A Phase Rotated Intense Source of Muons (PRISM) for a $\mu \to e$ Conversion Experiment

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Muon to electron ($\mu \to e$) conversion in a muonic atom is an excellent laboratory to search for charged lepton flavor violation (CLFV). Its discovery would be a clear signature of physics beyond the Standard Model (BSM), and the current generation of experiments will probe 10^4 beyond current limits. In order to further improve the experiments by an additional factor of 100 and study potential signals, the use of a Fixed-Field Alternating gradient (FFA) ring has been proposed to create a Phase Rotated Intense Source of Muons (PRISM). Short, high intensity proton bunches are sent to a production target followed by a high acceptance capture/transport system, where the muon beam will be formed and subsequently injected into the FFA ring. PRISM will allow significant purification of the muon beam and suppression of a typically large momentum spread by the use of RF phase rotation in the ring, both reducing the backgrounds and increasing the number of stopped muons relative to other methods. PRISM requires a proton driver capable of producing short, intense proton bunches. New facilities, in particular PIP-II at Fermilab equipped with a dedicated accumulator ring, or upgrades of other accelerator facilities, such as J-PARC and ESS, offer promising opportunities for providing the required intensity and time structure of the proton beam. The FFA would provide the world's forefront facility to explore CLFV physics with high-brightness muon sources.

I. INTRODUCTION

The non-conservation of lepton flavor among neutral leptons, demonstrated in neutrino oscillations, raises an important question about their charged partners: why has charged lepton flavor violation(CLFV) never been observed [1]? The search has been underway since the discovery of the muon, yet CLFV has never been seen. This LOI describes an accelerator system that will improve the sensitivity to CLFV by two orders of magnitude beyond planned experiments, down to $\mathcal{O}(10^{-19})$.

Muon-to-electron ($\mu \to e$) conversion is the coherent conversion of a muon to an electron in the field of a nucleus N, $\mu N \to eN$. This CLFV process is the focus of the experimental programs of COMET at J-PARC [2] and Mu2e at Fermilab [3]. Both experiments can improve the current limits by nearly four orders of magnitude [4]. $\mu \to e$ conversion measurements complement and extend decay searches such as $\mu \to e\gamma$ or $\mu \to 3e$. All of these processes can use intense muon beams that make it possible to investigate mass scales far beyond the reach of colliders. This LOI describes a new way to form a muon beam particularly suited for $\mu \to e$ conversion.

The $\mu \to e$ conversion rate depends on the Z of the nucleus according to the BSM physics, as well as being enhanced by the Z of the coherent conversion [5–10]. If $\mu \to e$ conversion signals are discovered in COMET and Mu2e, both of which will begin with conversion with aluminium, it will be necessary to change to other materials

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to investigate the Z-dependence of the conversion rate. If no signal is found, further searches with improved sensitivity and possibly with high Z targets may reveal a signal or use the Z dependence to set an even stronger limit. Unfortunately the current experiments are limited to low Z target materials with a long muonic atom lifetime (864 ns in Al), since pion contamination and the remnants from the initial proton collision in a muon beam set a lower limit on the measurement time window. These problems preclude the use of high Z, short lifetime materials (73 ns in Au). The FFA removes this restriction and has the further advantage of decreasing the muon momentum spread, as we discuss below.

This LOI describes the general concept of PRISM and outlines the study programme we plan to perform for Snowmass 2021. The PRISM FFA could be constructed at upgraded proton drivers at J-PARC [11] or the ESS [12]. Entirely new planned proton drivers, PIP-II and the Booster Upgrade at Fermilab, are especially promising [13, 14]. It should not be read in isolation, but as further documentation of an opportunity for a new muon facility [15, 16].

PRISM's FFA will apply RF phase rotation, accelerating slow muons and decelerating fast muons, to make the momentum spread narrow and to be able to stop the muons after a shorter length than would otherwise be possible. The momentum resolution of the detection of the $\mu \to e$ conversion signal is limited by the thickness of the muon stopping target; therefore, if the beam momentum and its spread are reduced the experiment can use a thinner muon stopping target. This improves the momentum resolution, which lowers backgrounds, thereby improving the ability to both set limits and discover a signal.

