Simulation Study of thermal muon formation at S-line for the Mu 1S-2S ionization experiment at J-PARC

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This note describes the simulation study for the surface muon stopping, the Muonium(Mu, μ^+e^-) formation and the production of the thermal muons for Mu 1S-2S experiment at J-PARC S-line (S2 area) in the future. The simulation for the surface muon transport along S-line was described in another independent note[1].

1 Surface muon stopping inside the target

The surface muon profile at S2 area was obtained from virtual detector, as shown in the Fig.1, positioning 163 mm upstream from the aerogel target by G4beamline simulation[1]. The profile was roughly optimized to reduce the beam size vertically (σ_x = 33.19 mm, σ_y = 12.7 mm) to accommodate the laser ionization region, which will be shot horizontally.

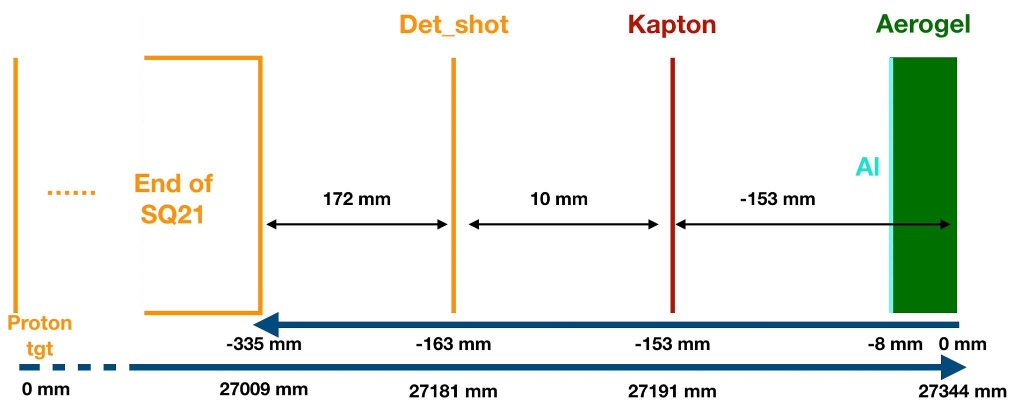

Figure 1: S2 area scheme. Surface muons along the S-line will exit from SQ21 and then go through the Kapton window and stopped inside the aerogel target. The distance in the figure is not scaled.

Geant 4 simulation was performed to obtain the fraction of the surface muon beam stopping in the target[1]. It contains the standard physics processes such as muon creation, decay, generation

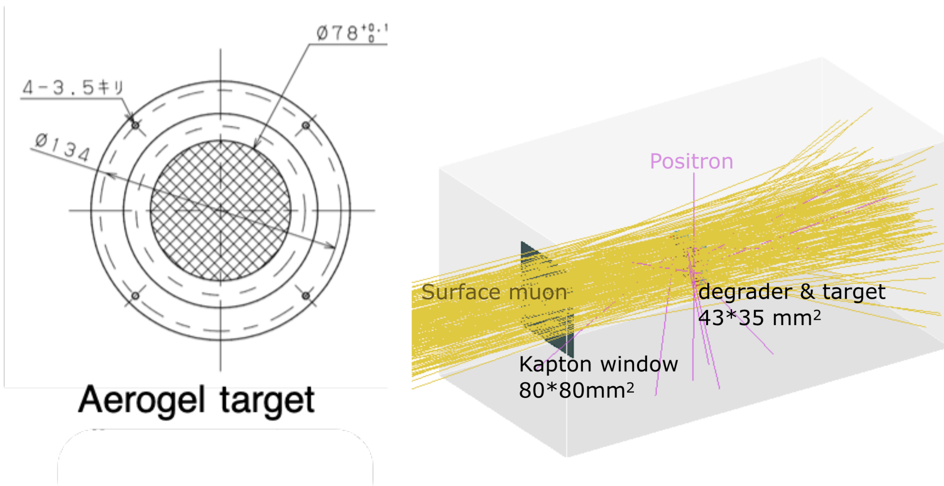

Figure 2: The size of the aerogel target and the G4 simulation scheme. In the target, the shadowed part is the aerogel with the diameter 78 mm.

