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The Effects of Neutron and Gamma Rays on CRV Deadtime in the Mu2e
Experiment at Fermilab

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The Effects of Neutron and Gamma Rays on CRV Deadtime in the Mu2e Experiment at Fermilab

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ABSTRACT (100-200 WORDS):

The muon to electron conversion experiment, otherwise known as Mu2e, is an experiment being carried out at Fermilab whose purpose is to observe a direct neutrinoless conversion of a muon to an electron in the presence of a nuclear field. If this conversion is observed, scientists are informed of the existence of new particles or forces of nature beyond the Standard Model. Understanding the relationship between muons and electrons will help scientists learn more about the particles themselves as well as the forces that govern their interaction.

Cosmic ray muons are a source of background in the Mu2e experiment, and the CRV, or the cosmic ray veto, is used to help detect these muons and reduce background rates. Since the probability to observe a neutrinoless muon conversion is so small, it is essential to detect and eliminate all sources of background so that the experiment does not obtain false positive results. Reducing the dead time of the CRV is critical to the accuracy of the results from the Mu2e experiment.

The goal here is to be aware of the different sources of background, learn how neutron and gamma rays are produced, and explain the impact of the neutron and gamma radiation on the dead time of the CRV.

THE EFFECTS OF NEUTRON AND GAMMA RAYS ON CRV DEADTIME IN THE MU2E EXPERIMENT AT FERMILAB

ALISON PEISKER

David Hedin, faculty mentor
April 15, 2016
Final Report

ABSTRACT. The muon to electron conversion experiment, otherwise known as Mu2e, is an experiment being carried out at Fermilab whose purpose is to observe a direct neutrinoless conversion of a muon to an electron in the presence of a nuclear field. If this conversion is observed, scientists are informed of the existence of new particles or forces of nature beyond the Standard Model. Understanding the relationship between muons and electrons will help scientists learn more about the particles themselves as well as the forces that govern their interaction.

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CONTENTS

1. Introduction: The Mu2e Experiment

1.1. **Physics Motivation.** If a muon disappears and an electron takes its place, it is typically due to muon decay accompanied by neutrinos. However, if there are no neutrinos, then the muon has changed flavor to look like an electron. If no neutrinos are produced, then the charged lepton flavor violation was not due to weak interaction, and is thereby caused by something physicists have not yet discovered.

1.2. **CLFV.** Charged lepton flavor violation, or CLFV, is forbidden in the standard model, but physics beyond the standard model allows it. The observation of CLFV would provide evidence for physics beyond the standard model, while failure to observe it would place strong constraints on theory beyond the standard model.

There are three flavors of leptons: the muon and the muon neutrino, the electron and electron neutrino, and the tau and tau neutrino. Neutrino oscillation has been observed, which means lepton flavor violation has in fact occurred. However, lepton flavor violation has not yet been observed in a decay of a charged lepton. Mu2e is one experiment that hopes to observe this phenomenon.

1.3. **Detector Overview.** The Mu2e detector is comprised of a production solenoid, transport solenoid, detector solenoid, tracker, calorimeter, and muon beam stop. A beam of 8 GeV protons strikes the production target inside the production solenoid. Pions are created in

these collisions and decay into muons. The muons then spiral backwards down the transport solenoid, and the collimator separates the positive muons from the negative muons. The negative muon beam travels into the detector solenoid, strikes the aluminum target, and some muons stop due to energy loss. The muons are captured and put into orbit around the aluminum nucleus. The electrons are detected by the straw tube tracker and their energy is measured by the tracker and calorimeter. The electron tracks are reconstructed and fit with momentum calculations to differentiate between conversions and normal atomic orbit decays. The remaining muons that have not been stopped in the detector solenoid are stopped in the muon beam stop. A diagram of the Mu2e apparatus and particle trajectories is shown in Figure 1.
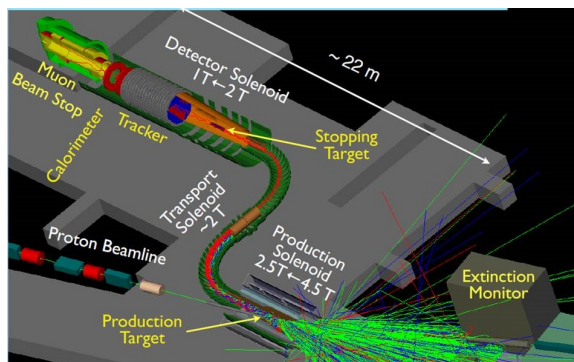

