A New Charged Lepton Flavor Violation Program at Fermilab

(ENIGMA: nExt geNeration experIments with hiGh intensity Muon beAms)

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The search for charged lepton flavor violation (CLFV) has been underway since the discovery of the muon. PIP-II and the Booster Upgrade at Fermilab offer a chance to improve the limits by two orders-of-magnitude and study discoveries [1, 2]. This LOI outlines a program based on a new muon facility that can provide both a high-intensity nearly continuous stopped muon beam to study CLFV in muon decay, and a pulsed muon beam using a small muon storage ring to supply a muon-to-electron conversion experiment. The complex would begin using the beam from PIP-II but be designed to increase by a further order-of-magnitude sensitivity with the Booster Upgrade. The combination would provide the world's leading facility to explore the conservation of charged lepton family number.

I. INTRODUCTION

CLFV is a promising and powerful way to search for new physics and muon CLFV has particular advantages [3]. This document calls attention to an opportunity to create a muon program that will perform the most sensitive searches in many muon channels using the Fermilab PIP-II and Booster Upgrade facilities. We outline the experiments, the two beams that are required, indicate how they could be built, and present their potential physics reach. This suggested muon facility has natural extensions: muonium-antimuonium transitions [4, 5], a possible storage ring muon EDM experiment [6], and μ spin rotation are just some of the possibilities. This LOI should not be read in isolation, but as further documentation of the promise of a new muon facility using PIP-II and a Booster Upgrade [7].

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II. EXPERIMENTS

Muon CLFV experiments fall into two general categories: decay searches ($\mu^+ \to e\gamma$ and $\mu^+ \to 3e$) and interactions with matter, usually muon-to-electron conversion ($\mu^- N \to e^- N$). The decay experiments use positive, slow μ^+ ($p < 30$ MeV/c) to rest in material and let them decay. Muon-to-electron conversion experiments use low-momentum negative μ^- instead. Because of their negative charge the μ^- can be captured in an atomic orbit and undergo a family-number violating conversion in the field of the nucleus. MEG and Mu3e at PSI are decay experiments; Mu2e at FNAL and COMET at J-PARC are conversion experiments [8–11].

III. EXPERIMENTAL REQUIREMENTS

A. Decay Experiments: $\mu \to e\gamma$ and $\mu \to 3e$

The decay experiments are currently limited by the available beam flux at PSI. The proposed High Intensity Muon Beam (HiMB) upgrade at PSI can increase the number of stopped muons to $\mathcal{O}(10^{10})$ stopped μ^+/s [12]. It would be advantageous to increase that rate. The availability of a higher beam intensity would open the option of converting the photon into an e^+e^- pair and using a magnetic spectrometer instead of a calorimeter to infer the energy of the photon from the two charged tracks in a magnetic spectrometer. A spectrometer and a conversion has two significant advantages over a calorimeter: a much better momentum resolution and knowledge of the conversion point [13, 14]. The measured e^+e^- tracks provide an estimate of the photon angle with a typical resolution of a few 10's of mrad. It is then possible to reconstruct the muon decay position by forming a vertex from the reconstructed photon with the measured positron track. In experiments like MEG the decay vertex is defined only by the crossing point of the positron track with the target, while the photon direction is inferred by extrapolating the photon conversion point from the calorimeter back to the vertex. This approach provides a very good photon angle resolution for signal events, $\mathcal{O}(5$ mrad) in MEG. Without the converter there is no handle to discriminate against background photons coming from a different point in or outside the target. Without the conversion, a normal muon decay $\mu \to e\nu\nu$ near the Michel endpoint, combined with an accidental photon, can fake signal: the photon point in the calorimeter is *assumed* to have a vertex with the detected electron, and that vertex can be anywhere in the target consistent with the electron track. With a photon conversion approach, the reconstructed e^+e^- pair gives a vertex. This extra constraint greatly reduces the accidental background. On the other hand, the converter decreases the statistical power because of the small conversion fraction (a thin converter is needed to keep multiple scattering and energy loss low); hence an increase in the beam rate is needed. In a configuration where only one conversion layer with a thickness of $0.05\ X_0$ is used, a beam rate of $\mathcal{O}(10^{12})$ is manageable and the sensitivity of MEG-II could be improved by one or even two orders of magnitude. At lower rates multiple conversion layers would be necessary, with the risk of compromising the resolution in other variables. The $\mu \to 3e$ channel needs no converter, and so in principle the experiment can use all of the statistical improvement from an increased flux.

The instrumentation and detectors for such experiments offer a number of interesting challenges. The $\mu \to 3e$ proposal at PSI already uses an innovative detector but the current plan is for $\mathcal{O}(10^{10})\mu^+$/s at the HiMB of PSI.

B. Muon To Electron Conversion Experiments

The signal for $\mu^- N \to e^- N$ is a single monoenergetic electron with energy just below the muon mass. The precise value of the energy depends on the atomic number Z.

Muons are brought to rest by energy loss in a stopping target, typically thin foils (the Mu2e experiment uses thin Al foils). The negative muons then fall into a muonic 1s state (they can enter high-order states but that is relatively rare). They can either be captured by the nucleus, decay in orbit (DIO), or undergo the signal conversion process. The experiments measure $R_{\mu e}$, the ratio of the conversion rate to the nuclear capture rate.

