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Toward a high-precision measurement of the muon lifetime with an intense pulsed muon beam at J-PARC

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The Fermi coupling constant can be determined with high precision by measuring the muon lifetime. Therefore, it has played an essential role in testing the Standard Model and searching for new physics. The positive muon lifetime is obtained by a time measurement of decay positrons. The statistical uncertainty limited the most precise result to date, so an experiment with an intense pulsed muon beam has the potential to improve the precision further. However, the signal pulse-pileup associated with instantaneous high counting rate is an obstacle in pulsed beams experiments. This paper proposes a new experiment to measure the muon lifetime using a pulsed muon beam at J-PARC and a segmented positron detector.

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1. Introduction

Precision measurements of the electroweak observables provide stringent constraints on physics beyond the Standard Model. For example, the Peskin-Takeuchi parameters [1] can evaluate loop-contributions of new physics to the electroweak observables using three input values; the fine structure constant α, the Fermi coupling constant G_F, and the Z boson mass M_Z.

The Fermi coupling constant defines the strength of the $V-A$ four-fermion interaction, which describes the weak interaction in the low-energy limit. The most precise way to determine G_F is to measure the mean lifetime of the muon τ_μ and use the following equation [2],

$$\frac{1}{\tau_\mu} = \frac{G_\mathrm{F}^2 m_\mu^5}{192\pi^3}\left(1+\Delta q\right). \tag{1}$$

Here, m_μ is the muon mass, and Δq contains higher-order corrections of quantum electrodynamics (QED). When G_F is determined using the above equation, the uncertainty derived from m_μ is 0.06 ppm [3] and the uncertainty from the QED correction is 0.14 ppm [2, 4]. On the other hand, the precision of τ_μ is 1.0 ppm [7]. Therefore, the precision of G_F is limited by the uncertainty of the muon lifetime.

Determining and comparing G_F in multiple independent ways is helpful in a search for new physics [5]. Recently, a tension of G_F obtained using a global electroweak fit and superallowed β decays was reported [6]. A new precision measurement of G_F will contribute to a deeper understanding of the situation.

2. Muon lifetime measurements

Muon lifetime measurements have a long history, and their precision has improved with advances in theoretical calculations. Figure 1 shows the measurement results and theoretical uncertainty. The most recent positive muon lifetime measurements are the MuLan [7] and FAST [8] experiments at Paul Scherrer Institute (PSI). Both were proposed in 1999 and conducted in the

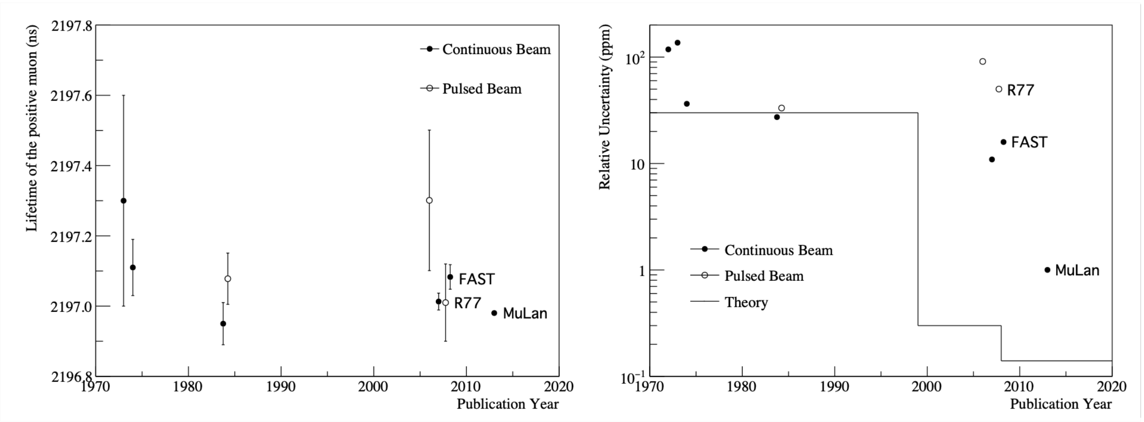

Figure 1: History of muon life measurements and theoretical calculations. (left) experimental results, (right) theoretical and experimental uncertainties.