FIGURE 1.   *The Mu2e apparatus consists of a production solenoid, transport solenoid, detector solenoid, calorimeter, tracker, and muon beam stop. The initial proton beam strikes the production target, creating muons that travel down the transport solenoid. The muons then strike the stopping target, the energy of the electrons are measured, and the remaining muons are stopped in the muon beam stop.*

2. CRV and Importance

2.1. **Physical Details.** The CRV is divided into six different sections: left, right, top, TS, upstream, and downstream. It is shown in Figure 2. Its area is 323 square meters. It contains 50 tons of counters, 50 kilometers of fibers, and 18,944 Silicon Photomultipliers (SiPMs). The counters are each five by two square centimeters in profile and have four layers, with aluminum absorbers between each layer. They require a hit coincidence in three of the four layers for a cosmic ray muon track.
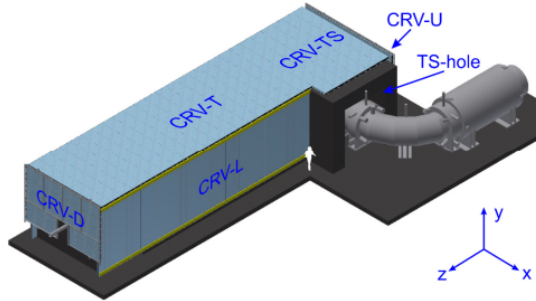
FIGURE 2.   *The CRV surrounds the Mu2e apparatus
and is divided into six parts. Its size scale and axis ori-
entation are shown above.*

2.2. **Importance in Mu2e.** The purpose of the CRV in Mu2e is to
detect cosmic ray muons, reduce background rates, and eliminate the
possibility for a false positive result. Cosmic ray muons are a source
of background for the Mu2e experiment. There are several processes
resulting from cosmic ray muons that can produce 105 MeV particles
that appear to come from the stopping target. This can cause the
cosmic ray muons to be misidentified as electrons. These backgrounds
can be reduced by shielding, by particle identification criteria using
the tracker and calorimeter, and by a veto detector whose purpose is
to detect penetrating cosmic ray muons.

2.3. **CRV Requirements.** The CRV needs to meet certain perfor-
mance requirements. It must operate with an efficiency of greater than
99.99%. It must limit the background to less than 0.1 events over the
duration of the run. It also needs to have a dead time of less than 10%
and use less than 20% of the data acquisition bandwidth.

3. NEUTRON AND GAMMA RADIATION

3.1. **Sources.** There a few different sources of the neutron and gamma
background. The primary 8 GeV proton beam is a major source of
background. This proton beam strikes the production target and di-
rectly produces neutrons and gammas. Neutrons are produced by pi-
ons, muons, and other components of the muon beam interacting in the
transport solenoid. They may also be produced by muons captured in
the stopping target and the muon beam stop.

There are also several physics processes that contribute to the depo-
sition of energy in the CRV counters from this background radiation.
Fast neutrons produce recoil protons through ionization and slow neu-
trons produce gammas when they are captured. In addition to slow

neutron captures, gammas may also be produced by bremsstrahlung and muon decays in the muon beam stop and the last collimator. The gammas that reach the CRV can then undergo Compton scattering, pair production, or the photoelectric effect, which deposits visible energy in the counters.

3.2. **Problems.** Neutron and gamma rays make hits in the CRV, faking cosmic ray muons and increasing the deadtime. They also cause radiation damage to not only the electronics used in the components of the experiment, but to people working on the experiment as well. The Silicon Photomultipliers are particularly sensitive to radiation.

