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DeeMe Experiment to Search for Muon to Electron Conversion at J-PARC MLF

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The DeeMe experiment is planned at J-PARC Materials and Life Science Experimental Facility. The experiment aims to search for the muon to electron conversion in the nuclear field, which is one of the charged lepton flavor violation processes, with a single-event sensitivity of 10^{-14}. While the processes are forbidden in the Standard Model of particle interactions, some theories beyond the Standard Model predict the existence of such processes at observable rates. Therefore, the experimental signature would be clear evidence of new physics. Preparation for the experiment is now ongoing. Four tracking detectors have been manufactured in 2017. Using these detectors and a spectrometer magnet, we took data of the momentum spectra of muon Decay in Orbit for a medium momentum region by using three kinds of targets made of C, Si and SiC. The current status of the preparation for the DeeMe experiment is reported in this paper.

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1 Introduction

1.1Charged lepton flavor violation and new physics

In the Standard Model (SM) of particle interactions, charged lepton flavor violating (CLFV) processes are forbidden. If we take into account neutrino oscillations, the branching ratio for $\mu \to e\gamma$ is still at the order of about 10^{-54} [1]. This is too low probability to observe the process experimentally. On the other hand, some theoretical models beyond the SM, such as models with supersymmetry (SUSY) or extended higgs sectors, predict branching ratios at the order of 10^{-12} to 10^{-17}. If we observe a CLFV process at a large rate, that will provide clear evidence of new physics.

1.2 Reactions of muonic atoms

A negative muon stops in matter to form a muonic atom. After it forms the lowest-energy bound state (1S), two processes occur in the SM: muon decay in orbit (DIO) $\mu^- \to e^- \nu_\mu \overline{\nu_e}$ and muon capture (MC) $\mu^- + (A, Z) \to \nu_\mu + (A, Z-1)$. The probabilities at which those processes take place depend on the nuclear mass.

The target in the J-PARC MLF muon facility is made of carbon (C). For a C muonic atom, the probability of the DIO is 92%, while that of the MC is 8%. To increase the reaction of nuclei and muons, we are considering a possibility of changing the C target to a silicon carbide (SiC) target. For a Si muonic atom, the DIO and MC will occur at the 33% and 66%, respectively.

In addition to the DIO and MC, muon to electron conversion $\mu^- + (A, Z) \to e^- + (A, Z)$, a coherent neutrino-less conversion of a muon into an electron in the nuclear field, which is one of the CLFV decay, may occur through some new interactions. The conversion electron is monoenergetic with an energy equal to the muon mass minus the binding energy of the muon and the nuclear recoil. For light nuclei like C and Si, the experimental signature is an electron with an energy of approximately 105 MeV.

1.3 Search for CLFV in photonic and non-photonic processes

Possible processes for CLFV can be classified as being photonic and non-photonic. These can be expressed by an effective Lagrangian written as,

$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\overline{\mu_{\rm R}}\sigma^{\mu\nu}e_{\rm L}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\overline{\mu_{\rm L}}\gamma^\mu e_{\rm L})(\overline{q_{\rm L}}\gamma_\mu q_{\rm L})$$

where κ is the relative strength of photonic and non-photonic processes, and Λ is the mass scale of new physics. If only photonic processes exist, the branching ratio for the muon to electron conversion is about one hundredth of that for $\mu \to e\gamma$. In contrast, if the non-photonic contribution dominates, the muon to electron conversion would occur at larger rates than those of $\mu \to e\gamma$. Both photonic and non-photonic processes have different underlying new physics, thus we must study CLFV processes with various approaches.

2 The DeeMe experiment

2.1 J-PARC MLF MUSE

The DeeMe experiment is planned to be conducted at the Muon Science Establishment (MUSE) of the J-PARC Materials and Life Science Experimental Facility (MLF) in Tokai village, Japan. We will utilize pulsed-proton beams from the 3 GeV synchrotron accelerator, Rapid

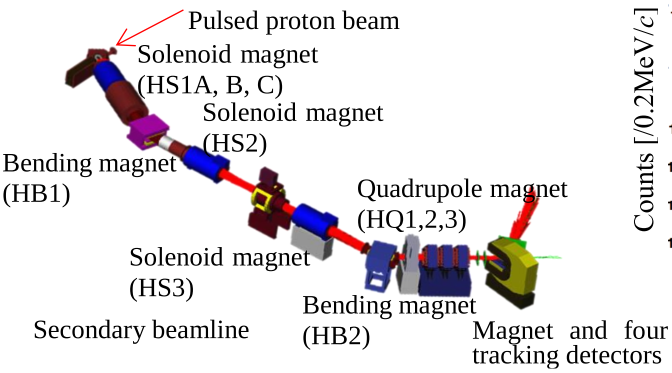

Figure 1: Experimental apparatus.

