FERMILAB-CONF-09-451-E

The Mu2e Experiment At Fermilab

D. Glenzinski

Fermilab (P.O. Box 500, Batavia, IL 60510)

Abstract. The physics motivations, target sensitivity, and status of the Mu2e experiment at Fermilab are described.

Keywords: muon-to-electron conversion, CLFV decays
PACS: 13.35.Bv, 12.15.Ff

INTRODUCTION

It is expected that in the next decade discoveries at colliders will help illuminate more fully the particle content of whatever New Physics (NP) model best describes Mother Nature. To get a more thorough understanding of the underlying dynamics responsible for the New Physics requires a plethora of measurements the colliders can't do. These include determining the parameters of the PMNS matrix, probing the parameters of the CKM matrix, searching for evidence of mixing in the charged lepton sector (charged lepton flavor violation – CLFV), searches for baryon number violating processes, and direct searches for dark matter candidates. The recently proposed Mu2e experiment at Fermilab [1] is a search for the CLFV process $\mu^- N \rightarrow e^- N$, which is the coherent conversion of a muon into an electron in the vicinity of a nucleus. Strictly speaking this process is forbidden in the Standard Model (SM). Once neutrino masses are included, the process is allowed but effectively still absent since the rate is proportional to $(\Delta m^2_{ij}/M^2_W)^2$, where Δm^2_{ij} is the mass difference squared between *ith* and *jth* neutrino mass eigenstates, and M_W is the mass of the W-boson. For example, the predicted rates[†] for the $\mu^- N \rightarrow e^- N$ and $\mu^+ \rightarrow e^+ \gamma$ CLFV processes are less than 10^{-50} each [2]. This makes these processes a very theoretically clean place to search for NP effects. In many NP models that include a description of neutrino mass, the rates for these processes are enormously enhanced so that they occur at a level to which next generation experiments will have sensitivity.

NEW PHYSICS SENSITIVITY

There are a variety of CLFV experiments with sensitivities approaching theoretically interesting regions. These include CLFV tau lepton, muon, kaon, and b-meson decays. Among these the $\mu^- N \rightarrow e^- N$ process has sensitivity to the broadest array of NP models. Like the $\mu^+ \rightarrow e^+ \gamma$, $\mu^+ \rightarrow e^+ e^- e^+$, or $\tau^+ \rightarrow \mu^+ \gamma$ processes, $\mu^- N \rightarrow e^- N$ is sensitive to NP contributions via loops, such as those expected in Supersymmetry via slepton mixing, induced in sea-saw models of Heavy Neutrinos, and present in two Higgs doublet models. In addition, the $\mu^- N \rightarrow e^- N$ process is also sensitive to NP contributions via contact interactions, such as those expected in Compositeness, Leptoquark, and GUT models with additional gauge bosons and/or anomalous couplings [2]. The above models predict rates as large as 10^{-15} in regions of phase space that overlap with LHC discovery sensitivities. For Phase-I the target discovery sensitivity on the rate of the $\mu^- N \rightarrow e^- N$ process, $R_{\mu e}$, is less than 10^{-16} and offers the Mu2e experiment great discovery potential over a wide array of New Physics models and enables it to probe mass scales as large at 10^4 TeV, well beyond what will be explored at the LHC.

The ratio of rates among various CLFV processes is model dependent and can differ by orders of magnitude. Measuring the rates of several CLFV processes will be important in elucidating the details of the underlying NP model.

[†] The "rates" reported for these processes are each normalized to a different process. The decay rate for $\mu^+ \rightarrow e^+ \gamma$ is normalized to standard Michel decays, while the decay rate for $\mu^- N \rightarrow e^- N$ is normalized to ordinary muon captures.

THE EXPERIMENT

At Fermilab there is an anticipated two phase program for Mu2e. The Phase-I Mu2e experiment will use Booster cycles left open from Nova to reach a single-event-sensitivity of 2×10^{-17}, about four orders of magnitude better than the current world's best [3]. The Phase-II Mu2e experiment would use spare protons from Project-X to improve the sensitivity by about another factor of ten. In this talk I discuss only the Phase-I proposal, which is largely based on the work of Ref. [4].

