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Perspective on cLFV with high-intensity muon beams at PSI and FNAL

Francesco Renga[a,*]

[a]*Istituto Nazionale di Fisica Nucleare, Sez. di Roma, P.le A. Moro 2, 00185 Roma (Italy)*

E-mail: francesco.renga@roma1.infn.it

In the next decade, significant upgrades to existing facilities will permit the delivery of muon beams with 100 times greater intensity than currently possible. This opens up a new perspective for the search for charged lepton flavor violation (cLFV) in the muon sector. I will briefly introduce the new facilities and present a review of the experimental ideas under study for their optimal exploitation.

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[*]Speaker

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1. Introduction

Lepton flavor violation (LFV) is a golden probe for the search of physics beyond the Standard Model (SM). Being lepton flavor conservation an accidental symmetry in the SM, its violation with rates accessible by present and near-future experiments is foreseen in several new physics models. Indeed, neutrino oscillations already provide evidence of LFV. However, the induced effects in the charged lepton sector are unobservably low in the SM, and any signal of cLFV would give unambiguous evidence of new physics.

In the muon sector, the golden channels to search for cLFV are the $\mu \to e\gamma$ and $\mu \to eee$ decays, and the conversion of muons to electrons in the Coulomb field of a nucleus, $\mu^- + N \to e^- + N$. For all these channels, the current exclusion limits are around or below one over 10^{12} standard transitions [1].

Reaching and overcoming such low exclusion limits requires muon beams with extremely high intensities, such as the ones delivered at PSI (Switzerland), FNAL (USA), and J-PARC (Japan). At PSI, continuous beams of positive muons are produced, with up to 10^8 μ/s delivered in the experimental halls, as required for the search of rare muon decays (the use of positive muons prevents their capture by the nuclei, so that purely at rest decays of free muons are obtained). At FNAL and J-PARC, pulsed beams for the muon-to-electron conversion experiments will be available soon, with more than 10^{17} stopped muons per DAQ year. In the meantime, upgrades of the existing facilities at PSI and FNAL are planned, which open new opportunities for cLFV searches, with increased rates and tailored beam specifications. I will briefly introduce these projects and discuss their impact on the design of a new generation of muon cLFV experiments.

2. HiMB at PSI and the Mu3e experiment

At PSI, muons are produced from a primary proton beam impinging on graphite targets, with the production of pions and their decay into muons. For rare muon decay searches, surface muons are used. These are muons with about 28 MeV/c momentum, produced by pions decaying at rest, approximately at the surface of the production target. Selecting these muons allows the production of high-intensity beams, with low electron and pion contamination, and a relatively small momentum byte. This monochromaticity is a critical benefit because rare decay searches require stopping muons in a very thin target, to not distort the kinematics of the outgoing decay products. The beamline with the best specifications in terms of intensity, beam purity and monochromaticity is πE5, which can deliver up to 10^8 μ/s into the experimental area, but another beamline, currently used for muon spin rotation experiments and called μE4, can reach 5×10^8 μ/s.

The High Intensity Muon Beam (HiMB) program is an upgrade of this facility, that envisages two new beamlines, the commissioning of which will start in 2027 [2]. In contrast with present beamlines, where muon transport and focusing are achieved with a mix of dipoles and quadrupoles, the two HiMB lines will be mostly made of solenoids. In combination with the newly designed target and muon capture solenoid, more than a factor 25 increase in beam intensity (compared to μE4) can be obtained. This improvement results from a 10 % increase in muon production, a factor 4 increase in muon capture, and a factor 6 increase in muon transport. More than 10^{10} μ/s are expected to be delivered to users starting in 2029.

The Mu3e experiment [3] was the main driver for the development of such new beamlines. The goal of the experiment is a search for the $\mu^+ \to e^+e^+e^-$ decay with a final branching-ratio (BR) sensitivity around 10^{-16}, 10000 times better than the current limits. The experiment was designed as a full-silicon tracker with fast scintillators for timing purposes, to cope with extremely high particle rates. A phased approach has been adopted. The Phase IA detector, composed of two double layers of silicon detectors in a 1 T solenoidal magnetic field, is currently under construction at PSI, and is expected to take data before the programmed shutdown for the HiMB commissioning in 2017. Additional silicon layers will be added in the future to improve the tracking resolution. A sketch of the full detector, which was designed to be operated with beam rates exceeding 2×10^9 μ/s, is shown in Fig. 1. The HV-MAPS technology is adopted for the silicon sensors. They are made of silicon pixels, 50 µm thick, on top of a 100 µm kapton structure, including the power and signal routing, for a total of less than 10^{-3} radiation lengths per layer. Such a light detector is necessary to achieve good resolutions for electrons and positrons with momenta below 50 MeV/c, because the interactions with the detector materials (multiple scattering and energy loss) dominate the tracking performance in this regime.