3.3. **SiPM Radiation Damage.** The CRV contains many Silicon photomulitpliers (SiPMs) that are used to detect the cosmic ray muons. Neutron radiation can cause overall bulk damage to the silicon lattice, which reduces the signal-to-noise ratio of the device. The integrated flux to the SiPMs is required to be less than $1 \times 10^{10} n/cm^2$. Figures 3 and 4 show the results of a simulation of radiation damage to the SiPMs. The plots represent the energy spectrum of the neutrons and gammas reaching the CRV. They illustrate the effects of shielding on radiation damage to the CRV's electronics and demonstrate the need for sufficient shielding.
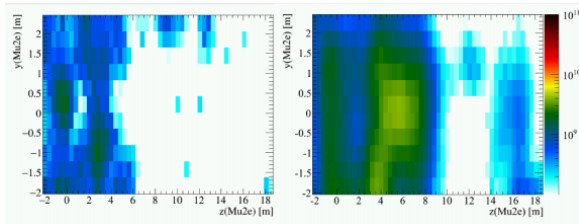

FIGURE 3. *SiPM radiation damage vs. yz axis in CRV-right before and after changes. The decrease is likely due to the addition of blocks in this section of the CRV.*

4. Shielding from neutrons and gammas

The CRV needs to be shielded from the gamma and neutron radiation backgrounds. This may be accomplished by surrounding the CRV by concrete blocks. The CRV is mounted on one yard of concrete walls. The concrete blocks are T-shaped in order to avoid direct cracks in the shielding.

There are a few different options for the type of concrete to use. Regular concrete is the most cost-effective, and it has a density of 2.35
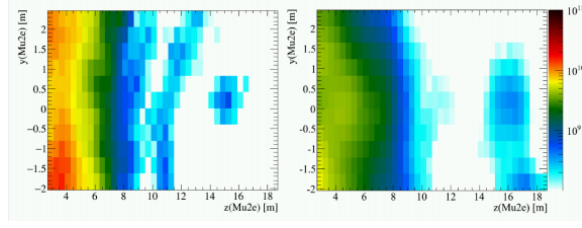
FIGURE 4. *SiPM radiation damage vs. yz axis in CRV-left before and after changes. The increase is likely due replacing barite blocks with boron in this section of the CRV.*

g/cm3. Boron concrete is regular concrete plus 0.007 boron carbide by weight, and has a density of 2.35 g/cm3. Barite concrete contains 44% barium by weight, and its density is 3.5 g/cm3. Boron concrete is effective at shielding neutrons and gammas produced from neutron captures.

The majority of the shielding is regular concrete. However, there are a few regions that need enhanced shielding due to higher neutron and gamma radiation rates. For example, the region near the transport solenoid is shielded by a mix of boron concrete with regular concrete, and the region around the stopping target is shielded by barite concrete.

The deadtime of the CRV is sensitive to the shielding geometry details. Figure 5 demonstrates the effect of boron concrete as opposed to concrete without boron. It shows that adding boron concrete effectively reduces the rate of high-energy gammas.
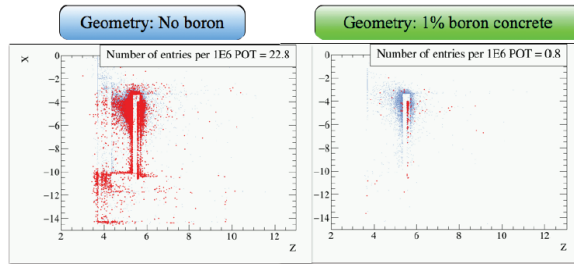

FIGURE 5. *The red points represent sources of delayed gammas with energies of greater than 0.5 MeV in the CRV-U. The blue points represent all particles reaching the CRV-U.*