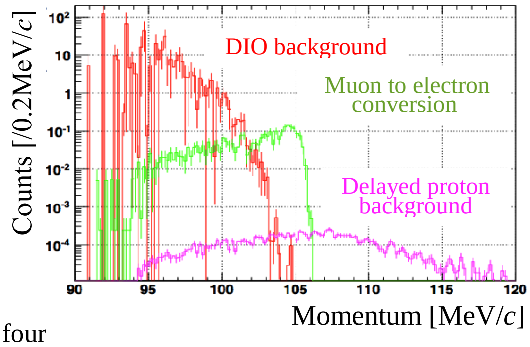

Figure 2: Momentum spectra of signal electrons and backgrounds (RCS 1 MW for 2×10^{7} s, SiC target, the branching ratio of muon to electron conversion 3×10^{-14}, delayed proton rate $< 10^{-19}$).

Cycling Synchrotron (RCS), with a fast extraction operation mode. The pulsed-proton beams consist of two bunches with 600 ns spacing and the repetition frequency is 25 Hz. The design power of RCS is 1MW and the operation up to 500 kW has been currently achieved.

2.2 Experimental concept

The experimental apparatus is shown in Fig. 1. First the pulsed-proton beams are injected into the target to produce pions. Then, the pions decay in flight into muons, and the muons become bound by the target atoms to form muonic atoms. Approximately 10^{10} muonic atoms per second will be produced operating with a beam power of 1 MW. We will look for the signature, a delayed electron with a monochromatic momentum of 105 MeV/*c* from the muonic atoms [2].

In conventional experimental setup, there are a pion-production target, a pion-decay and muon-transport section, and a muon-stopping target. On the other hand, it is noticed that a large amount of muonic atoms are produced on the target, thus in our case the pion-production target plays roles as a pion/muon-transport section and muon stopping target.

The secondary beamline will transport particles with momenta near 105 MeV/*c* and the low-momentum backgrounds will be removed. We will search for the signature by using a magnetic spectrometer, consisting of a spectrometer electromagnet and four tracking detectors.

2.3 Sensitivity goal and backgrounds

The current limit on the branching ratio of the muon to electron conversion is 4.6×10^{-12} for a titanium target obtained by the experiment at TRIUMF [3], 4.3×10^{-12} for a titanium target and 7×10^{-13} for a gold target by the SINDRUM-II experiment [4]. The goal of DeeMe is to achive a single event sensitivity of 1×10^{-13} for a C target or 2×10^{-14} for a SiC target for 1 year to improve the current limit by one or two orders of magnitude.

There will be some background in the region close to the signal-momentum value. Beam pion or muon capture by nuclei occurs, and then the de-excitation gamma rays will produce electrons and positrons. These electron backgrounds are produced at the beam-prompt timing, thus we are not taking the data while the beam-prompt backgrounds are coming. In the signal-momentum region, electrons from DIO are 0.09 per one year. Delayed protons which may come from the accelerator at the irregular timing would induce backgrounds. The amount is estimated

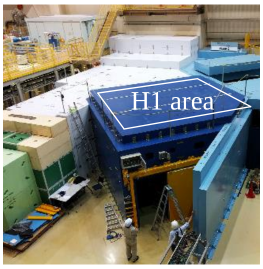

Figure 3: The radiation shields of the H1 area.