Unlike the search for $\mu^+ \to e^+e^+e^-$, exploiting an increased beam rate in $\mu^+ \to e^+\gamma$ experiments presents peculiar challenges which will be discussed in detail in Sec. 4

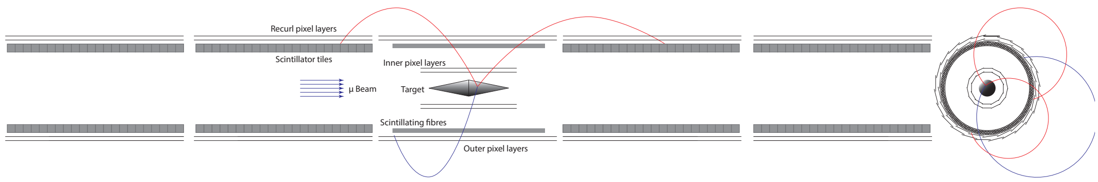

Figure 1: A schematic view of the Mu3e Phase II experiment.

3. The future of $\mu \to e$ conversion experiments and an Advanced Muon Facility at FNAL

The plans for the search of the $\mu^- \to e^-$ conversion in the Coulomb fields of nuclei already foresee significant upgrades beyond the two main experiments currently under construction, Mu2e [4] at FNAL and COMET [5] at J-PARC. The signature of the signal is a monochromatic electron with an energy slightly below the muon mass. Such electrons must be separated in energy from the ones produced by conventional decays of muons while orbiting around a nucleus, the energy spectrum of the latter having a long tail extending up to the signal energy. Both experiments exploit a tracking system with gas wire detectors in a magnetic field, complemented by a fast and high-resolution calorimeter that provides particle identification and inputs for the track reconstruction. The target sensitivity is 10^{-16} on the ratio between the $\mu \to e$ conversion rate and the nuclear capture rate.

With the upgrade of the muon campus at FNAL, exploiting the higher proton current provided by the PIP-II complex, a Mu2e-II experiment is foreseen [6], with new targets and detectors designed to cope with the higher particle rates. One of the main challenges will be the production of a proton

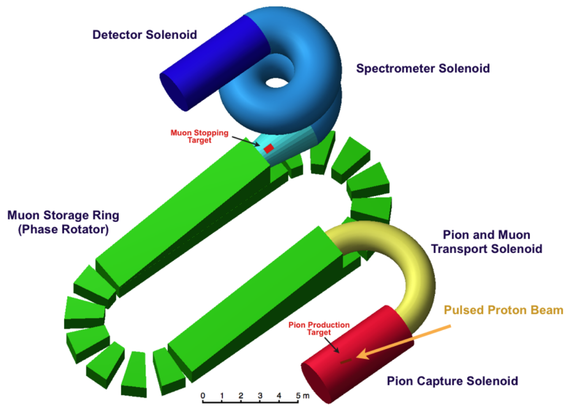

Figure 2: A possible layout for the Advanced Muon Facility (AMF) at FNAL.

target with the capability of dissipating 100 kW of power. Targets with moving elements are being designed as, for instance, tungsten or carbon spheres moving inside a pipe duct, to be exposed to the beam for a short time before being cooled down. On the detector side, calorimeters with innovative, very fast and radiation-hard inorganic scintillators like BaF_2 will be necessary to cope with the extremely high particle rates, while preserving a very good energy resolution. A better tracking resolution will also be needed, and R&D efforts are ongoing to develop extremely thin straw tubes (down to a wall thickness of a few μm) to reduce the multiple scattering contributions. An improvement in sensitivity of over 10 times compared to Mu2e is expected.

Both COMET and Mu2e (as well as its upgrade Mu2e-II) exploit the beam extinction technique to avoid backgrounds from proton or pion interactions. After ensuring that only an extremely low number of protons can reach the target in between two consecutive pulses, data is collected starting after several hundred nanoseconds from the beam pulse, when almost all pions already decayed. This technique prevents using heavy target nuclei, which would provide higher sensitivity to the $\mu \to e$ conversion, because muonic atoms with such nuclei have short lifetimes, well below 100 ns. For this reason, the target nucleus used by both COMET and Mu2e will be Aluminum, which gives a lifetime of 864 ns. To avoid this limitation, an Advanced Muon Facility (AMF) has been proposed at FNAL [7]. The idea is to store muons and pions in a ring after they have been produced and let them travel inside until most of the pions decayed. At this point, a pure beam of muons can be extracted and stopped in the target. A fixed-field alternating-gradient (FFA) storage ring would be used, following the PRISM/PRIME idea. Such a ring would also rotate the beam phase space, producing longer bunches of more monochromatic muons, so that thinner stopping targets could be used to reduce the energy straggling of the electrons to be reconstructed. A sketch of a possible AMF layout is shown in Fig. 2.