Table 1: Optimization of the Al degrader thickness

Thickness [μm]	N(initial)	N(Stopped)	N(Stopped within rear 2 mm)	Efficiency
400	10949	2369	1445	0.216
425	10949	4169	1926	0.381
435	10949	4852	1943	0.443
450	10949	5828	1825	0.532

of secondaries electrons, energy loss (ionization) and multiple scattering, etc.

At the entrance of the S2 area, a Kapton window will be set to separate the vacuum between the S-line and the chamber. Inside the chamber, a aerogel target with Al degrader will be centered. The Al degrader was overlaid on the aerogel target. These setups are shown in the Fig.1 and Fig.2.

The incident surface muons penetrate the Kapton foil window with a thickness of 100 μm and the diameter of 80 mm. Then muons will stop inside the aerogel target. The diameter of the Al degrader and the aerogel target are both 78 mm. As shown in the Fig 2.

The thickness of the Al target was tuned to optimized the number of stopping muons inside the aerogel target, especially the number within the 2 mm from the downstream surface of the aerogel target.

In the simulation, the surface muon was shot into aerogel target in z-direction. Table.1 and Fig.3 shows the results in the stopping simulation, the Stopping number as the function of the thickness of the degrader. Fig.4 shows the Z-distribution of the stopping muon inside the aerogel under thickness of 435 μm Al degrader with the efficiency of 44.3%. Also the mean stopping time for the muon is about 350 ns. These information will be used into next stage simulation.

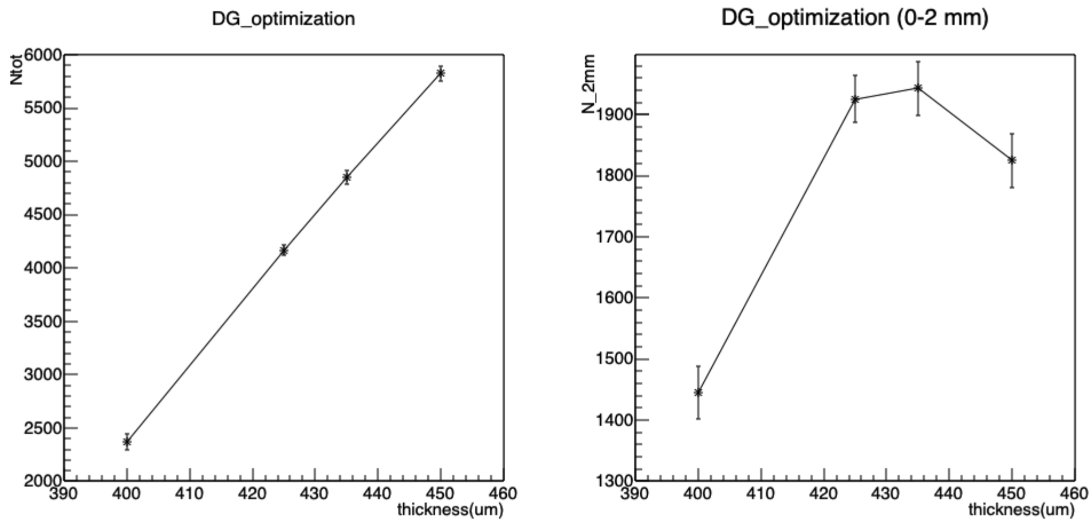

Figure 3: Al degrader optimization. Al thickness is optimized to be 435 μm. Left is all the stopping events as the function of thickness. Right is only the stopping events within rear 2 mm.

