American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-8, Issue-12, pp-115-119
www.ajer.org
Research Paper
Open Access

Study of Al Degrader to Optimize Muonium Production from Silica Aerogel Target at J-PARC/MUSE

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To achieve high intensity and low energy spread of an ultra slow muon beam in the ultra slow muon beamline (U-line), Muon Science Establishment (MUSE), Japan Proton Accelerator Research Complex (J-PARC), Japan, we optimized stopped muons near the rear surface of muonium production target – silica aerogel using Monte Carlo simulation. The Al degrader thickness and momentum of incident muon beam were optimized to achieve high intensity of stopped muons near the rear surface of the silica aerogel target.

Keywords: *Ultra slow muon, Al degrader, silica aerogel, muonium*

Date of Submission: 29-11-2019 Date of Acceptance: 16-12-2019

I. INTRODUCTION

We have been developing ultra slow muon microscope on the Super-omega muon beamline, ultra slow muon beamline, called U-line, at the Muon Science Establishment (MUSE), Japan Proton Accelerator Research Complex (J-PARC), Japan [1-8]. Ultra slow muons are generated by resonant laser ionization of muonium (Mu) produced from a Mu production target. Mu is a bound state of a muon and an electron and is similar to a light isotope of hydrogen. Thus far, two Mu production target materials have shown relatively higher Mu yield than others: hot tungsten at 2000 K [9, 10] and laser-ablated silica aerogel at room temperature [11]. To use the laser-ablated silica aerogel as a Mu production target on the U-line, the use of a degrader and optimization of the momentum of muon are necessary. The muon that is stopped in the aerogel will pick up an electron and form Mu that diffuses to the rear surface of the aerogel. The muon generated by ionization of Mu produced from laser-ablated silica aerogel at room temperature has narrower energy spread than the muon generated by ionization of Mu produced from hot tungsten. This paper discusses a simulation study for optimizing the thickness of the aluminum (Al) degrader and the momentum of a surface muon on the U-line to achieve intense Mu generation from the silica aerogel target.

II. ULTRA SLOW MUON BEAMLINE (U-LINE)

U-line, ultra slow muon beamline, is located next to the D-line in Experimental Hall 2, Materials and Life Science Facility (MLF), J-PARC [6]. As shown in Fig. 1, when a proton beam is incident on a muon production target, pions are generated along with other particles. Muons produced by the decay of these pions on the surface of the muon target are captured using a capture solenoid and then transported using a curved transport solenoid and axial focusing solenoid [5, 12] to the Mu chamber where the Mu production target is installed. Muons pass through a SUS window (50 μm) to enter the Mu chamber. The Al degrader is set upstream of the target. Mu emitted from the rear surface of the target is ionized by resonant lasers [13] to generate slow muons. These slow muons are extracted, accelerated, and transported to experimental areas using slow muon optics [7, 8].

The U-line has two experimental areas: U1A and U1B (Fig. 1). In the U1A area, an ultraslow muon beam with energy of 20 eV–30 keV and size of 1–10 mm is available for nanoscience studies. In the U1B area, a micro muon beam with energy of 200 keV–1 MeV and size of ten to several tens of micrometers after reacceleration is available for three-dimensional visualization of small materials. A muon spin rotation and relaxation (μSR) spectrometer furnished with a set of Helmholtz coils to apply an external field to a sample in an ultrahigh vacuum environment is installed at the end (sample position) of the U1A area [6].

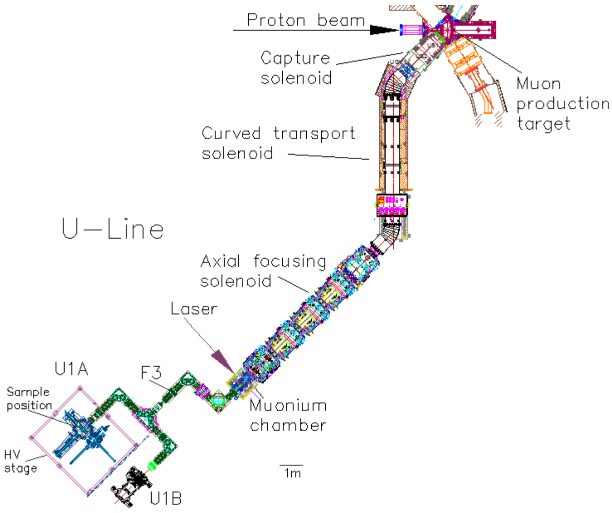

Fig. 1. Outline of U-line, MLF, J-PARC.