5. Deadtime Estimation

5.1. **Sources.** Cosmic ray muons and backgrounds are both sources of deadtime. A cosmic ray muon stub in the CRV is defined to be a coincidence of hits in at least three of the four counter layers within a 5 ns time window. This can come in the form of accidental correlation, semi-correlation, or full correlation. Accidental correlation is when a coincidence of hits in three different counters from three separate source particles is produced. Semi-correlation is when a coincidence of hits in two counters from a single source particle with a hit in a different counter from a second source particle occurs. Full correlation occurs when there is a coincidence of three hits in three counters from a single source particle. Fully-correlated hits contribute the most to CRV deadtime.
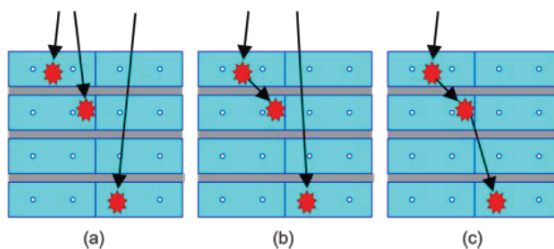

FIGURE 6.   *Sources of background in the cosmic ray veto fall into three categories: (a) accidental coincidence, (b) semi-correlated coincidence, and (c) fully-correlated coincidence.*

5.2. **Simulating Deadtime.** The deadtime simulations are done on the Mu2e computing system using a program called CRVFluxAnalyzer. To use this program, one needs input ROOT files that contain information about the particle fluxes in the CRV shielding. It also needs information about the proton beam and an output directory. The program outputs plots of the accidental, semi-correlated, and fully-correlated deadtime rates for the detector solenoid and transport solenoid regions. An example of the plots CRVFluxAnalyzer produces is shown in Figure 7 below.

5.3. **Properties of Hit Rates.** Figure 7 shows plots produced by CRVFluxAnalyzer. The rates start out high at z = -2 m because of the Production Solenoid sources. The correlated rate is lower since the dominant source of radiation is the gammas that are produced by neutron capture. The bump at z = 4 m corresponds to the region in
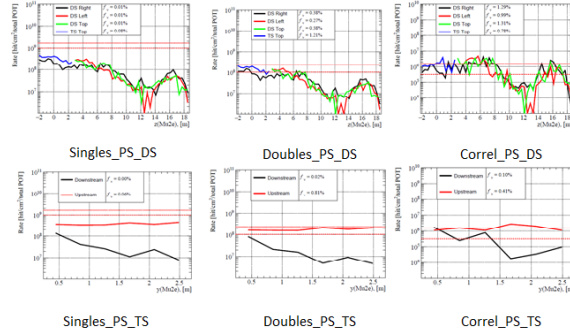
FIGURE 7.   *Plots produced using CRVFluxAnalyzer show the rates vs placement in the Mu2e apparatus. The top graphs represent the rates in the detector solenoid region and the bottom graphs represent the rates in the transport solenoid region. The accidental correlation, semi-correlation, and full correlation rates are displayed in separate plots.*

between the last collimator and the stopping target. The slight dip at z = 6 m corresponds to the location of the stopping target that is shielded by barite-loaded concrete. Here the gamma rate is significantly reduced by the barite, but the neutrons are not being effectively shielded. The muon beam stop is located at z = 16 m. The dominant source of radiation in the correlated rates here is the high-energy gammas from muon decay in the muon beam stop. Figure 8 shows precisely where the particles hit the CRV.
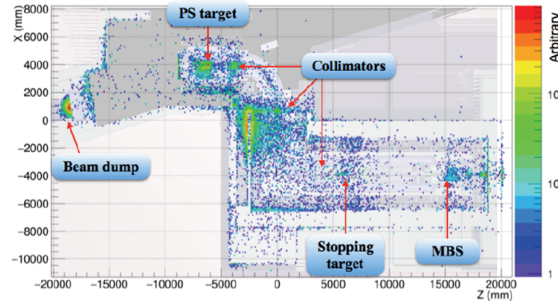

FIGURE 8.   *This plot shows the production position of the neutrons or gammas reaching the CRV after 500 ns. It is clear to see that the majority of the particles origi- nates from the production solenoid.*