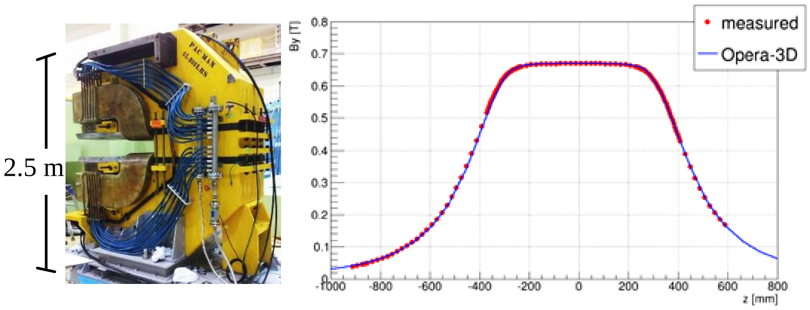

Figure 4: The magnet PACMAN (left). Measured and calculated magnetic field as a function of distance from the center of the magnet (right).

to be less than 0.027 in the ratio of the delayed protons to the main-beam protons < 10^{-19}. Cosmic-ray backgrounds will be suppressed because the analysis-time-window width of 10 μs is short enough compared to the cycles of the accelerator 40 ms, and they are estimated to be less than 0.018 and 0.001 events/yr for the electron and muon event, respectively. The RCS energy is 3 GeV, therefore there are no backgrounds induced by anti-protons [5, 6].

Figure 2 shows the momentum spectra of signal electrons and two main backgrounds. The background in the low-momentum region will be suppressed by the secondary beamline. To separate the signature from the high-momentum tail of backgrounds, we will need a spectrometer with a good momentum resolution, less than 1 MeV/*c*.

3 Current status

3.1 H Line and H1 area

The DeeMe experiment will use a new high-momentum muon beamline, H Line, which is under construction. The radiation shields down to the experimental hall, H1 area (Fig. 3) have been completed.

3.2 Magnetic spectrometer

3.2.1 Spectrometer magnet PACMAN

We will use a dipole electromagnet, PACMAN shown in Fig. 4. This magnet was used by the PiENu experiment at TRIUMF until 2012 [7].

The magnet is about 2.5 m in height and weighs 30 t. The nominal field is 0.4 T in the central part of the magnet, which bends the momentum direction of electrons with 105 MeV/*c* by an angle 70 degree. We tested the operation up to 500 A and measured the magnetic field. The magnetic calculation using a simulator OPERA-3d agrees reasonably well with the measurement. We will use the field map obtained from the calculation for tracking.

3.2.2 Detector

Figure 5 shows a schematic plot of number of charged particles expected to hit the detectors. There will be beam-prompt bursts, which are produced by pulsed-proton beams from the RCS hitting the target and pass through the H Line, and delayed-signal electrons with a monochromatic energy from the muon to electron conversion we search for. When the prompt burst hits the detectors, the rate of charged particles is approximately 70 GHz per mm^2 (10^6 to 10^7 charged

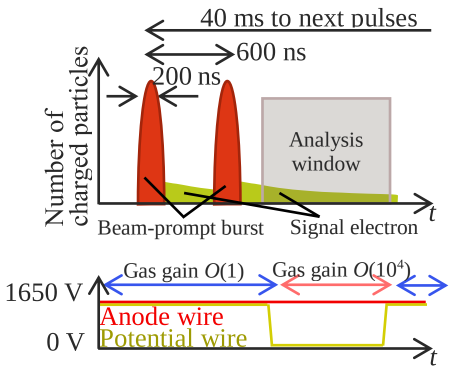

Figure 5: Expected charged particles which hit the detectors (upper), the high voltage applied to the MWPCs and their gas gain (lower) as a function of time.

particles per readout) at most. Soon after the prompt burst hits the detectors, detectors need to restore operation immediately to detect a single electron. To achive that, we will use cathode-strip-readout MWPCs with two types of wires, anode wires and potential wires, stretched alternately (Fig. 6). During the time window we search for the signal electrons, the MWPCs are operated with high-gas gain. For the rest of the time, such as the beam-prompt timing, the gas gain is kept at low values.

The MWPC has cathode strips with a width of 3 mm on the x-axis and with a total width of 15 mm on the y-axis. The active area is 250 mm×200 mm. For the readout electronics, we use amplifiers with large current tolerance [8] and 10-bit flash analog-to-digital converters (FADCs) with a sampling rate of 100 MHz [9].

We tested and confirmed that the detector works well in the analysis window after it is hit by charged particles as many as those of the prompt burst expected for the DeeMe experiment at the H Line [10].

