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Studies of the impact of magnetic field uncertainties on physics parameters of the Mu2e experiment

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The Mu2e experiment at Fermilab proposes to measure the ratio of the rate of neutrinoless coherent conversion of muons into electrons in the field of a nucleus, relative to the rate of muon capture on the nucleus. The conversion process is an example of charged lepton flavor violation. Observation of this process would provide unambiguous evidence for physics beyond the Standard Model. The design of the experiment is based on three superconducting solenoid magnets. The most important uncertainties in the magnetic field of the solenoids can arise from misalignments of the Transport Solenoid, which transfers the beam from the muon production area to the detector area and eliminates beam-originating backgrounds. In this work, the field uncertainties induced by possible misalignments and their impact on the physics parameters of the experiment are examined. The physics parameters include the muon and pion stopping rates and the scattering of beam electrons off the capture target, which determine the signal, intrinsic background and late-arriving background yields, respectively. Additionally, a possible test of the Transport Solenoid alignment with low momentum electrons is examined, as an alternative option to measure its field with conventional probes, which is technically difficult due to mechanical interference.

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1. Introduction

The Mu2e experiment [1] at Fermilab will search for a signature of charged lepton flavor violation, via the neutrinoless coherent conversion of muons into electrons in the field of a nucleus. Its observation would be a signal of New Physics. The desired single-event sensitivity of 2.87×10^{-17} implies highly demanding requirements of accuracy in the design and operation of the experiment. It is therefore important to investigate the tolerance of the experiment to instrumental uncertainties and provide specifications that the design and construction must meet.

The design of the experiment is based on three superconducting solenoid magnets. One of the most important instrumental uncertainties can arise from misalignments of the Transport Solenoid (TS), since the coils are subjected to mechanical and magnetic forces during the cooling and powering up of the solenoid. This paper reports the effect of rigid-body rotations around the X and Z axes. We study these displacements because they are possibly the most dangerous; unlike random misalignments, which tend to cancel as particles move down the beam axis, these rigid body displacements can be additive, and potentially producing significant effects. We examined rotations of the order of $\sim 0.1^{\circ}$, which we regard as realistic, and $\sim 1^{\circ}$, which we believe to be unreasonably large, and simulated the effect on muon and pion stopping rates on the target and on the beam electron background. We also studied the effects on a proposed cross-check of direct field measurements using low-momentum electrons. Misalignments of the TS are simulated using standard magnetic field calculation tools. Particle transport is simulated using the Mu2e Offline software, which includes GEANT4 [2].

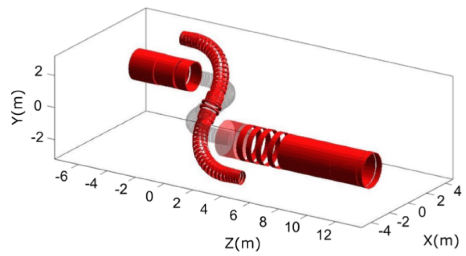

Figure 1: Rotation of TS with respect to +Z axis. The displayed effect is highly exaggerated for clarity.

2. Muon and pion stopping rate studies

TS misalignments can affect the space and time distributions of the particles arriving at the stopping target, thus changing the electron yields from muon capture (producing either signal or *decay in flight* background) and pion absorption (producing *radiative capture* background). Table 1 shows the muon (R_{μ}) and pion (R_{π}) stopping rates for the default and the rotated maps. The rate is the number of captured particles in the stopping target divided by the number of protons hitting the production target. Table 1 also shows the fractional yield difference for all the rotated maps, for both μ^{-} ($\delta N_{\mu}/N_{\mu}^{(0)}$) and π^{-} ($\delta N_{\pi}/N_{\pi}^{(0)}$). This number is the relative difference of the rates with rotated and default fields, and evaluates how much the rates scale in case of misalignments. The effect of realistic variations ($\sim 0.1^{\circ}$) on the muon and pion stopping rates is only on the normalization factor: the fractional yield difference with respect to the default field is of the order of $\sim 2\%$.