Muon storage rings or long straight muon beam lines have been proposed as well. A muon storage ring is better than a prohibitively long straight beam line and also reduces the number of the RF cavities required for RF phase rotation. Muon beams have large beam emittance and muons decay, placing constraints on the time for RF manipulation. An FFA ring provides quick acceleration/deceleration in a fixed magnetic field along with a large beam momentum acceptance.

Performing phase rotation in an FFA is therefore a superior solution, which led to a proposal for a Phase Rotated Intense Source of Muons (PRISM) [17]. A $\mu \to e$ conversion search with PRISM allows the use of high Z target materials and could reach a single event sensitivity of better than 10^{-19} with proton beam power of $\mathcal{O}(1)$ MW.

The PRISM concept starts with a pulsed proton beam that is sent to a production target. Outgoing pions are produced and captured in a high acceptance solenoid capture system. A negative muon beam resulting from pion decay is then injected into the FFA ring where RF phase rotation occurs. The muon beam after RF phase rotation will be sent to the muon stopping target, where the muons stop, are captured by a nucleus, and can undergo $\mu \to e$ conversion.

II. PROTON DRIVER REQUIREMENTS

The phase rotation of the muon beam in an FFA ring imposes limits on the length of the proton bunch. In addition, the preferred energy is set below 8 GeV in order to avoid the antiproton production threshold. To create intense, compressed bunches several techniques can be used. Proton drivers typically use an H^- linac followed by an accumulation using stripping charge exchange injection into a ring. The beam may undergo further acceleration and/or RF compression in the same or other rings. Those proton bunches would be then sequentially extracted to the pion-production target using an extraction kicker with the repetition rate up to 1 kHz. A possible scheme using PIP-II at Fermilab is discussed in [18].

III. ACCELERATOR SYSTEM FOR PRISM

The PRISM based experimental system [19, 20] consists of several functional elements downstream of the proton driver: (1) the pion production target can be based on existing graphite technology; (2) the pion capture system around the target would use a superconducting solenoid with high magnetic field (10-20 T) and presents challenges similar to the Muon Collider target solenoid [21, 22]; (3) the pion/muon beam transport and matching into an FFA ring, which is difficult due to a very different optical conditions in the capture solenoid and an FFA, and can incorporate low-Z absorbers to use ionization cooling [23] to improve the beam quality; (4) an FFA ring with its subsystems, requiring a demanding injection/extraction and RF; and (5) the beam transport downstream of an FFA to the muon-stopping target.

Several designs for an FFA ring exist and the current baseline assumes a scaling 10-cell ring with FDF symmetry. A significant challenge arises from the FFA's injection system with a septum magnet and an injection kicker, both with a large aperture. For the kicker, 1 kHz repetition is considered challenging but possible. The injection and extraction kickers of the FFA ring would provide extra extinction of beam particles causing backgrounds, in addition to the proton beam extinction. It needs to be noted that very significant progress on an experimental verification of the PRISM system, including the feasibility of the FFA magnets and the RF system using Finemet cores, was demonstrated in the dedicated prototype studies at the Research Center of Nuclear Physics (RCNP), Osaka University [24]. In addition, a preliminary simulation study showed a factor of 10 reduction in momentum spread can be achieved after 5 turns of 90° phase rotation with the proposed RF system. With a ring circumference of about 30 meters, 5 turns in the PRISM ring would give suppression of the order of 10^{-20} for low energy pions.

IV. STUDY FOR SNOWMASS 2021

The PRISM Task Force was formed to provide further necessary progress towards designing the experiment and addressing the most challenging aspects. The progress in high intensity proton drivers capable of producing compressed bunches, high magnetic field capture systems and the development of large acceptance beam transport channels offers possibilities to improve the beam quality, and thus the sensitivity of next generation experiments. The authors of this LOI, including members of the PRISM task force, wish to perform further studies of the experimental system focusing on solving the feasibility issues and evaluating the physics potential; one such system, the PRIME detector including a curved solenoid spectrometer, is discussed in Ref. [17]. We will focus on the most challenging issues such as matching and injection into an FFA ring. The study aims to produce an approximate Monte Carlo simulation of the entire system and evaluate its physics reach.

V. CONCLUSION

This LOI presents compelling and novel opportunities in the search for $\mu \to e$ conversion, based on the PRISM system. New and/or upgraded proton drivers open the possibility to create compressed high intensity bunches necessary to realise this experiment. 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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