2000s. The final results of each are

$$\text{MuLan} \quad \tau_\mu = 2.1969803(21)_{\text{stat}}(7)_{\text{syst}}\ \mu\text{s}, \tag{2}$$

$$\text{FAST} \quad \tau_\mu = 2.197083(32)_{\text{stat}}(15)_{\text{syst}}\ \mu\text{s}. \tag{3}$$

The MuLan and FAST experiments measured the lifetime with a precision of 1.0 ppm and 16 ppm, respectively. The two results differ by about 100 ps, corresponding to a discrepancy of 47 ppm. In addition to the experiments at PSI, the R77 experiment was performed to measure the muon lifetime with an intense pulsed muon beam at Rutherford Appleton Laboratory (RAL) [9].

In the MuLan experiment, a continuous muon beam was pulsed with an electrostatic kicker to achieve high statistical precision. In general, an experiment using a pulsed beam is statistically efficient because no trigger pileup occurs. On the other hand, the higher the beam intensity, the higher the requirement on the high-rate tolerance of the detector. The MuLan's positron detector covered 70% of 4π steradians with 170 segments. The contribution of the statistical uncertainty to the precision of 1.0 ppm was 0.95 ppm, and the main systematics was 0.2 ppm each for muon spin rotation (μSR) and detector's gain variations.

3. A proposal of new experiment at J-PARC

3.1 Experimental overview

The MuLan experiment showed that the use of pulsed muon beams is effective in measuring the muon lifetime precisely. On the other hand, the instantaneous high counting rate leads to counting losses due to signal pulse-pileup, which is a source of systematic uncertainty. To further improve the precision of a lifetime measurement, we propose a new experiment combining an intense pulsed muon beam at J-PARC MLF MUSE [1] with a segmented, high-rate capable particle detector.

A conceptual design of the experiment is shown in Fig. 2. The muon beam is stopped at a solid target, and the emission time of decay positrons is measured by a segmented detector surrounding the target. The detector consists of plastic scintillator tiles and silicon photomultipliers (SiPMs).

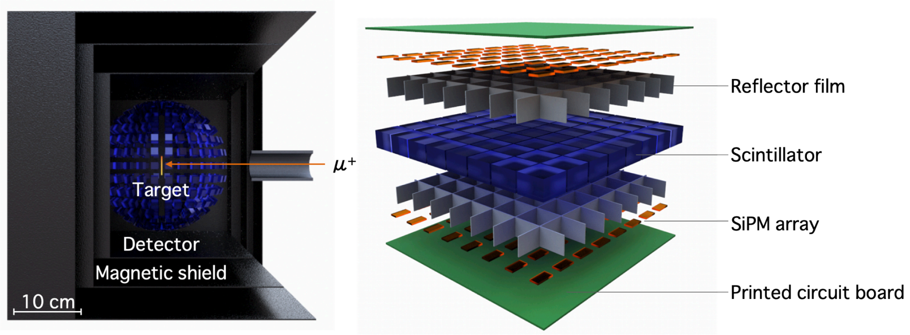

Figure 2: Experimental schematic: (left) overall view of the setup, (right) exploded view of the detector.

At H-Line, a new beamline under construction at MUSE, the intensity of surface muon beam is expected to be 10^8 μ^+/s [10]. With a detector's solid angle of 80% $\times 4\pi$, 1.6×10^{14} positrons

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[1] MLF and MUSE stand for Materials and Life Science Experimental Facility and Muon Science Establishment, respectively.

can be detected in 23 days of measurements. This is equivalent to 100 times MuLan's statistics. The detector is segmented into 14,000, 3-mm×3-mm tiles and placed on a 10-cm radius sphere to keep the counting rate at an acceptable level. A magnetic shield surrounds the target and detector to reduce the static magnetic field at the target to near zero, thereby minimizing the effects of μSR.