The experiment starts with a beam of low momentum (<60 MeV/c) muons produced via upstream charged pion decays. The muons are stopped in the detector volume in a high Z target. The stopped muons are trapped in orbit around the target nucleus with a characteristic decay time, τ_μ^N. The $\mu^- N \rightarrow e^- N$ process is coherent, leaving the nucleus in tact, and thus yields a single mono-energetic electron in the final state. The energy of the electron is equal to the muon mass less the recoil energy of the nucleus less the binding energy of the muonic atom. Good choices of stopping target material have long τ_μ^N and small binding energies so that the energy of the electron is $\sim m_\mu$. The Phase-I Mu2e experiment plans to use an aluminum target with τ_μ^N=864 ns and E_e=104.96 MeV [5]. The long decay time in aluminum is exploited to suppress prompt backgrounds by defining a signal window that is delayed relative to the arrival of the muon beam at the stopping target. The large energy of the signal electrons is important for suppressing the intrinsic backgrounds discussed in the next section since they predominantly yield electrons of lower energy.

Backgrounds

For 10^{18} stopped muons delivered in 2×10^7 seconds of beam time the total background is estimated to be less than one event. The contributions are summarized in Table 1 and fall into three main categories, Intrinsic, Late Arriving, and Miscellaneous.

Intrinsic: When a muon is stopped by a nucleus it does one of two things: decays in orbit, or gets captured by the nucleus. Each of these processes has the potential of generating an electron that mimics the signal process. Since these backgrounds scale with the number of stopped muons in the same way the signal does they are labeled Intrinsic backgrounds.

The muons will decay in orbit (DIO) 39% of the time for an aluminum stopping target [6]. The resulting electron energy spectrum is dominated by the Michel spectrum with a sharp fall-off near 53 MeV. However, the decay electron can occasionally recoil off of the nucleus so that there is a long tail out to the kinematic endpoint of 104.96 MeV. The spectrum is falling very rapidly as it approaches the endpoint, roughly as E^{-5}. The background contribution from DIO electrons is driven then by the spectrometer resolution. The spectrometer in the Mu2e proposal has a target resolution of <1 MeV at FWHM for 105 MeV electrons.

The muons will be captured on the nucleus 61% of the time for an aluminum stopping target [7]. The ordinary muon capture process, $\mu^- N_Z \rightarrow \nu N_{Z-1}$, does not produce a source of background electrons. However, about one in 10^5 captures are radiative (RMC) and produce a photon $\mu^- N_Z \rightarrow \nu N_{Z-1} + \gamma$. In aluminum the photon energy has a kinematic endpoint of about 102 MeV. The photon can asymmetrically pair produce in the target material to produce a background electron.

The Intrinsic backgrounds are dominated by the DIO contribution, which accounts for about 55% of the total background.

Late Arriving: Backgrounds arising from interactions that occur at the production target are overwhelmingly prompt and arrive at the stopping target in time with the muon beam. These backgrounds are eliminated by only accepting electrons appearing 700 ns after the main beam pulse. However, out-of-time protons impinging on the production target will produce background electrons that fall into this delayed signal-timing window. To suppress these backgrounds it's necessary to minimize the ratio of out-of-time to in-time protons impinging on the production target. An extinction ratio of 10^{-9} is required to achieve the background levels listed in Table 1.

The largest contribution to the Late Arriving backgrounds comes from pion capture on the nucleus. Like the RMC process, the radiative pion capture (RPC) process produces a photon that can pair produce to yield a background electron. The energy spectrum for the RPC photons extends up to 140 MeV, well beyond most other backgrounds. This can be used to provide an *in situ* cross check of this background contribution. Another important contribution to the Late Arriving backgrounds comes from muon decays in flight in which the electron scatters into the spectrometer acceptance due to interactions in the stopping target material. Electrons, mostly from upstream π^0 decays, can also scatter in the target to produce background.

The Late Arriving backgrounds all scale linearly with the extinction ratio and taken together account for about 40% of the total background.