The monoenergetic line from conversion electrons is broadened by stochastic energy loss in the foils. This stochastic broadening then introduces a background from $\mu^- \to e^-\bar{\nu}_e\nu_\mu$. The $V - A$ decay spectrum of a free muon is distorted in the presence of a nucleus; the endpoint energy, up to negligible terms in the neutrino mass, is at the conversion energy [15]. Experimental resolution effects then mix the signal and background. This background falls as roughly $(E_{\text{conversion}} - E)^5$ near the endpoint and so small errors in the resolution can lead to significant background. Therefore the thinnest target and lowest-mass tracking with the best possible resolution are needed. Another source of background is due to the small fraction of π^- that do not decay but reach the stopping target and stop there: this background arises from radiative pion capture (RPC), $\pi^- N \to \gamma N$, followed by internal or external conversion of the outgoing photon [16]. The need to minimize this background leads to the pulsed structure of the Mu2e beam; the pulsed beam allows the experiment to wait for the pions to decay while the much longer-lived muons remain, suppressing the background (in Mu2e by $\times 10^{11}$ or more) with a much smaller loss of signal. Both the RPC and DIO backgrounds are proportional to the number of stopped muons. Another potentially significant background arises from electrons produced by cosmic rays (CR). If the CR hits the stopping target, a CR muon or neutron can produce electrons indistinguishable from signal. Unlike the

RPC and DIO backgrounds, the CR background scales with running time.

Possibly the most important change is that the experiments will want to explore higher-Z materials such as Au — the atomic number dependence of $R_{\mu e}$ can reveal the nature of any new physics [17, 18]. The experimental problem is that the lifetime of the muonic atom decreases as Z increases. The lifetime in Au is ≈ 84 ns [19], compared to 864 ns for Al. The Au lifetime is well within the beam pulse width of about 125 ns, and the resultant debris ("beam flash") from the initial proton beam makes an experiment impractical. The proposed solution is to first collect the muons in a storage ring.

IV. BEAM REQUIREMENTS

A. Decay Experiments

The decay experiments would benefit from an increase of the beam flux. In particular, the search for $\mu \to 3e$ is currently limited by the available muon stopping rate at PSI. The proposed High Intensity Muon Beam (HiMB) would achieve $\mathcal{O}(10^{10})$ stopped μ^+/s [12]. For $\mu \to e\gamma$, the resolutions of the current MEG-II detector limit the exploitable muon beam rate to 7×10^7 μ^+/s.

Decay experiments have relied on a surface muon beam [20]. Surface beams bring pions to rest and then collect decay muons from near the stopping "surface"; hence the muons are nearly monochromatic and have close to 100% polarization. Surface muons are a convenient choice for rare muon decay searches because they allow to combine high intensity with a relatively low momentum (≈ 30 MeV/c and a few percent momentum bite). Most of the muons can be stopped on a thin target, minimizing the multiple scattering of positrons and electrons and the production of background photons by positrons annihilating in flight in the target material.

An important limitation to the intensity of the surface muon beamlines at PSI comes from the relatively small thickness of the muon production target, owing to the necessity of preserving most of the proton beam to serve as a spallation neutron source. A thicker target would allow an immediate increase in the deliverable intensity, which could be further enhanced by a muon capture solenoid, as proposed for the MuSIC facility, coupled to an FFA, or in the megawatt-class as envisioned for muon colliders [21, 22].

Based on operation of the πE5 beamline at PSI we expect a future facility with ≈ 100 kW of power would suffice for a 10^{12} μ^+/s beam. The main requirement for the beam is that it be as continuous as possible to reduce combinatoric backgrounds from simultaneous muon decays. The time between proton pulses does not need to be smaller than the π lifetime of 26 ns. PIP-II is therefore more than sufficient.

B. Muon-to-Electron Conversion

Here more radical changes are needed. The combined Mu2e tripartite solenoid system [23] and beam timing (a pulese every 1695 ns) will not work for the short-lifetime, high-Z materials since the solenoid system transmits the pulsed beam with its large beam flash, and the pulsed beam is required to suppress the RPC background. One promising alternative is a fixed-field, alternating gradient synchrotron (FFA) considered for PRISM/PRIME at J-PARC [24, 25] and work for this LOI in [26]. Storing muons lets (1) any remaining pions decay, removing the RPC background, and (2) would not transmit the beam flash, allowing the experiment to probe very high Z. An FFA would allow us to phase rotate the beam to reduce the momentum spread of the muons (while spreading them out in time). If combined with technology to further slow the muon beam (e.g. an induction linac) this system has the further advantage of a better defined stopping location: if the stopping range is R, $\Delta R/R \propto p^{3.5}$ [20]. The phase rotation takes time; the system requires a compressor ring to rebunch the 1.5×10^8 protons/bunch at < 20 ns from PIP-II to $\mathcal{O}(10^{12})$ protons/bunch [27]. A significant limitation is the kicker that would inject the beam into the FFA; 1 kHZ is the maximum assumed in Ref. [25], limiting the rate of proton pulses and ultimately the number of observed muons. We expect to build the complex for PIP-II at 100 kW, but with the proposed Booster Upgrade we would increase the proton beam energy for a final beam power of $\approx$ 1MW.

V. CONCLUSION

This program provides logical, compelling, and transformative studies of charged lepton flavor violation. CLFV (or the lack of it) is a central question in flavor physics and in muon-to-electron transitions, provides unique probes into physics beyond the standard model. We believe that the Snowmass process should begin to develop and P5 should endorse both the importance of the physics and the studies necessary to make this program a reality.

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