The FFA ring could store also positive muons and, thanks to the phase space rotation, the extracted beam would be almost continuous. Finally, the muons could be slowed down by adding an induction linac downstream, to be stopped in extremely thin targets. With these cares, a positive muon beam tailored for rare muon decay searches could be delivered. Compared to HiMB at PSI, the AMF could provide comparable or even higher muon rates.

4. A future search for $\mu \to e\gamma$

As explained in the previous sections, both Mu3e and Mu2e collaborations have clear plans to exploit the increased beam rates that the PSI and FNAL upgrades will make available in the next decade. The situation is completely different for the $\mu \to e\gamma$ searches.

The best limits on the BR of this decay come from the MEG and MEG II experiments, the combination of which gives $BR(\mu^+ \to e^+\gamma) < 3.1 \times 10^{-13}$ at 90 % confidence level [8]. With increased statistics, MEG II aims to lower the expected limit down to 6×10^{-14}. The statistical sensitivity of these experiments is determined by the capability of discriminating the signal against the accidental background made by the time coincidence of a positron and a photon from two different muon decays. This background B scales with the square of the beam rate, while the signal S scales linearly, so that the $S/\sqrt{B}$ ratio (and hence the sensitivity) does not improve with an increase of the beam rate. Instead, higher rates deteriorate the detector performances, due to the pileup and the aging of the detectors. So, while Mu2e is not affected by accidental coincidences, and Mu3e will start becoming sensitive to them only at the highest rates foreseen in Phase II, MEG II is already in a condition where the beam intensity (currently at 4×10^7 μ/s) cannot be further increased without a loss of sensitivity. Moreover, the detector technologies adopted in MEG II (a drift chamber for positron tracking and a LXe calorimeter with UV-sensitive silicon photon detectors) are not suitable to tolerate much higher particle rates.

The only way to suppress the accidental background, and hence make possible an increase in the beam rate, is an improvement of resolution on the kinematical observables that allow separating the two-body-decay signal from the accidental coincidences (the photon and positron energy, their relative angle and their relative time), possibly in combination with new detection concepts, while ensuring a good high-rate tolerance. As a consequence, an obvious solution to make a further step in the search for $\mu \to e\gamma$ does not exist.

In the last years, a study group has been formed, with researchers from the MEG II and Mu3e collaborations, to develop new ideas and perform R&D studies for the next generation of $\mu \to e\gamma$ experiments. A conceptual sketch of a possible detector working at future facilities with more than 10^9 μ/s is shown in Fig. 3. The positron spectrometer could be instrumented with silicon pixel layers, following the example of Mu3e, to ensure the necessary high-rate capabilities (in terms of pileup multiple track separation and aging), possibly with a reduced thickness to avoid a performance deterioration compared to gaseous detectors. For photon detection, the pair conversion technique could be adopted: photons are converted into e^+e^- pairs in a thin layer of dense material, their energy is reconstructed from the momenta of the e^+ and e^- in a magnetic spectrometer and, if the conversion material itself is active, also the energy loss within it can be recovered. This approach guarantees extremely good energy resolution, while the scarce efficiency of the conversion process can be compensated by an increase in the beam rate, up to a few 10^9 μ/s. With multiple conversion layers, this approach should allow exploring branching ratios well below 10^{-14} [9].

5. Conclusions

The upgrades of the existing facilities delivering high-intensity muon beams will allow, in the upcoming decades, to significantly boost the searches for charged lepton flavor violation in the muon

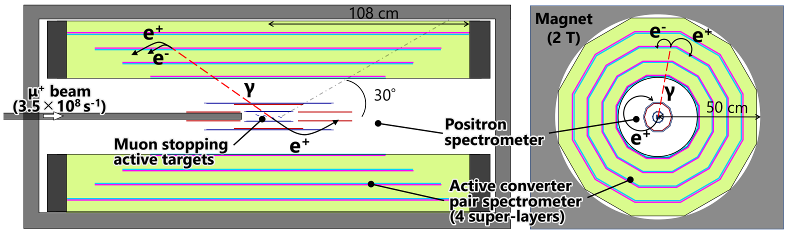

Figure 3: A possible layout of a $\mu^+ \to e^+\gamma$ experiment based on a silicon positron tracker and a photon conversion detector.

sector. The Mu3e experiment at PSI and an envisaged upgrade of the Mu2e experiment at FNAL will be able to reach sensitivities at the limits of the present and next-future detector technologies. At the same time, new concepts are being developed to overcome the current limitations in the search for $\mu \to e\gamma$. These efforts open intriguing perspectives for some of the golden probes of new physics beyond the Standard Model.

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