Miscellaneous: The remaining background sources are dominated by contributions from cosmic rays. Cosmic ray muons can produce background electrons either by decay or by interactions in the material. A

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.225
	Radiative μ Capture	<0.002
Late Arriving	Radiative π Capture	0.072
	Beam Electrons	0.036
	μ Decay in Flight	<0.063
	π Decay in Flight	<0.001
Miscellaneous	Cosmic Ray	0.016
	Long Transit	0.006
	Pat. Recognition Errors	<0.002
Total		0.42

TABLE 1. Estimated background contributions for the Phase-I Mu2e experiment. These umbers assume 10^{18} stopped muons are delivered in 2 x 10^7 seconds of run time, an inter-pulse extinction ratio of 10^{-9}, and a cosmic ray veto efficiency of 99.99%.

combination of passive and active shielding is required to suppress the cosmic ray background to sufficiently small levels. A veto efficiency of 99.99% is required to achieve the cosmic ray background estimate listed in Table 1. The cosmic ray background scales linearly with the *inefficiency* of the veto system.

Signal Acceptance

Genuine $\mu^-N \rightarrow e^-N$ events produce an isolated electron with an energy of 104.96 MeV. Energy loss and scattering in the target and dectector material result in an observed energy spectra with a mean of about 104 MeV and an estimated FWHM of 0.9 MeV. About 62% of the signal electrons have energies in the range 103.6 – 105.0 MeV, which is defined as the signal energy window. For comparison, the fraction of DIO electrons which satisfy this criteria is estimated to be about 2.5 x 10^{-18}. As mentioned above, by only accepting signal candidates after a 700 ns delay the prompt backgrounds are eliminated.

For the Phase-I Mu2e experiment the proton pulses will arrive at the production target every 1.7 μs. Candidate signal electrons will be required to fall into the timing window 0.7-1.7 . For an aluminum stopping target (τ_μ^N=864 ns) about 51% of $\mu^-N \rightarrow e^-N$ electrons will satisfy this requirement. The trigger efficiency is assumed to be 90% and detailed simulations estimate that the reconstruction efficiency for signal electrons is about 44%, dominated by the geometric acceptance of 50%. Additional requirements on the quality of the reconstructed helix and matching to hits in the calorimeter have an estimated efficiency of 72% while dramatically reducing background contributions from pattern recognition errors. The total efficiency times acceptance for signal electrons is estimated to be 8.5%. In aluminum the capture fraction is 0.61 so for 10^{18} stopped muons the single-event-sensitivity (ses) is estimated to be $(10^{18} * 0.61 * 0.085)^{-1} = 2 \text{ x } 10^{-17}$. Several NP models predict $\mu^-N \rightarrow e^-N$ rates as large as $R_{\mu e}=10^{-15}$, for which the proposed Mu2e experiment would expect to observe $R_{\mu e}$/ses = 50 signal electrons on a background of 0.42 events. It should be noted that the acceptance for the signal electrons varies weakly with reasonable variations in the range of accepted energies while the backgrounds fall very steeply with energy. For example, by narrowing the range of accepted energies it's possible to further reduce the background by about a factor of two while reducing the signal acceptance by only about 10% relative.

Beamline

The Mu2e beamline has two main components: the Production Target (PT) and the Transport Solenoid (TS). The μ^- beam originates from a π^- beam produced at the PT and decaying in the TS to $\pi^- \rightarrow \mu^- \nu$. The pions are produced by a proton beam with a kinetic energy of 8 GeV incident on a gold or tungsten target. The target is surrounded by a solenoid with a graded field that varies from 2.5 to 5.0 Tesla in the direction of the incoming proton beam. The solenoid traps charged particles and passes them to the TS in the backwards direction, opposite the proton beam. The solenoid at the production target is about 4 meters long with a 1.5 meter bore diameter. The TS is an S-shaped solenoid with collimators to momentum and sign select the secondary beam. The TS has an axial length of 13 meters and a 0.5 meter bore diameter. The field is graded and decreases from 2.5 Tesla near the production target to 2.0 Tesla near the Mu2e detector. The S-shape eliminates a line-of-sight between the PT and the detector to reduce background, rate, and heat load at the detector.

Using Booster cycles left unused by the neutrino program and the Debuncher and Accumulator to stack and slow extract the protons, the Phase-I Mu2e experiment will receive an average of about $2 \text{x} 10^{13}$ protons/s in micro-bunches of about 3-6 x 10^7 protons each with a bunch spacing of 1.7 μs. Several schemes are being explored with duty factors in the range of 50-90%. The number of stopped muons per proton on target is estimated to be 0.0025 with an uncertainty of a factor of two dominated by modeling uncertainties in the π^- production at the PT. This modeling is in the process of being tuned to recent data [8].