6. Muon Beam Stop

6.1. **The detector.** Muons that do not stop in the stopping target pass through the detectors and are transported to the muon beam stop. The muon beam stop is designed to absorb the energy of muons that reach the end of the detector solenoid. This is required to reduce activity in the detectors from muon decays, which is especially important during the measurement period. The muons have a short lifetime in the aluminum stopping target, but the muon beam stop is constructed with materials so that the muons almost have a lifetime of that of a free muon. It is also constructed with polyethylene, which is intended to reduce neutron rates. The apparatus is approximately four meters long and weighs around 5000 kilograms. Figure 9 shows the different pieces and relative lengths of the steel and plastic that make up the muon beam stop.
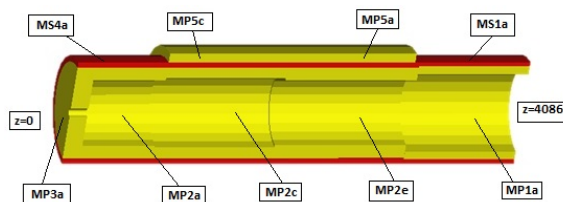

FIGURE 9. *The muon beam stop is about 4 meters in length and is made up of several different steel (shown in red) and plastic (shown in yellow) pieces.*

6.2. **Design Challenges.** From an engineering standpoint, there are necessary constraints placed on the muon beam stop. These constraints are due to the physical supports for the muon beam stop apparatus. There is one support at the back and one at the front. The supports for the muon beam stop determine the acceptable values for its center of mass and total mass.

The center of mass can be obtained by taking into consideration the locations and densities of the different pieces that make up the muon beam stop, and the total mass is determined by adding up the masses of all of the individual pieces of the MBS. Once these two values are calculated, it is plotted on a graph of total mass vs. center of mass, and is compared to the constraint plot given by the engineers to ensure it falls within the allowable range. Figure 10 is an example of a constraint plot given by engineers. It shows the allowable areas and the areas that are not allowed for the total mass and center of mass of the muon beam stop.
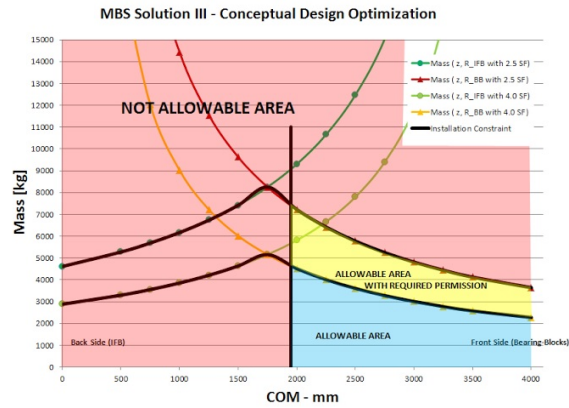
FIGURE 10. *A constraint plot of total mass measured in kilograms vs the center of mass measured in millimeters. The optimum value is that with the greatest total mass and a center of mass that falls below the two lowest curves.*

7. CONCLUSIONS AND CURRENT STATUS

The most recent geometry shows radiation hot spots in the upstream part of the CRV-left region. The sources of the radiation are the initial proton beam and the production solenoid. In order to reduce these effects, barite concrete will be used instead of regular or boron concrete, which causes no major changes to the deadtime. The CRV top region around the stopping target currently has the highest cosmic muon rate. To reduce this rate, barite shielding is needed on the top and sides of the CRV.

Due to a recent update of the Geant4 simulation software, there has been an observed increase in nuetron and gamma flux in certain regions of the CRV. In order to reduce the deadtime produced by the flux increase, a few shielding enhancements are needed. These modifications include adding barite concrete around the muon beam stop and transport solenoid region and using borated barite in the upstream region and around the stopping target. Currently, the correlated hits have the largest impact on deadtime because of the high-energy neutrons and gammas hitting the CRV.

Even with the previously described recent challenges, the current shielding design meets the CRV detector requirements. The CRV deadtime and radiation damage estimates are within acceptable values with the current shielding.

8. Acknowledgements

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