The Mu2e Experiment at Fermilab

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Elsevier use only: Received date here; revised date here; accepted date here

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Abstract

The Mu2e experiment endeavors to search for the coherent decay of a muon to an electron in the Coulomb field of a nucleus with an expected sensitivity of $R_{\mu e} < 6 \times 10^{-17}$, at the 90% confidence level. This process is sensitive to many new physics scenarios beyond the standard model. Mu2e has received strong support from Fermilab and the US funding agencies, and is projected to begin data taking in 2017.

Mu2e Experiment Fermilab

1. Introduction

In the process of muon to electron conversion the initial state is a muonic atom that transitions to a 2-body state consisting of a mono-energetic electron recoiling against the intact atomic nucleus. There are no neutrinos in the final state. The recoiling nucleus is not observed, leaving an observed final state of a high energy mono-energetic electron, with an energy of the muon rest mass minus corrections for the nuclear recoil and the K-shell binding energy of the muon. The result of the experiment will be expressed by the ratio,

$$R_{\mu e} = \Gamma[\mu^- N(A,Z) \rightarrow e^- N(A,Z)] / \Gamma[\mu^- N(A,Z) \rightarrow \nu_\mu N(A,Z-1)]$$

where N(A,Z) denotes a nucleus with mass number A and atomic number Z. The numerator is the rate for the conversion process and the denominator is the rate for normal muon capture on the same nucleus. In the standard model, including finite neutrino masses, $R_{\mu e}$ is non-zero but is much smaller (10^{-54} !) than the reach of present or imagined experiments. This leaves a large window of opportunity for the observation of physics beyond the standard model and most new physics scenarios predict that this process will occur at a level far above the standard model rate. In particular, scenarios that predict that SUSY is within the reach of the LHC also predict $R_{\mu e} \sim 10^{-15}$, a rate for which Mu2e would observe, about 40 events on a background of fewer than 0.5 events after 2 years of running.

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The process of muon to electron conversion is just one example in the broader field of Charged Lepton Flavor Violation (CLFV). An excellent review of CLFV and the flavor physics of leptons can be found in reference [1]. Two classes of diagrams can contribute to conversion. The first class includes magnetic moment loop diagrams with a photon exchanged between the loop and the nucleus; these diagrams can proceed with many different sorts of particles in the loop, including, but not limited to, SUSY particles, heavy neutrinos and a second Higgs Doublet. This class of diagrams also produces non-zero rates for the process $\mu \rightarrow e\gamma$. The second class includes both contact terms that parameterize compositeness and the exchange of a new heavy particle, perhaps a lepto-quark or a Z^0. This class of diagrams does not give rise to the process $\mu \rightarrow e\gamma$. The bottom line is that, through these processes, Mu2e has sensitivity to new-physics mass scales up to about 10,000 TeV/c^2, far beyond the scales that will be accessible to direct observation at the LHC.

2. Experimental Technique

The Mu2e apparatus is described in detail in the Mu2e proposal [2]. The concept of the Mu2e experiment is based on the MECO [3] experiment, which, in turn, was motivated by the MELC experiment. A beam of low momentum negative muons is stopped on a set of thin Al target foils and muons are captured into the Al atomic inner K-shell, forming a muonic atom. The Bohr radius of the K-shell of muonic Al is about 20 fm and nuclear radius of Al is about 4 fm, which provides a large overlap between the muon wave-function and that of the nucleus.

The two major decay modes of muonic Al are muon decay in orbit (DIO), which occurs about 40% of the time, and normal muon capture (NMC) on the nucleus, which occurs about 60% of the time. DIO produces electrons with a continuous energy spectrum, which is essentially the Michel decay spectrum, modified by the orbital motion of the muon and the form-factor and recoil of the nucleus. In an extreme configuration, both neutrinos are at rest and the electron recoils against the intact Al nucleus. This is the configuration in which the electron has the maximum energy in the lab frame, up to the conversion signal region (105 MeV) for muonic Al. The energy spectrum falls to this end point roughly as $(E-E_{max})^5$. In contrast NMC produces, protons, neutrons and photons which drive the hit activity in the detector but produce re-constructible high momentum electrons only via secondary processes. The μ to e conversion produces a mono-energetic electron with an energy, ignoring neutrino masses, equal to that of the endpoint of the continuous spectrum from DIO (105 MeV for Al). In summary, the technique is to carefully measure the momentum spectrum from electrons emitted from the target foils and to search for an excess at the endpoint.

The muon beam that drives Mu2e is produced by 8 GeV protons from the Fermilab proton source. In order to mitigate construction costs, Mu2e will reuse many parts of the existing 8-GeV complex following the completion of Tevatron collider running.

A bunch of protons with a full width of about 100 ns is extracted onto a thin cylindrical gold target located in the middle of a high field graded-field solenoid, the Production Solenoid (PS), shown in Figure 1. In the production target, p-Au interactions produce pions that are captured into helical trajectories in the field of the solenoid; these pions decay into muons that are also captured by the field of the solenoid. The relevant pion momenta are produced in the backward direction, which the graded PS magnetic field (5 Tesla at the proton-downstream end falling to about 2.2 Tesla at the proton-upstream end) drives these low momentum pions toward the experiment. The backward going muons exit the PS and enter the S-bend graded field Transport Solenoid (TS), also shown in Figure 1. The bend in the TS induces a dipole term which allows, by appropriate placement of absorbers and collimators, the sign selection of the muon beam and the stopping of any anti-protons accompanying the muon beam. The TS transmits the μ^- beam into the Detector Solenoid (DS) where it encounters the foils that comprise the stopping target where about 30% of the muons are stopped.