	$R_\mu(\times 10^{-3})$	$R_\pi(\times 10^{-7})$	$\delta N_\mu/N_\mu^{(0)}(\%)$	$\delta N_\pi/N_\pi^{(0)}(\%)$	$N_{bkg}(\times 10^{-5})$
DEFAULT (OLD DESIGN)	1.86 ± 0.04	6.22 ± 0.08			13
DEFAULT (NEW DESIGN)	1.83 ± 0.04	6.25 ± 0.08			19
NEW DESIGN 0.15° wrt $-Z$ TSu, 0.15° wrt $-Z$ TSd	1.85 ± 0.04	6.10 ± 0.08	-1.04 ± 3.33	-3.42 ± 0.95	14
NEW DESIGN 0.50° wrt $-Z$ TSu, 0.50° wrt $-Z$ TSd	1.78 ± 0.04	6.09 ± 0.08	3.16 ± 3.22	-3.06 ± 0.95	17
OLD DESIGN 0.1° wrt $+X$ TSu, 0.1° wrt $-X$ TSd	1.87 ± 0.04	6.02 ± 0.08	-0.32 ± 3.29	-0.80 ± 0.90	27
OLD DESIGN 0.1° wrt $-X$ TSu, 0.1° wrt $+X$ TSd	1.81 ± 0.04	6.29 ± 0.08	2.52 ± 3.22	0.55 ± 0.90	27
OLD DESIGN 0.1° wrt $+X$ TSu, 0.1° wrt $+X$ TSd	1.92 ± 0.04	6.30 ± 0.08	-3.17 ± 3.36	-1.63 ± 0.91	28
OLD DESIGN 0.1° wrt $-X$ TSu, 0.1° wrt $-X$ TSd	1.81 ± 0.04	5.82 ± 0.08	2.31 ± 3.22	5.60 ± 0.86	17
OLD DESIGN 1° wrt $+X$ TSu, 1° wrt $-X$ TSd	1.77 ± 0.04	6.95 ± 0.10	4.73 ± 3.16	-5.16 ± 0.93	0
OLD DESIGN 1° wrt $-X$ TSu, 1° wrt $+X$ TSd	1.47 ± 0.04	3.53 ± 0.05	21.21 ± 2.75	25.33 ± 0.73	180
OLD DESIGN 1° wrt $+X$ TSu, 1° wrt $+X$ TSd	1.47 ± 0.04	4.79 ± 0.07	20.94 ± 2.76	32.55 ± 0.68	2
OLD DESIGN 1° wrt $-X$ TSu, 1° wrt $-X$ TSd	1.02 ± 0.03	2.61 ± 0.05	45.22 ± 2.13	44.11 ± 5.93	42

Table 1: Stopping rates and fractional yield differences (in percentage) for μ^- and π^- and estimates of the beam-electron induced background yield for various field configurations, including TS misalignments. Two different geometry designs of the coils have been used (old and new designs [4]).

3. High momentum electron background studies

We used varied field maps to estimate the background due to beam flash electrons.These electrons can be produced either from pion decays in the production target or, predominantly, from decays and scattering of particles in the Mu2e beam transport line. If these electrons enter the Detector Solenoid and scatter to large angle off the stopping target, they can mimic the conversion electrons, thus representing direct background. The last column of Table 1 shows the background estimates for different field configurations. A detailed description of the calculation is presented in Ref. [4]. The background yields assuming the 0.1° rotations (more realistic misalignments, i.e. more likely to happen) cluster around 2.5×10^{-4} with a dispersion of about 1.2×10^{-4}. Taking conservatively this number as an average estimate of the background in account of misalignments, the final estimation is $(2.5\pm1.2)\times10^{-4}$ or $<5\times10^{-4}$ at 90% C.L.