III. METHOD

The surface muon beam profile incident on the Al degrader in Mu chamber was calculated using the G4beamline code [14] with the current set values of the electric and magnetic components in capture solenoid, curved transport solenoid, and axial focusing solenoid on Super-omega beamline. Fig. 2 shows the momentum distribution of the surface muon beam incident on the SUS window, Al degrader, and silica aerogel in the Mu chamber. These profiles are used in the form of TRIM.DAT, in which energy and direction cosines (RMS value of cosX = 0.013, cosY = 0.121, cosZ = 0.120, where X is incident angle of muons with beam direction, Y and Z are angles transverse of beam direction) of incident muon are used from the output of the G4beamline simulation of surface muon beam, in Stopping and Range of Ions in Matter (SRIM) Monte Carlo simulation code [15, 16]. The momentum scale (pScale) of 100% corresponds to the experimentally optimized current set values of all components until the last focusing solenoid for tungsten target corresponding to ~ 27 MeV/c. The stopping range of muon in each material is estimated from the simulation. The thickness of the Al degrader and the stopped muon near the rear surface of the aerogel were estimated. The silica aerogel has density and thickness of 30 mg/cm^3 and 8.7 mm, respectively. SUS304 with density of 8.03 g/cm^3 was used in the simulation. The stopped muon percentage was calculated with respect to the intensity of incident muons (100%). The intensity of incident muon was taken over at least 10^4 events.

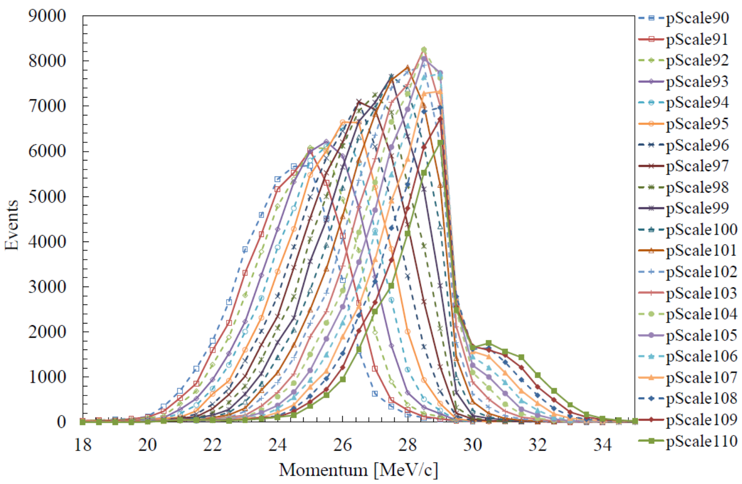

Fig. 2. Momentum distribution of surface muon beam using G4beamline incident on SUS window, Al degrader and silica aerogel in muonium chamber on U-line, MLF, J-PARC. The points are joined to guide the eyes and pScale in legend represents the momentum scale (%).

IV. RESULTS AND DISCUSSIONS

Fig. 3 shows the stopped muons in the SUS window, silica aerogel, and Al degrader and transmitted through the aerogel for pScale of 100% and different Al degrader thicknesses. The stopped muon percentage in the Al degrader increases with its thickness. By contrast, that in the silica aerogel increases with Al degrader thickness, peaks at thickness of ~325 µm, and then decreases (red marks in Fig. 3). These muons are those that stopped within the 8.7-mm-thick aerogel; however, our focus is to optimize the intensity of muons stopped near the rear surface of the aerogel. The muon that has stopped in the aerogel picks up an electron and forms Mu. Some of these Mu diffuses (~30 µm within lifetime at room temperature) [11] through the aerogel into vacuum.

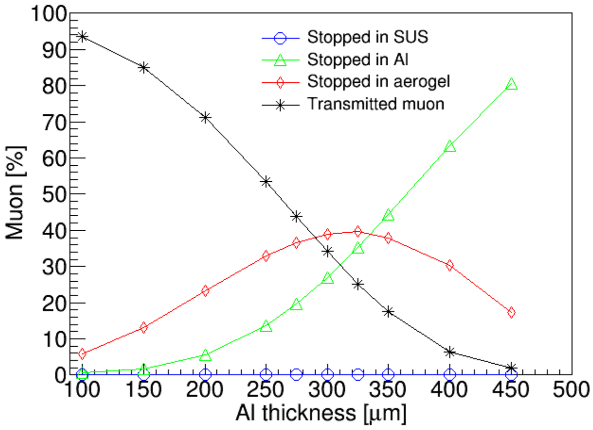

Fig. 3. Percentage of stopped muons in SUS window, Al degrader, and silica aerogel and of transmitted muons with Al degrader thickness. Curves are fitted to the points to guide the eyes, and the statistical error is indicated.

To estimate the optimized muons near the rear surface of the aerogel with respect to the momentum of incident muons, simulations must be conducted with different momentums of incident muons. Fig. 4 shows the stopped muon percentage in the silica aerogel with different Al degrader thicknesses (150, 200, 250, 300, 325, and 350 µm) as obtained using a momentum distribution profile with different scaling factors (90%–110%). The stopped muon percentage is the maximum at Al thickness of 150 µm with pScale of 90%. Fig. 5 shows the stopped muon percentage per millimeter of silica aerogel. The 150- and 200-µm-thick Al degrader at pScale of 93% and 95%, respectively, show higher density of stopped muons within 0.87 mm from the rear surface of the aerogel compared to the other cases. The muon stopped per mm near rear surface of aerogel is estimated around 5.5% of incident muon. At Al 200 µm and pScale 95% case, the stopped muon percentage was 5.6 % in the Al and 23.2 % in the silica aerogel.