Downstream of the stopping target is a tracking system and downstream of that is an electromagnetic calorimeter (ECal). In both of these devices, the inner annular region to a radius of about 38 cm is empty. This allows those muons that do not stop in the stopping target to pass through the detector to a beam dump. The DS magnetic field is also graded to form a magnetic mirror that reflects half of the conversion electrons back toward the tracker. In the volume occupied by the tracker and ECal, the DS magnetic field is highly uniform at 1.0 Telsa. When a conversion or DIO electron is emitted from the stopping target, it travels in a helical trajectory and, if it has sufficient transverse momentum, (p_T) its trajectory will be measured by the tracker. Only those electrons with p_T > 55 MeV/c will reach the tracker and only those with p_T > 80 MeV/c will intersect enough of the tracker to form a reconstructible track.

Because almost all tracks from DIO have $p_T < \frac{1}{2} m_\mu$ they will never reach the tracker. This is the key to making a measurement of $R_{\mu e}$ with a sensitivity of $O(10^{-17})$: the apparatus is only sensitive to the tail of the DIO energy distribution. High momentum electrons that pass through the tracker will eventually intersect the ECal, where they will provide an independent energy measurement and a position measurement, both of which can be used to confirm track candidates. The μ^- beam that reaches the stopping target is contaminated by many e^- and some π^-, both of which can produce false signals when they interact with the stopping targets. These backgrounds occur promptly. To defeat them, the experiment exploits the lifetime of muonic Al, about 864 ns: Mu2e waits for 700 ns following the arrival of the proton bunch at the production target and then begins counting electrons that are emitted from the Al foils of the stopping target. By this time, all of the beam from the production target has passed through the stopping target and the prompt backgrounds have died away. After a total of 1694 ns the cycle is repeated. It is also critical that few protons arrive at the production target between the bunches. If protons arrive out of time, they can produce e^- and π^- that arrive at the stopping target within the live gate. To reduce this background Mu2e requires a beam extinction of 10^{-9}; that is, for every 10^9 protons that arrive at the production target within the bunch, there should be no more than one proton (on average) between bunches. The dominant background sources are expected to be poorly measured DIO electrons (0.225 events), radiative π^- capture on the target foils (0.063‡), scattered beam electrons (0.036‡), μ decay in flight (0.036 ‡), cosmic ray induced (0.016), and six other processes (0.039) for a total estimated background of 0.415 events.

These numbers are quoted for a nominal 2 year run. The processes marked ‡ scale with extinction and are reported for a beam extinction of 10^{-9}. The critical path for the Mu2e apparatus is the design and construction of the solenoid system. If all resources are made available as required, the solenoids could be installed by 2016 with data taking beginning in 2017. The total project cost (in US DOE accounting) is $200M.

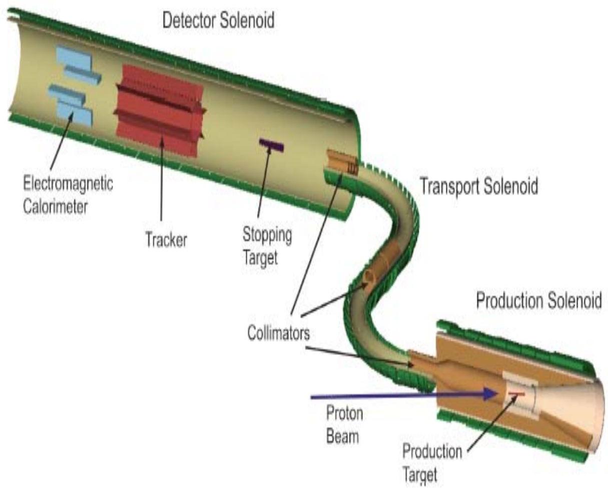

FIGURE 1. Diagram of the Mu2e muon beam-line and detector. The proton beam enters from the left. A back-ward produced pions decay to muons that are captured by the Production Solenoid and transported through the S-bend Transport Solenoid to the stopping targets. Conversion electrons, produced in the stopping target are captured by the magnetic field in the Detector Solenoid and transported through the Tracker, which makes a precision measurement of the momentum. The conversion electrons then strike the Electromagnetic Calorimeter.

3. Summary

The goal of the Mu2e experiment is to observe m to e conversion or to set an upper limit of $R_{\mu e} < 6 \times 10^{-17}$ at the 90% CL and to do so in two years of running. This is 10,000 times better than the previous best limit [4] and mass scales up to O(10,000 TeV) are within reach. For $R_{\mu e} = 10^{-15}$ the detector would see about 40 events on a background of less than 0.5 events. The experiment has been strongly endorsed by Fermilab and the US funding agencies, Visit the Mu2e home page [5] to keep up to date with the experiment.

Acknowledgments

This work is supported in part by the U.S. Department of Energy, the U.S. National Science Foundation, INFN in Italy, and the U.S.-Japan Agreement in High Energy

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