

Considerations for a Mu2e-II Stopping Target Monitor

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Charged lepton flavor violation searches provide a unique window into physics beyond the Standard Model. The search for neutrinoless coherent muon to electron conversion at Fermilab in the Mu2e and proposed Mu2e-II experiments provide extremely sensitive searches, up to six orders of magnitude greater than current exclusion bounds. The figure of merit for both experiments is the number of conversion candidate events, normalized to the number of nuclear capture muons observed. The Stopping Target Monitor subsystem provides this normalization for Mu2e, but may require modifications to handle the higher event rates expected in Mu2e-II. We discuss some of the challenges involved in designing an upgraded detector system capable of achieving the goal of a 10% measurement uncertainty.

I. THE MU2E STOPPING TARGET MONITOR

The Mu2e experiment at Fermilab [1] will search for the charged lepton flavor violating neutrinoless coherent conversion of a negative muon into an electron in the Coulomb field of a nucleus, with a four-order-of-magnitude sensitivity improvement over the current exclusion bounds. The proposed Mu2e-II experiment [2, 3] will improve the sensitivity to this channel by another one to two orders of magnitude. To achieve this goal at modest incremental investment, we plan to use the increased beam power available following the PIP-II accelerator complex improvements [4]; beam improvements should provide a factor of three increase in beam intensity at greater than 90% duty factor, compared to the 30% duty factor in Mu2e. Additionally, we plan to reuse as much of the Mu2e apparatus as possible, with targeted upgrades to address higher signal and background rates.

The figure of merit for conversion searches is $R_{\mu e}$, defined as the number of conversion candidate events normalized to the number of nuclear capture events:

$$R_{\mu e} = \frac{\mu^- + A(Z, N) \rightarrow e^- + A(Z, N)}{\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z-1, N)},$$

where $A(Z, N)$ is the nuclear species with charge Z . The bulk of the experiment is designed to measure the numerator of this expression, identifying conversion candidate events in a well-controlled, very low-background environment. The Stopping Target Monitor (STM) subsystem is designed to determine the denominator of $R_{\mu e}$ to of order 10% over the live time of the experiment.

For nuclear targets of interest (particularly, ^{27}Al and ^{48}Ti), stopped muons either capture on the nucleus or decay in orbit to $e\nu\bar{\nu}$ with very well known branching fractions. Further, when negative muons come to rest in matter, they behave as heavy electrons, capturing atomically

and cascading rapidly to the atomic ground state, accompanied by characteristic x-ray and gamma-ray emission lines; for many of these lines, the emission probabilities are known very well in the literature. Thus, one can determine the number of nuclear captures by counting the number of characteristic gamma emissions and multiplying by well known factors.

The Mu2e STM was conceived to measure a number of these emission lines from the ^{27}Al :

1. a 347 keV emission from the $2p \rightarrow 1s$ transition, which is prompt with the muon stop,
2. a 1809 keV emission from the nuclear capture, with the characteristic muonic aluminum lifetime of 864 ns, and
3. a 844 keV emission from the decay of the metastable $^{26}\text{Mg}^*$ capture product, with a lifetime of 9.5 min.

As the 1809 keV photons are emitted within the live-gate of the Mu2e experiment, and should be well separated from nearby peaks, it appears to be the “golden channel” for capture event monitoring.

The STM consists of a pair of detectors - a high-purity germanium (HPGe) solid-state photon detector operated at liquid nitrogen temperatures, and a scintillating crystal LaBr_3 calorimeter. These detectors are housed in a shielded enclosure, and view the muon stopping target through a collimation system and vacuum window from a distance of about 34 m. The large distance, small collimator openings, and plastic absorber placed between the stopping target and detectors should reduce the photon rate to manageable levels, albeit with relatively long integration time before returning a luminosity estimate - our goal is to measure to 10% over a one hour period.

II. STRENGTHS AND ISSUES

The Mu2e STM design has a number of strengths:

1. The detector position outside the vacuum volume that contains the detectors for the conversion mea-

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surement allows us to easily calibrate the absolute count rates of the detectors, using commercially available absolutely calibrated sources.

2. The detectors are positioned very close to the centerline of the stopping target foils; their geometrical view of the target gives very uniform acceptance across the entire face of the target, with calculable corrections for scattering and energy loss.
3. The detector choices have complementary strengths: HPGe has very good resolution (of order a 1-2 keV for energies of interest), allowing discrimination of closely spaced transitions, while LaBr₃ has high rate capability and excellent radiation hardness.

Unfortunately, a number of these design strengths arise because we have chosen to place the detector systems directly along the muon beam direction. The passage of the beam through the stopping target foils leads to an extremely intense bremsstrahlung flash, with a high end-point energy of order 60 MeV - an order of magnitude larger than our highest signal energy - with an average energy deposition of 5 MeV per photon. Particularly with HPGe and its slow recovery time, this beam induced background requires significantly constraining collimator apertures to reduce event rates incident on the detectors. This results in a very small rate for the desired signal lines relative to the prompt beam induced flash. While the system should adequately handle the stopped muon rates of Mu2e, it may be a challenge to handle the higher rates of Mu2e-II.