3.2 Positron detector

The main requirement for the detector is high-rate tolerance in terms of double-pulse resolution. Pulse-pileup leads to rate-dependent positron count loss, which distorts the time spectrum of decay positrons from a simple exponential function. A fast-response front-end electronics for SiPM readout is essential to suppress the systematics arising from pulse-pileup. As a candidate for the readout circuit, a series of Kalliope electronics [11] is considered.

As a feasibility study of the new lifetime measurement, a time spectrum of decay positrons taken with Kalliope in the MuSEUM experiment at J-PARC was analyzed considering pulse-pileup. As shown in Fig. 5 of Ref. [12], the pileup loss is well described as a function of the instantaneous count rate by a pulse-height analyzer (PHA) windowing model in Ref. [13]. A detailed study of the systematic uncertainty in the lifetime measurement due to pulse-pileup is underway and will be reported in a separate paper.

3.3 Magnetic shield

In the presence of a magnetic field, muon spin precession with the Larmor frequency occurs. Since the direction of decay positron emission correlates with the muon spin, the muon spin rotation imparts an oscillating component to the positron time spectrum. To reduce the systematic uncertainty due to μSR, a precisely controlled near-zero magnetic field is to be prepared.

For the MuSEUM experiment, a three-layered box-shaped magnetic shield made of permalloy was developed to suppress the stray fields from the beamline magnets, and geomagnetism [14]. As shown in Fig. 3, magnetic field distributions were measured with a fluxgate probe and compared with and without the magnetic shield. The residual magnetic field in the shield was suppressed to less than 100 nT in the region where a 10-cm radius sphere could be placed. The systematic

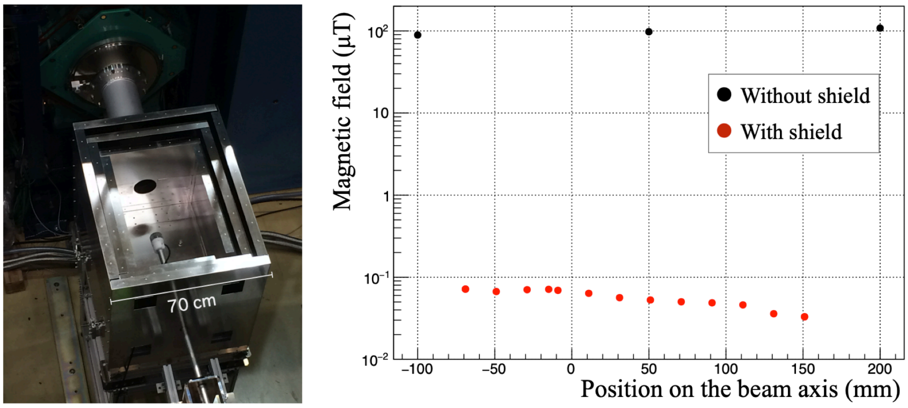

Figure 3: The magnetic shield: (left) photograph of the shield, (right) the static magnetic field with and without the shield. Zero on the horizontal axis corresponds to the center of the magnetic shield.

uncertainty arising from μSR at 100 nT is estimated by a Monte-Carlo simulation and found to be negligible compared to the statistical uncertainty at the sub-ppm level.

4. Summary

High-precision measurement of the muon lifetime derives the Fermi coupling constant, which determines the nature of weak interaction. A new experiment using a high-intensity pulsed muon beam at J-PARC was proposed to improve the precision of G_F by order of magnitude. The positron detector is being developed, and a precise model of pulse-pileup is under study. Suppression of the systematic uncertainty originating from muon spin rotation using the magnetic shield was evaluated.

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