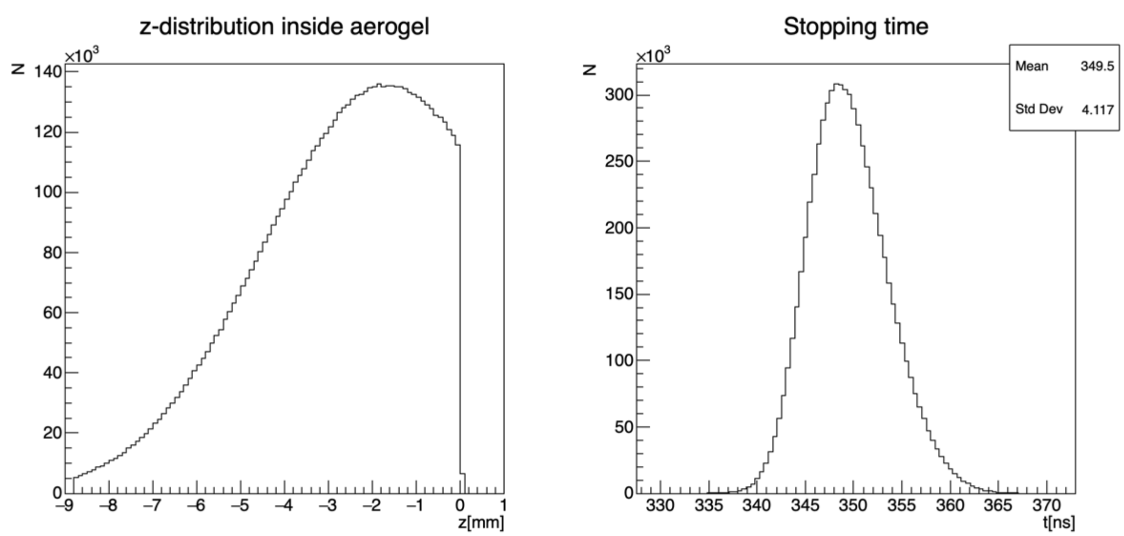

Figure 4: Surface muon stopping inside the aerogel target. Al thickness is 435 μm. Left is all the stopping events and right is the time distribution, where the mean value is about 349.5 ns, starting from the generation of the surface muons at S-line.

2 Muonium diffusion and the thermal muon yield

The Mu production simulation was developed to estimate the Mu yield number in the laser ionization region. The surface muon beam stopping distribution by Geant-4 were used as input. The 52% of the stopped muon form Mu's[1]. But for the convenience of statistics, in the simulation we assume 100% of the muon events will form Mu. The 52% efficiency will only be counted in the final efficiency.

The diffusion model in the target is based on a three-dimensional random walk in which each step is taken with a speed drawn from the Maxwell thermal distribution and a mean free path[2]. The simulation parameters of the thermal temperature and the diffusion constant were determined to be T = 322 K and D = 870 cm^2s^{-1}[3]. They were taken from the fitting results of our measurement at TRIUMF, in which the validation of the simulation was checked and there was a good agreement between the measurement and the simulation[4].

Note that the microscopic structure of the silica aerogel is not implemented in the simulation. The aerogel sample with the best Mu yield over the 23 samples from 2017 TRIUNF experiment is the aerogel target labeled S19, whose density is 23.2 $mgcm^3$ and the thickness is 8.8 mm. This density is different from the aerogel sample we used in the 2013 TRIUMF experiment and fitted for the diffusion model, whose density is 30 mg/cm^3. To make it consistent for the entire simulation chain, we will take the later value in the stopping simulation. The yield number will be scaled but will not vary significantly. Details are in the Ref. [3]