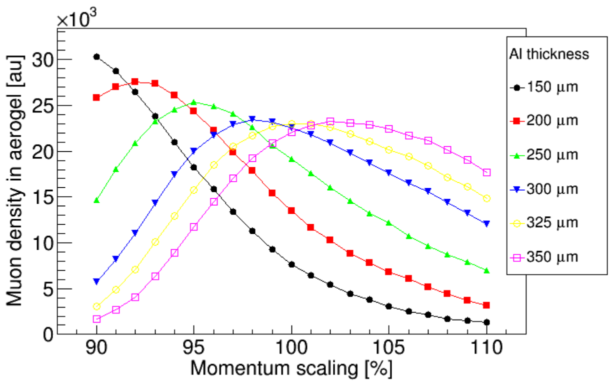

Fig. 4. Stopped muons in 8.7 mm aerogel with change of momentum scaling of surface muon beam and at different thickness of Al degrader. The points are joined to guide the eyes and the statistical error is inserted.

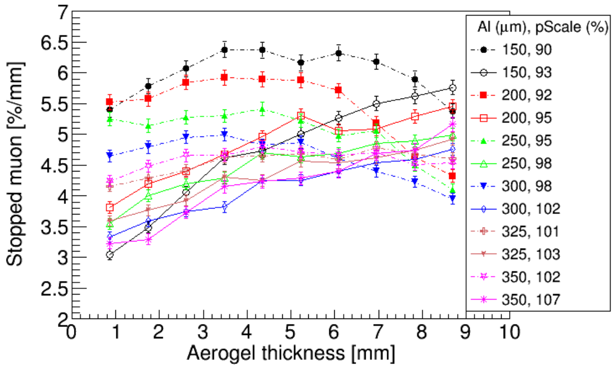

Fig. 5. Comparison of stopped muons in Al degrader of 150 μm, 200, 250, 300, 325 and 350 μm thicknesses at around peak positions (Fig. 4) of stopped muon in 8.7 mm of silica aerogel. The points are joined to guide the eyes and the statistical error is inserted.

In the case of low momentum and thin degrader the stopped muon near rear surface of the silica aerogel shows higher density. So, at present, the 200-μm-thick Al degrader is installed in the beamline. Fig. 6 shows the intensity of muons stopped within 100-μm depth from the rear surface of the aerogel at this thickness. The peak value is estimated at pScale of 95%.

The simulation may deviate from the measurement owing to factors such as the density and thickness of the silica aerogel, mismatch between incident muon profiles in the simulation and the real beamline, and role of laser-ablated surface/depth of silica aerogel. If the surface muon beam profile in the beamline differs (e.g., because of peak shift) from that used in the simulation, the peak in Fig. 6 may shift accordingly. In a real aerogel sample, laser ablation occurs; however, this is not considered in the simulation. It may cause nonuniform density of the aerogel near the pore wall and deep inside. The Mu diffusion length, pore size, pore separation, etc. may also play some role in the deviation. Measurements with the silica aerogel will be presented in future papers.

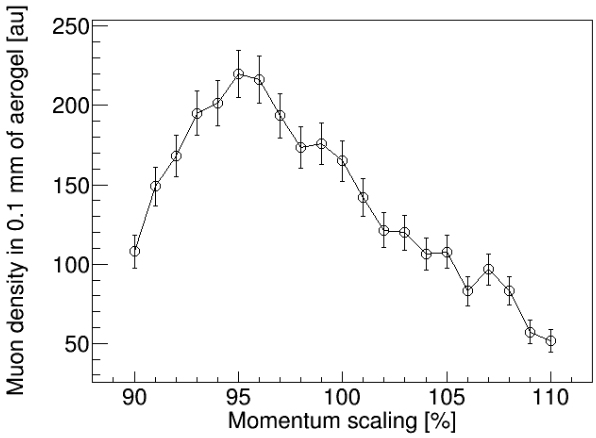

Fig. 6. Muon density within 0.1 mm depth from rear surface of 8.7 mm aerogel using Al degrader of 200 μm. The points are joined to guide the eyes and the statistical error is inserted.

V. CONCLUSION

For optimizing Mu emission from a laser-ablated silica aerogel as a Mu production target for generating an ultraslow muon beam, we simulated muons stopped in an Al degrader set upstream of the silica aerogel target and in the silica aerogel target itself. Based on the intensity of stopped muons near the rear surface of the aerogel, the optimized Al degrader thickness was estimated to be 200 μm at pScale of 95%.

ACKNOWLEDGEMENTS

This study was supported by a Grants-in-Aid for Scientific Research in innovative areas by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan (grant number 23108002).

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