The resolution of an HPGe detector will suffer from neutron-induced displacement damage. This resolution can normally be recovered by an annealing process, but this requires removing the detector from service for an extended period of time. Mu2e purchased two identical detectors so the second could be swapped in while the first is removed for annealing. Simulations of Mu2e indicate that HPGe will operate without significant resolution loss for somewhere between a few months and a few years before annealing will be required. The order-of-magnitude increase in radiation damage rates during Mu2e-II may be another significant challenge for HPGe.

III. POTENTIAL SOLUTIONS AND PITFALLS

If the current position of the STM must be maintained in Mu2e-II, it seems unlikely that the HPGe detector will be able to handle the higher rates and neutron backgrounds of the new experiment. Since the collimator hole in front of the HPGe is only of order 1 cm², it can't be reduced much more for Mu2e-II. We can significantly reduce the low-energy portion of the bremsstrahlung flash by increasing the absorber thickness, but at the cost of signal rate. The resolution of the HPGe is still required, however, to identify and separate contaminant peaks in the neighborhood of signal lines; it may be possible to use the HPGe to identify these peaks during special low-

intensity runs, and use that data to calibrate a detector with lower resolution but higher rate capability, such as the current LaBr₃, BaF, etc, with corresponding complications in the uncertainty analysis. If the rates on the LaBr₃ detector exceed its capability, we could gate off the photodetector during the beam flash; at the very least, that will require additional studies to measure and correct for gain variations following the restoration of power. Gating only works, however, for target materials with prominent, delayed emission lines - such as the 1809 keV line in ²⁷Al; for other materials of interest - such as ⁴⁸Ti - no such lines are available, and the STM must be able to operate during the flash.

Ideally, muon stop monitoring for Mu2e-II would place the detectors out of the bremsstrahlung flash; we would also be able to place the detectors closer to the stopping target to increase signal event rates by collecting through larger solid angle. A number of potential solutions immediately come to mind; unfortunately, all of them suffer from pitfalls of various kinds that will need to be investigated and overcome.

Since the flash is highly directional, while the signal lines are isotropic, moving the detectors off-axis while still directly observing the target could in principle significantly improve the situation. However, few options are available if we desire to reuse the Mu2e solenoid investment: there is little, if any, space and poor access for mounting additional detectors within the vacuum volume enclosed by the solenoid system. Additionally, charged particle and neutron backgrounds in the neighborhood of the stopping target will be significantly higher than in the current position 34m away. Placing the detectors outside the solenoids but off axis poses different but no less daunting challenges: the current solenoids provide no line-of-sight through vacuum windows to view the target, which would require observing photons that pass through the solenoids and vacuum vessels themselves. All off-axis positions complicate understanding the geometric acceptance compared to the highly symmetric situation for Mu2e, and additionally require explicitly folding the muon stopping distribution into the overall acceptance. A less conventional solution would be to replace some crystals in the calorimeter with LYSO or LaBr₃. However, integrating the Calorimeter with the STM raises numerous problems; for example, the process of performing an absolute calibration of the STM becomes very restrictive. Substantial effort will be required to work out a method for calibration, given access for a substantially limited time once per year.

Rather than the detectors directly observing the secondary beam impinging on the stopping target, we could alternatively create a tertiary photon beam and view that instead. In fact, one could create multiple tertiary beams around the secondary beam feeding multiple detectors to increase the net signal rates. Compton scattering and Bragg diffraction offer two alternatives. The Compton scattering process, unfortunately, strongly compresses the dynamic range of the beam energy, leading to unre-

alizable detector energy resolution requirements. Bragg diffraction as realized through bent crystal monochromatization offers another potential avenue that has been used to great effect in measuring nuclear energy level transitions in the past. However, as the Mu2e signal photons carry up to 2 MeV, relatively high order diffraction is required to achieve reasonable angular separation from the primary beam, and that comes with an associated reduction in count rate. It is also currently unclear if the materials used in commercially available bent crystal monochromators are sufficiently radiation hard for use in this application.

IV. CONCLUSION

We have outlined a number of the strengths and weaknesses of the Mu2e Stopping Target Monitor subsystem, whose design goal is a 10% measurement of the number of captured muons accumulated during the live time of the experiment. The current system design may be challenged by the higher rates expected of an upgraded Mu2e-II experiment in the PIP-II era, without some potentially extensive modifications. We have outlined some of these issues, and suggested a few paths we could explore to improve the capabilities for the future. Additional ideas - including completely new concepts for monitoring schemes - are welcome and encouraged.

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