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Optimization of the Muon Stopping Target of the Mu2e Experiment

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The Mu2e experiment being constructed at Fermilab will search for the coherent neutrino-less conversion of muons to electrons in the field of an atomic nucleus. Mu2e is designed to achieve a sensitivity four orders of magnitude better than previous experiments to this charged lepton flavor violating process. An essential part of the Mu2e experiment is the aluminum muon stopping target. The stopping target is responsible for the energy loss and capture of the muons to be studied and provides the material in which the muon to electron conversion can emerge by interactions with the target nuclei. In the interplay with the muon beam, the magnetic field and the active detector components such as the straw tube tracker, the muon stopping target significantly affects the achievable sensitivity of the overall Mu2e experiment. We present preliminary results of computational simulation studies carried out to optimize the performance of the muon stopping target.

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The Mu2e experiment being constructed at Fermilab will probe for the coherent neutrino-less conversion of muons into electrons in the field of an atomic nucleus. Due to the tiny neutrino masses, this charged lepton flavor violating (CLFV) process is extremely suppressed in the Standard Model (SM). The predicted SM rates are of order $\leq 10^{-50}$, which is below any experimental sensitivity at the present time or in the foreseeable future. However, many extensions of the SM predict sizable enhanced CLFV rates, for example, Supersymmetry, Grand Unified Theories and models predicting heavy neutrinos, lepto-quarks, little Higgs or extra spacetime dimensions. See Reference [1] for a review. Any observation of the neutrino-less $\mu^- \to e^-$ conversion would be an unambiguous sign of new physics. The Mu2e experiment is designed to have a discovery sensitivity of five standard deviations or better for all conversion rates greater than about 3×10^{-16}, which is an improvement of four orders of magnitude compared to previous experiments searching for $\mu^- \to e^-$ conversions [2]. This sensitivity enables Mu2e to probe for physics beyond the SM on effective mass scales up to the order of 10^4 TeV [3], which is beyond the reach of the direct new physics searches accessible by present or future collider experiments operated at the highest accelerator energies.

An essential component of the Mu2e experiment is the muon stopping target. The muon stopping target is made out of aluminum and placed in the detector solenoid to cause the energy loss and the stopping of muons from the low momentum muon beam. Stopped muons are captured and form muonic atoms with the nuclei of the aluminum target. The interactions with the target nuclei enable the direct neutrino-less $\mu^- \to e^-$ conversion to emerge within the stopping target. In the interplay with the muon beam, the magnetic field and the active detector components such as the straw tube tracker, the physical configuration of the muon stopping target directly affects the achievable sensitivity of the overall Mu2e experiment. Even small changes to the target configuration can significantly increase the performance of the Mu2e experiment. To fully exploit potential improvements in sensitivity to the neutrino-less $\mu^- \to e^-$ conversion, in-depth computational simulation studies are performed to optimize the performance of the muon stopping target with respect to the Mu2e physics observables.

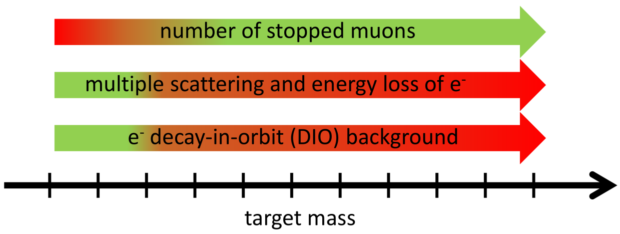

Figure 1: Illustration of the first order effects related to the mass of the Mu2e muon stopping target.

In the optimization of the muon stopping target, several competing effects need to be considered. Important first order effects that directly depend on the mass of the stopping target are illustrated in Figure 1. First, the mass of the stopping target defines the scale of the material that the low momentum muons of the beam need to traverse. In general, the higher the target mass the more muons can come to rest within the physical volume of the stopping target. Increasing the number of stopped muons effectively increases the luminosity and the probability for the conversion process to emerge. However, increasing the target mass has several adverse effects. The higher the target mass the larger is the amount of material that electrons originating from the decay of stopped muons need to traverse to reach the tracking detector. More material increases the effects of multiple Coulomb scattering and energy loss of the outgoing electrons, and this degrades the achievable resolution of the electron momentum and energy reconstruction by the straw tube tracker and the electromagnetic calorimeter. The target mass also directly determines the scale of the dominant background which are electrons that originate from the ordinary weak decay of bound muons decaying in orbit (DIO electrons) of the target nuclei. Further first and higher order effects are the matter distribution and geometry of the stopping target, the position of the stopping target relative to the tracker entrance and within the graded magnetic field, that acts as a magnetic bottle, and more effects such as on other irreducible background sources e.g. electrons originating from radiative pion captures.