4. Tests of the Transport Solenoid field with low momentum electrons

Since the TS field uncertainties can potentially affect the physics parameters of the experiment and it is mechanically difficult to measure this field, we must test the TS performance prior to data-taking. An effective test can be done using a narrow beam of electrons emitted by a low-energy β source (^{90}Sr/^{90}Y) located in the Production Solenoid (PS). Such electrons spiral around the field lines with a small pitch and small Larmor radius and thus approximately trace the field lines. Using a detector with reasonable resolution for low-momentum e^-, such as a fiber tracker [3], the electrons can be detected at various positions along the transport line and provide information about TS misalignments.

We have performed simulations with varied field maps, which trace the electrons generated by a ^{90}Sr/^{90}Y point source and save their position along TS. The requirements for the test are a detector spatial resolution of $\sim 300\ \mu$m and a pressure of 1 Torr. Fig. 2 shows the overall shifts of the electron hit distributions that result from a 0.50° TS rotation about the $-$Z axis. We report the mean and its uncertainty ($RMS/\sqrt{N}$, where N is the number of electrons hitting the detector) of the X and Y distributions in the bottom plots of Fig. 2. If TS is misaligned, the TS collimators may cut some electrons, thus N gets lower resulting in a bigger mean uncertainty. The distance between the mean values tell us that this test resolves misalignments down to the level of $\sim 0.1°$.

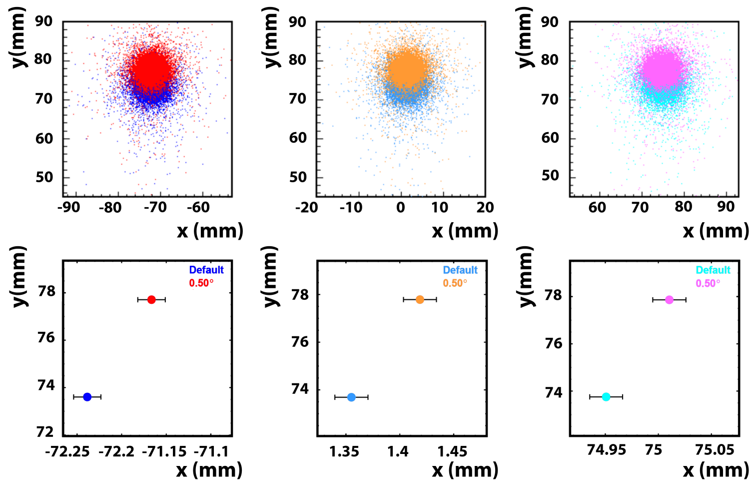

Figure 2: Upper plots: detected electrons beam profile for 3 locations of the source in the XY plane near the production target: -50 mm (left column), 0 mm (central column) and $+50$ mm (right column) from the PS geometric axis. Scatter points simulated with a misaligned field (0.50° rotation of TS about the $-Z$ axis) are drawn on top of scatter points simulated with the design field. Lower plots: Mean values with their uncertainites for the electron hit distributions of the upper plots. Corresponding maps have the same color.

5. Summary

The potentially dangerous rigid-body misalignments studied in this work were found to have acceptably small effects on the experiment up to a maximum coil displacement of 10 mm. Beam electron background was estimated to be $(2.5 \pm 1.2) \times 10^{-4}$ or $< 5 \times 10^{-4}$ at 90% C.L., i.e. it is one of the minor backgrounds of the experiment. Physics parameters, such as beam electron background and stopping rates affecting signal and background yields, are barely sensitive to realistic TS misalignments of $\sim 0.1°$. The β source test was found to be sensitive to misalignments of $\sim 0.1°$, provided that a reasonably good resolution detector (~ 300 μm) and a mild vacuum (~ 1 Torr) are used.

References

[1] Mu2e Collaboration, *Mu2e Technical Design Report*, arXiv:1501.05241.

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[4] F. Bradascio, *Studies of the Impact of Magnetic Field Uncertainties on Physics Parameters of the Mu2e Experiment*, FERMILAB-MASTERS-2016-04.