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Mu2e
Letter of Interest for Snowmass 2021

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on behalf of the Mu2e Collaboration

The Mu2e experiment, based at Fermilab, will search for the coherent, neutrino-less conversion of a negative muon into an electron in the field of an aluminum nucleus. An observation would be the first evidence of Charged Lepton Flavor Violation and an unambiguous signal of physics beyond the Standard Model (BSM). Mu2e aims to improve the current limit by four orders of magnitude, reaching an unprecedented single-event sensitivity of 3×10^{-17} on the conversion rate, a 90% CL of 8×10^{-17}; and a 5σ discovery potential at 2×10^{-16}. Mu2e is sensitive to a wide range of BSM models, probing effective mass scales up to 10^4 TeV/c^2. Construction for the project is well-underway, with many components already procured, delivered and fully tested. Experiment operations are planned to begin over the next few years. Mu2e will be an indispensable piece of the global search for BSM over the upcoming decade. This letter will outline the physics motivations, design, and current status of the Mu2e experiment.

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Observation of neutrino-less muon-to-electron conversion would provide unambiguous evidence for physics beyond the Standard Model (BSM). This conversion is an example of Charged Lepton Flavor Violation (CLFV). While neutrino oscillations are definite proof that lepton flavor is not conserved, flavor violation in the charged-lepton sector has never been observed. Neutrino oscillations within the Standard Model provide a mechanism for CLFV via loop lepton mixing, but the rate is extremely suppressed (e.g. $BF(\mu \to e\gamma) \approx 10^{-54}$ [1]), far below the reach of any conceivable experiment. Any detected signal is therefore an unambiguous evidence of new physics.

The Mu2e experiment [2] is seeking to measure the ratio ($R_{\mu e}$) of the rate of neutrino-less, coherent conversion of a negative muon to an electron ($\mu^- N \to e^- N$) in the field of an aluminum (Al) nucleus, relative to that of ordinary muon capture:

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(Z,A) \to e^- + N(Z,A))}{\Gamma(\mu^- + N(Z,A) \to \nu_\mu + N(Z-1,A))}. \tag{1}$$

The current best experimental limit on the conversion rate is $R_{\mu e} < 7 \times 10^{-13}$ (90% CL), set by SINDRUM-II [3]. Mu2e expects to probe four orders of magnitude beyond this limit, achieving a single-event sensitivity of 3×10^{-17} on the conversion rate, a 90% CL of 8×10^{-17}, and a 5σ discovery reach at 2×10^{-16}.

CLFV processes offer deep probes into an array of new physics [4], including super-symmetric theories [5], extended Higgs sectors, and theories invoking Extra Dimensions. Searches for CLFV are highly motivated and share connections with many areas of the global BSM program. As the charged counterpart to neutrino oscillations, CLFV measurements are very important to the physics behind the neutrino mass generation mechanism. The non-universal lepton interactions suggested by the coherent pattern of anomalies in B-meson decays are closely associated with violation of lepton flavor conservation [6]. And the same effective operators that mediate CLFV could have a flavor-conserving component that gives rise to the muon $g-2$ discrepancy, as well as to leptonic electric dipole moments. Mu2e has world-class sensitivity to a wide range of possible new physics models and will explore effective mass scales up to 10^4 TeV/c^2, well beyond what can be directly accessed at the LHC or any foreseeable future collider.

The Mu2e experiment can also provide complementary information regarding the Majorana nature of neutrinos. A search for $\mu^- \to e^+$, i.e., $\mu^- + N(Z,A) \to e^+ + N(Z-2,A)$, can be conducted in parallel to the primary search. This conversion violates both lepton number ($\Delta L = 2$) and lepton flavor conservation, and can only proceed if neutrinos are Majorana particles. The Mu2e sensitivity to $\mu^- \to e^+$ extends beyond the current best limit [7], with a $< m_{e\mu} >$ effective Majorana neutrino mass scale sensitivity down to the MeV region, surpassing the $< m_{\mu\mu} >$ sensitivity in the kaon sector which is limited to the GeV region [8].

The signals for both $\mu^- \to e^-$ and $\mu^- \to e^+$ in Al are monoenergetic electrons of energy 104.97 MeV [9] and 92.32 MeV, respectively. A major background source to the primary channel arises from $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ decays. In the Coulomb field of the nucleus, the energy spectrum of these electrons approaches the endpoint at the conversion energy. Taking into account energy loss in material and detector resolution, the tail of this component overlaps the expected signal distribution [9]. For $\mu^- \to e^+$, background from radiative muon capture dominates (($\mu^- + N(Z,A) \to \nu_\mu + N(Z-1,A) + \gamma$, $\gamma \to e^- e^+$), which has an endpoint $k_{max} = 90 \pm 1.8$ MeV [10].