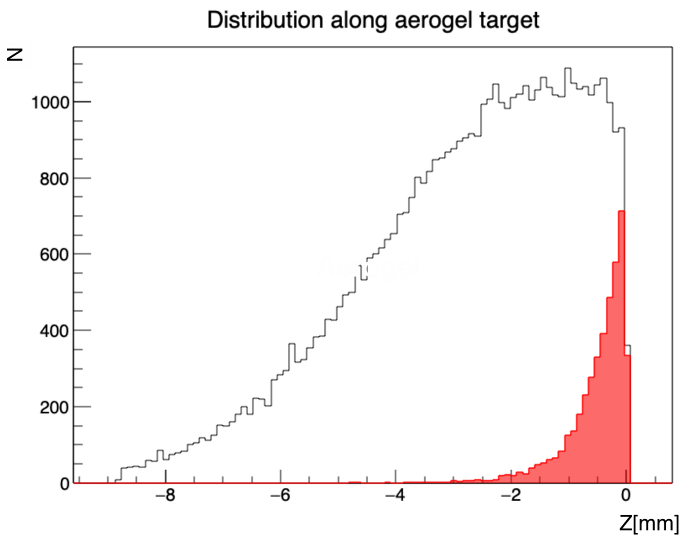

Figure 5: Red part of the stopping surface muon will yield out of the aerogel target. Al thickness is 435 μm.

After the diffusion process, in the Fig.5, the red colored part of the events inside the target will be able to get out of the target. The total yield muon events in the simulation is 570 076 while the total stopping muon inside the target is 7 037 598. Therefore the efficiency of Muonium vacuum yield is estimated to be 0.081.