Due to the complexity caused by the various different physics processes, the simulation and optimization studies of the Mu2e muon stopping target require to explore a high-dimensional configuration space. The studies are performed by realistic GEANT4 simulations, which account for the full Mu2e instrumentation and the expected experimental conditions. As part of the optimization studies a tool has been developed to estimate the Mu2e performance accounting for all experimental conditions and the dominant background sources. The tool is used to optimize the performance of different stopping target configurations and to evaluate the expected sensitivities to the Mu2e physics observables, for example, the expected single-event-sensitivity (SES) or the expected upper limit on the branching fraction of the $\mu^- \to e^-$ conversion. The optimization studies follow two main objectives. First, the baseline design of the muon stopping target constructed from aluminum foils is optimized. Second, the potential of alternative stopping target materials and configurations is explored. The status of these studies are briefly summarized below.

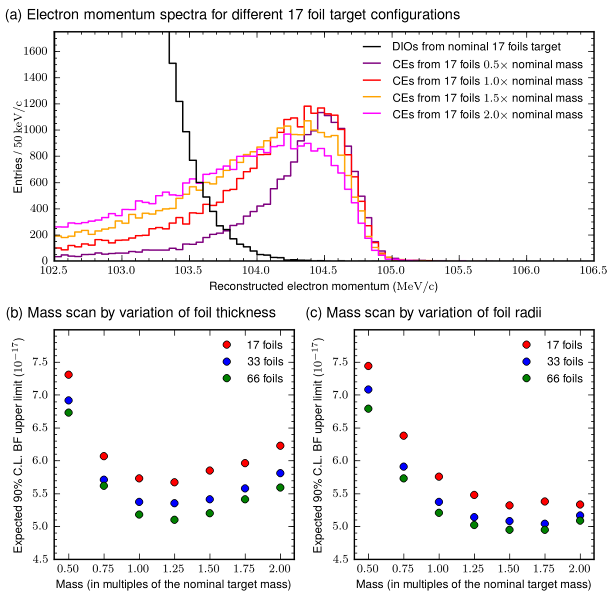

Figure 2: Examples of simulation results for reconstructed electron momentum shapes and expected branching fraction upper limits for different Mu2e stopping target configurations using an aluminum foil design.

The original baseline design of the Mu2e experiment is a tapered muon stopping target composed of 17 aluminum foils of 200 μm thickness with average radii of 75 mm that are equidistantly spaced by 5 cm [4]. The stopping target has a length of 80 cm and is located about 2.2 m from the entrance of the tracking detector. Each foil of the stopping target is supported by three tungsten wires that are connected to structures in the inner detector solenoid. Numerous simulations of variations to the baseline design of the stopping target have been performed. The variations include changes in the number of foils, foil thickness, foil radii, spacing and location within the magnetic field, and further modifications. Examples of results of simulations performed for the nominal 17 foil stopping target and variations of the number of foils and the target mass are shown in Figures 2a), b) and c). Figure 2a) illustrates the effect of the target mass discussed above. Depending on the target mass, the reconstructed signal shapes of the $\mu^- \to e^-$ conversion, which has the physical signature of a single mono-energetic 105 MeV electron, clearly change in position, width and behavior of the low momentum tail. Figure 2b) and c) show results on the expected $\mu^- \to e^-$ branching fraction upper limit for variations of the target mass achieved by changes of the foil thickness and radii for stopping targets composed of 17, 33 and 66 foils. The simulations show a clear trend for the minimum of the branching fraction upper limit and an improvement of the performance for stopping target configurations composed of many thin foils. Stopping targets with more and thinner foils reduce the multiple Coulomb scattering of both $\mu^- \to e^-$ conversion electrons and DIO electrons which improve the signal reconstruction efficiency and reduce the expected background in the momentum signal region. By using thinner foils, the overall Mu2e performance can be increased by about 10%. These and further results of the simulation and optimization studies contributed to a change of the Mu2e baseline design to a muon stopping target composed of 34 aluminum foils with a reduced thickness of 100 μm.

The Mu2e muon stopping target simulation and optimization studies are currently ongoing and include the investigation of alternative target configurations composed of low effective densities, for example, realized by wool- and screen-like materials made out of aluminum. These alternative materials allow to even further reduce the effect of multiple Coulomb scattering of electrons and to increase the target mass to achieve more stopped muons. Compared to the foil design, these alternative target configurations show encouraging preliminary results and offer other advantages, for example, for the engineering and realization of the instrumentation.

In summary, the Mu2e muon stopping target is an essential component of the Mu2e experiment and has together with the muon beam, the magnetic field and the active detector components a direct effect on the sensitivity of the Mu2e experiment to the $\mu^- \to e^-$ conversion process. The stopping target simulation and optimization studies demonstrate ways to significantly improve the overall Mu2e performance by both modifications to the baseline foil design and using alternative target materials and configurations.

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