Mu2e is based upon a concept proposed in [11], and is designed to overcome the limitations faced by SINDRUM-II. Mu2e uses a pulsed proton beam, devised to produce an intense secondary muon beam with a ≈ 250 ns wide "microbunch" every 1695 ns. Beam-related backgrounds can arise from pions, antiprotons, or electrons that remain in the beam when it arrives at the Stopping Target. The mean lifetime of a captured muon in an aluminum nucleus is 864 ns, so the microbunch spacing is about two muon lifetimes. A delayed "livegate" allows efficient suppression of pion induced backgrounds, while retaining a signal acceptance of about 70%: pions decay much more quickly than muons, so delaying the gate suppresses pions while retaining muons. The pulsed beam of Mu2e is therefore central to the improvement over SINDRUM-II, which used PSI's 50.1 MHz beam. If protons arrive at the production target between microbunches, then the beam-related backgrounds could arrive at the same time as the muonic atoms are decaying. Protons outside the pulse created during microbunch formation must therefore be "extinguished": the experiment requires a proton bunch extinction factor, defined as the ratio of out-of-time to in-time protons, of $< 10^{-10}$. A dipole with a time-varying B-field tuned to the microbunch period ("AC dipole") and collimators are used to suppress proton transport between successive pulses. An extinction monitor system, located proton downstream of the tungsten production target provides a direct measurement of the extinction factor.

A system of three superconducting solenoids provides efficient muon collection and transport delivering $\approx 3 \times 10^{10}\mu$/s. The three superconducting solenoid systems are the Production (PS), Transport (TS) and Detector (DS) solenoids. The PS and TS direct slow muons to the Stopping Target, located near the entrance of the DS. The PS is a high field superconducting magnet with a graded field that redirects particles from proton-nucleus interactions in the tungsten Production Target, primarily muons and pions, towards the TS. Most pions will decay to muons in the TS. In the TS, negatively charged particles with low momentum are selected via an S-shaped solenoid configuration and collimators. The Stopping Target consists of thin Al foils with an optimized geometry. Stopped muons are captured in an atomic excited state, and promptly cascade to the $1s$ state. In aluminum 61% of muons will be captured on the nucleus while 39% will decay-in-orbit.

Cosmic-rays induce a background when they interact with material in the experiment and produce an electron in the signal region. This background scales with running time. This is particularly a problem in the Stopping Target region, where a $\sim 105\,\mathrm{MeV}$ electron generated from a cosmic-ray striking the Al Stopping Target would be indistinguishable from the conversion signal. Passive shielding suppress the cosmic ray flux passing into the detector volume. An active veto detector, the Cosmic-Ray Veto (CRV), surrounds the DS and part of the TS and detects incident cosmic-ray muons. Suppressing this background to an acceptable level requires a veto efficiency of 99.99% [2]. Strict particle identification criteria at the tracker and calorimeter further suppress these backgrounds.

The momentum of the electron is measured primarily through a low-mass proportional straw tube tracker. The tracker consists of $20,736$ straws with wall thickness of 15μm, the thinnest walled proportional tube straws used in any experiment to date. The tracker is an annular cylinder and the central region is un-instrumented. This purposely blinds the detector to nearly all muonic atom backgrounds and remnant beam, vastly reducing occupancy and making the detector insensitive to particles produced in the initial proton collision and transported to the Stopping Target. With an overall geometric acceptance of about 20%, conversion electrons will leave hits in roughly 40 straws with a reconstructed momentum resolution better than 180 KeV/c.

The calorimeter, downstream of the tracker, consists of two annular disks composed of $1,348$ pure cesium iodide (CsI) crystals, each coupled to 2 silicon photomultipliers (SiPMs). The calorimeter provides redundant energy, position, and timing information. It complements the tracker in providing particle identification, background rejection, and supplies a fast trigger.

The normalization for the muon conversion rate is provided by a pair of high-resolution photon detectors, collectively known as the Stopping Target Monitor (STM), mounted ~ 34 m downstream of the Stopping Target. These detectors monitor the number of muon stops and captures via the characteristic photons emitted during the formation of a muonic atom and the associated cascade to the $1s$ level, or from emission of gamma rays emitted by secondary nuclei following nuclear capture.

Mu2e construction is nearly complete. The Mu2e beamline is essentially finished. The superconducting cable for the solenoids has been procured, and the winding for all three solenoid units is well-underway, the TS coils have already arrived at Fermilab. The tracker straws, FEE prototypes, calorimeter crystals and SiPMs, STM detectors, and CRV counters are complete. Assembly and testing of these detector components is on-going. Early-career collaborators can now make major contributions to commissioning and debugging the detector and their participation is essential to the success of the experiment. The Mu2e project will transition to installation in 2021, with detector commissioning beginning in 2022 and commissioning with beam continuing through 2023. Physics running is expected to begin in late 2023.

Mu2e is at the forefront of an active global CLFV program that will improve sensitivity in multiple channels by orders of magnitude. Complementary experiments such as COMET [12], MEG-II [13] and Mu3e [14] will all take data in the coming decade making this a very promising time to study muon-to-electron CLFV processes. Measurements in the muon-to-electron sector, where we can produce high-intensity beams, provide uniquely powerful probes while both complementing and extending searches using decays such as $\tau \to e\gamma$ or $\mu\gamma$ and processes like $H \to e\tau, \mu\tau$, or μe. Mu2e provides discovery potential over a wide range of well motivated BSM models. As an indispensable piece of the global search for new physics over the next decade, Mu2e operation should be strongly supported. Finally, we encourage support for R&D for experimental proposals that would follow Mu2e, such as Mu2e-II [15] [16] that will begin a vibrant international program.

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