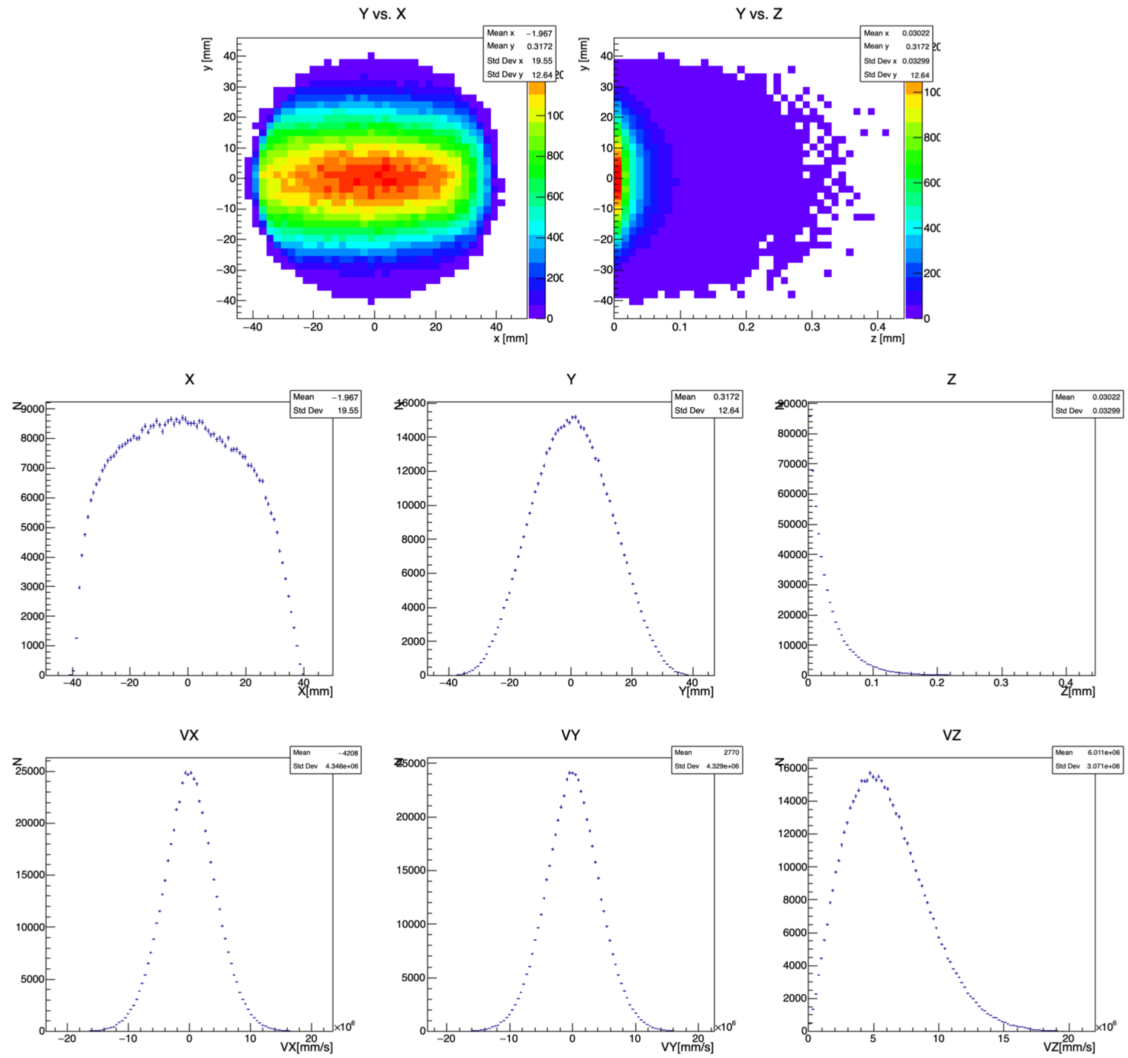

Figure 6: Distributions of the Mu events on the downstream surface of the aerogel target. Top 2D plots are the Y vs. X and Y vs. Z. The rest of the histograms are space distribution and the velocity distributions.

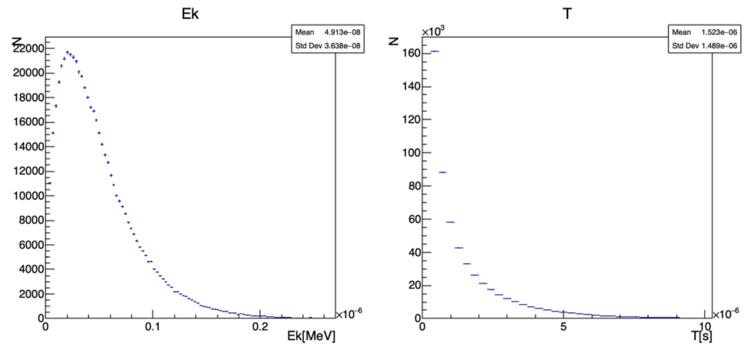

Figure 7: Kinetic energy and time distributions of the Mu events on the downstream surface of the aerogel target. The time distribution inherits the stopping time structure from Fig.4. The mean value now is 1.52 μs.

The distributions of those muons at the surface of the target is in the Fig.6 and Fig.7, including the spatial distribution, energy and time distributions. These events will be used as the input into laser simulation in the next stage.

3 Summary

The surface muon stopping simulation and the Muonium diffusion model were applied and the important efficiency results are summarized in the Table.2.

Table 2: Summary of the stopping simulation and the diffusion model

Step	N(initial)	N(left)	efficiency
Surface muon Stopping	15 057 073	7 037 598	0.467
Muonium formation			0.52
Muonium vacuum yield	7 037 598	570 076	0.081

References

[1] G. A. Beer, Y. Fujiwara, S. Hirota, K. Ishida, M. Iwasaki, S. Kanda, H. Kawai, N. Kawamura, R. Kitamura, S. Lee, W. Lee, G. M. Marshall, T. Mibe, Y. Miyake, S. Okada, K. Olchanski, A. Olin, H. Ohnishi, Y. Oishi, M. Otani, N. Saito, K. Shimomura, P. Strasser, M. Tabata, D. Tomono, K. Ueno, E. Won, and K. Yokoyama. Enhancement of muonium emission rate from silica aerogel with a laser-ablated surface. *Progress of Theoretical and Experimental Physics*, 2014(9):1–8, 2014.

[2] Technical design report for the measurement of the muon anomalous magnetic moment g − 2 and electric dipole moment at j-parc. 12 2017.

[3] Glen Marshall. Models of muonium diffusion. (October 2011).

[4] Ce Zhang. Mu target design study for g-2 experiment at j-parc. Technical report, 9 2018. E34-NOTE-0053.