Detector

The Mu2e detector has three main components, the stopping target, the spectrometer, and the calorimeter.

The stopping target is composed of 17 aluminum foils each 200 μm thick with radii that taper from 10.0 to 6.5 cm in the direction of the incoming muon beam. The tapering radii reduce the number of scatters for a signal electron originating in one of the upstream foils. About half the incoming muons will stop in the foils. Down stream from the stopping target is a straw-tube tracking detector immersed in a uniform 1.0 Tesla solenoidal field. In the present design the tracker consists of 2.8k 2.4 meter long straw tubes oriented parallel with the muon beamline. The inner radius of the tracker is 38 centimeters, which allows a large flux of particles with a transverse momentum of less than 55 MeV/c to escape undisturbed into a downstream beam stop. These low momentum particles are mainly from DIO electrons, protons, neutrons, and photons knocked-out of the aluminum foils by the stopped-muons, beam electrons, and the residual muon beam. The momentum resolution of the tracker is scattering dominated and has a FWHM estimated to be 900 keV for signal electrons. The present design has a lead-tungstate calorimeter composed of 1.2k crystals. It provides a measure of the electron energy with a resolution of about 5% at 100 MeV and has a position resolution of about 1 cm. It serves as a trigger for the experiment and provides a confirmation of tracks reconstructed in the tracker.

STATUS

The Phase-I Mu2e experiment has received Stage-I approval by the Fermilab PAC and expects to receive CD-0 approval from the U.S. Department of Energy before the end of 2009. Assuming a technically limited schedule, construction will begin in early 2013 and last for three years. A 2-4 year data taking run would follow. The total cost of the project is estimated to be about 200M USD, fully loaded, escalated, and including contingencies.

At present, a broad R&D program is underway to re-optimize the design of the experiment and to demonstrate the feasibility of the most technically challenging parts of the proposal. More information about the Mu2e experiment can be found at http://mu2e.fnal.gov/ on the web.

CONCLUSIONS

The Phase-I Mu2e experiment is a proposed experiment at Fermilab that could begin taking data as early as 2016. It aims to search for the charged lepton flavor violating process $\mu^- N \rightarrow e^- N$ with a single-event-sensitivity of about 2×10^{-17}, an improvement over the current world's best result by four orders of magnitude. While this process occurs in the Standard Model with rates too small to ever be observed ($R_{\mu e} < 10^{-50}$), a wide variety of New Physics models predict rates to which Mu2e will have discovery sensitivity ($R_{\mu e} \sim 10^{-16}$-10^{-15}). Assuming 2×10^{18} stopped muons are delivered to the experiment in 2×10^{7} seconds of run time the Phase-1 Mu2e experiment would expect to observe 50 signal events for $R_{\mu e} = 10^{-15}$ on a background of less than 0.5 events. To achieve this background requires a momentum resolution with FWHM of <1 MeV for 105 MeV electrons, an inter-pulse beam extinction of 10^{-9}, and a cosmic ray veto efficiency of 99.99%. A broad R&D program is underway to address the technical feasibility of meeting these challenging goals. In addition, a Phase-II experiment is envisioned using the increased beam power available with Project-X to improve the sensitivity by another order of magnitude.

ACKNOWLEDGMENTS

The author would like to congratulate and thank the organizers of NuFact09 for a very nice and informative conference.

REFERENCES

1. R. M. Carey, et al. (Mu2e Collaboration), Fermilab Proposal 0973 (2008).
2. See for example, Y. Kuno and Y. Okada, *Rev. Mod. Phys*. 73, 151 (2001) or M. Raidal et al., *Eur. Phys. J* C57, 13 (2008).
3. C. Dohman et al. (SINDRUM-II Collaboration), *Phys. Lett. B* 317, 631 (1993).
4. RSVP Proposal, available at http://meco.ps.uci.edu/old/ (1999).
5. Bergbusch et al., *Phys. Rev. C* 59, 2853 (1999).
6. The DIO fraction is $f_{DIO}=(1-f_{OMC})$, where f_{OMC} is the ordinary muon capture fraction taken from Ref. [7].
7. T. Suzuki et al., *Phys. Rev. C* 35, 2212 (1977).
8. HARP Collaboration, arXiv:0909.0337 [hep-ex] (2009).