounts for signal attenuation along strips and better protects photo-detectors that are located at outer ends of strips.
Table 1. Summary of neutron and gamma abundance behind a shield comprised of layers of reinforced concrete, polyethylene and lead.

| Reinforced concrete, cm | Polyeth., cm | Lead, cm | # of neutrons behind shield | # of gammas behind shield | # of coincident signals in counters |
|------------------------|-------------|---------|-----------------------------|--------------------------|----------------------------------|
| 25                     | 10          | 5       | 9600                        | 5800                     | 242                              |
| 30                     | 5           | 5       | 14000                       | 5200                     | 200                              |
| 30                     | 10          | 5       | 6000                        | 4100                     | 142                              |
| 35                     | –           | 5       | 21400                       | 4000                     | 183                              |
| 40                     | –           | 5       | 13000                       | 2600                     | 114                              |
| 50                     | –           | –       | 6100                        | 11300                    | 381                              |

6. Conclusion
The COMET experiment provides a large window on new physics beyond the Standard Mode. Its first phase allows us to probe the CLFV at a new level. The detector of the experiment have to be surrounded by a cosmic-veto system, which is optimized in our studies. Modeling of the system has demonstrated viability of the necessary high cosmic-muon registration efficiency. Simulations of the efficiency value have shown that it meets COMET requirements even at the 11-pixel threshold. Operating at high thresholds has an advantage of low rate of fake signals caused by both the photo-detector noise and background neutrons, which results in shorter time lost during data taking.

To optimize shielding against the background neutrons, Geant4 simulations of the system have been performed including details of signal coincidence in a scintillator strip veto counter. The simulations have shown that a mix of iron and concrete performs quite well as a base material for the inner shield of the system. In the conjunction with the solenoid yoke, a shield composed of reinforced concrete, polyethylene and lead drastically reduces the neutron flux at the counter strips. The time loss concerned with fake veto signals of neutrons can be reduced to a tolerable value of 1% of data-taking time by a 40–50 cm thick shield even at the 5-pixel threshold of photo-detectors.

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