3.3 Measuemement of muon Decay in Orbit (DIO)

There is D2 area of D Line in the MLF and it provides up to 10^6 muons per second. We measured the medium-region momentum spectrum of DIO (Fig. 7) at the D2 area. The motivation is (1) to test the magnetic spectrometer, including four MWPCs and DAQ, (2) to confirm that the momentum spectrum around the high momentum edge of 52.5 MeV/*c* agrees with theoretical calculation by Czarnecki [11].

We used three kinds of targets, C, Si and SiC. The beam time was two days in March and five days in June in 2017.

Black rectangles in Fig. 8 show some hits of the MWPC. The spectrometer system worked without any serious problems. Using positive muons, we get the momentum spectra for the calibration of the spectrometer (Fig. 9). We are analyzing the data of DIO from the C, Si or SiC target to test whether the data agree with the theoretical calculations of the DIO spectra and the Fermi-Teller Z-law or not.

4 Summary

The DeeMe is an experiment to search for one of CLFV processes, muon to electron conversion, with a sensitivity of 10^{-14}. We will conduct the experiment at the H1 area of the H Line using muon beams, which prodive approximately 10^{10} muonic atoms per second with the RCS operating with a power of 1 MW.

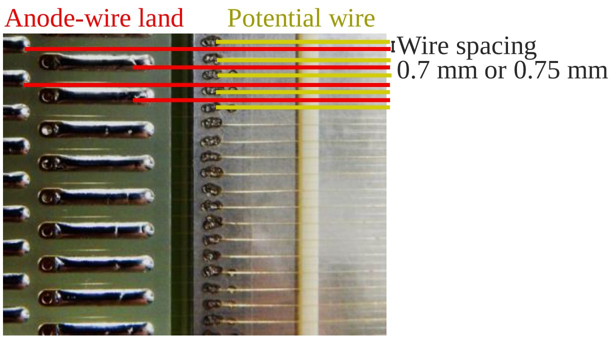

Figure 6: Zooming in the part inside the MWPC where the wires are stretched inside the MWPC.

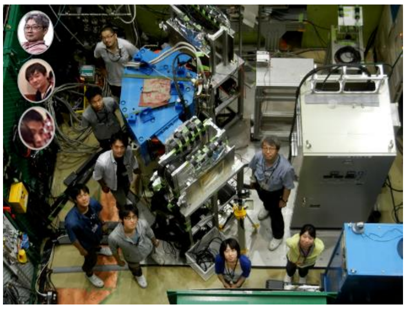

Figure 7: Experimental setup for measuring the DIO at the D2 area of D Line.

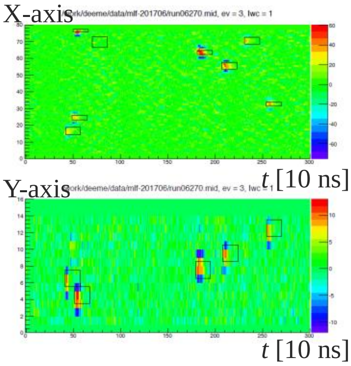

Figure 8: Event display of one MWPC.

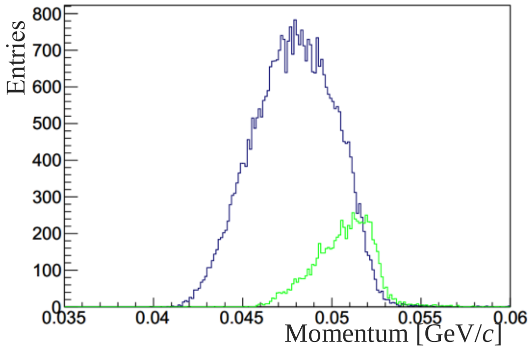

Figure 9: The momentum spectra for spectrometer calibration (dark blue: the spectrometer momentum 45 MeV/c, green: 52.5 MeV/c).

Four tracking detectors, MWPCs, have already been manufacutured in 2017. Spectrometer magnet PACMAN was tested in 2015. At the D2 area of the D Line, we took the data of the medium-region momentum spectrum of DIO with three kinds of target materials, C, Si and SiC.

The DeeMe experiment will start soon after completion of the H Line construction.

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