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Optimization of momentum of muon beam and thickness of cell-window for muon experiment in bio-sample: a simulation study

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ABSTRACT

In order to study the bio-samples (aqueous solutions) using muon spin rotation and relaxation (μSR) method, the optimization of momentum of incident muon beam and selection of material for window of sample cell towards muon side are the initial steps for the μSR measurement. Rather than several experimental trials, we used to perform simulation study to optimize the momentum of muon beam and thickness of window of the sample cell. Monte Carlo simulation for optimization of momentum of monoenergetic surface muon beam in different material/thickness of window of the sample cell indicates that the Al or Kapton window of thickness less than 0.3 mm is suitable to maximize the intensity of the stopped muons (momentum between 25.8 MeV/c to 29.8 MeV/c) within 1 mm of water (bio-samples). This simulation will help to design the sample cell for the study of application of muon in life science.

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1. Introduction

Muon spin rotation and relaxation (μSR) method is being popular for study of life and materials. In this method, decay positron from the muon can be detected by spectrometer around the sample and the information about the desired properties of the material can be extracted from the time evolution of muon spectra [1]. Since muon is like a light proton, and its bound state with an electron is like a light isotope of hydrogen atom, this method can be used to understand the local electronic and dynamics states of the materials. Not limited to materials and life science [2-4], the muon can be used for discovery of new physics beyond standard model, nuclear physics, advancement of technology, etc [5]. In order to apply the muon to understand the properties of materials, it should be stopped in the sample material and the background should be minimized. Selection of proper momentum of muon beam and optimization thickness of window of sample cell (especially for bio-samples) are preliminary and the most important steps in this method. For the experiments to be performed in high vacuum and samples in which different muon charge states will be expected, especial care should be taken to select/use the material for sample cell.

Muon is an elementary particle which is like a light proton ($m_\mu \sim 1/9\ m_p$; $\mu_\mu = 3.18\ \mu_p$) and sensitive to magnetic field. For μSR experiment, high intensity muons can be generated in accelerator facilities however it is also possible to perform μSR studies using cosmic muons. Because of fully polarized and asymmetric decay to positron, it is used as promising tool to study the local electronic and dynamic states of materials in which it stops. Moreover, its unique and wide time window (~ ps to few μs) provides more advantages over other resonance techniques (NMR, ESR, Mössbauer, etc.) [1, 6]. When muon incident in sample, based on nature/properties of samples, muon can be found as diamagnetic muon, muonium or other states in the sample. After its average life 2.2 μs, it decays to positron along the direction of muon spin at the time of decay. Such positrons are collected by the detectors installed around the sample. The time evolution of polarization provides the information about the materials. So the μSR method has been used in wide varieties of samples without any external perturbations [1].

In our previous study of application of muon for cancer study, we have used decay muon of momentum of 60 MeV/c at RIKEN/RAL, UK [7-9]. For such beam, bio-samples of around a liter volume were used. As a next step, we plan to perform experiment in small and real bio-samples rather than dilute aqueous solutions. For such purpose, the low momentum muon (surface muon of momentum ~ 29 MeV/c) will be used at J-PARC, Japan. Before such experiments, it is necessary to optimize the thickness of windows of sample cell and momentum of muon beam so that muon can stopped in the targeted region of sample. In this work, the Monte Carlo simulation study to optimize the momentum of muon beam and thickness of sample cell-window to maximize the stopped muon in the targeted sample is presented.

2. Methodology

Based on materials and thickness of sample cell-window (Fig. 1), the incident monoenergetic surface muon beam stops in window materials and/or sample. To optimize/estimate the thickness of the sample cell-window and momentum of muon beam, the Stopping and Range of Ions in Matter (SRIM-2013) Monte Carlo simulations code [10, 11] were used. The momentum and energy of surface muon beam are 29.79 MeV/c and 4.119 MeV, respectively [12]. Based on

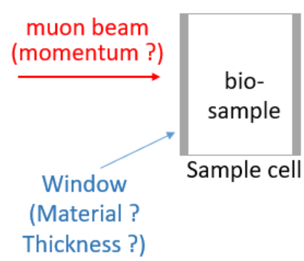

Fig. 1. Schematic diagram of incident of muon beam in bio-sample.

transportation of beam in beamlines, the real momentum will be less than the 29.79 MeV/c.

So, the simulations were performed at different momentum and materials. Among them three momentum data in two materials – aluminum (Al) and Kapton have been discussed here. In simulation, water is used instead of bio-sample because the aqueous bio-sample or real bio-sample some extent of water exists. The density of water is less than that of bio-sample so the stopping information in water is fine for bio-samples.

The Al of density 2.7 g/cc and Kapton of density 1.42 g/cc were used in simulation. The Kapton is polyimide which is used for different purposes – electric and thermal insulation, windows for high vacuum, protection layer, etc. The intensity of incident muon was taken over at least 10^4 events.

3. Results and Discussion

The simulation of muon stopping in both Al and Kapton sheets of different thicknesses have been performed at three different momentum of monoenergetic surface muon beam. Figure 2 shows the stopping range of muon in water. Even the muon beam of momentum 25.79 MeV/c can pass the 0.1 mm (Fig. 2(a)) and 0.3 mm (Fig. 2 (b)) of Al cell-window. However, in the case of 0.4 mm thickness (Fig. 2 (c)), a small fraction (< 1% of incident muon) of 25.79 MeV/c muon stopped in the window. Furthermore, in the case of 0.5 mm thickness (Fig. 2 (d)), all the 25.79 MeV/c muon stopped in the window.

The muon of momentum 25.79 MeV/c, 27.79 MeV/c and 29.79 MeV/c passes through the Kapton windows and stopped in water are presented in Fig. 3. In the case of Kapton thickness 0.05 mm (Fig. 3(a)) and 0.4 mm (Fig. (b)), all muons stopped in water within 2 mm depth. When the thickness of Kapton is increases to 0.6 mm, only small fraction (< 1% of incident muon) of muon of 25.79 MeV/c stopped in the Kapton window. In the case of thickness 0.8 mm (Fig. 3(c)), the 25.79 MeV/c muon stopped in the Kapton however other higher momentum muon passed the window and stopped in the water.

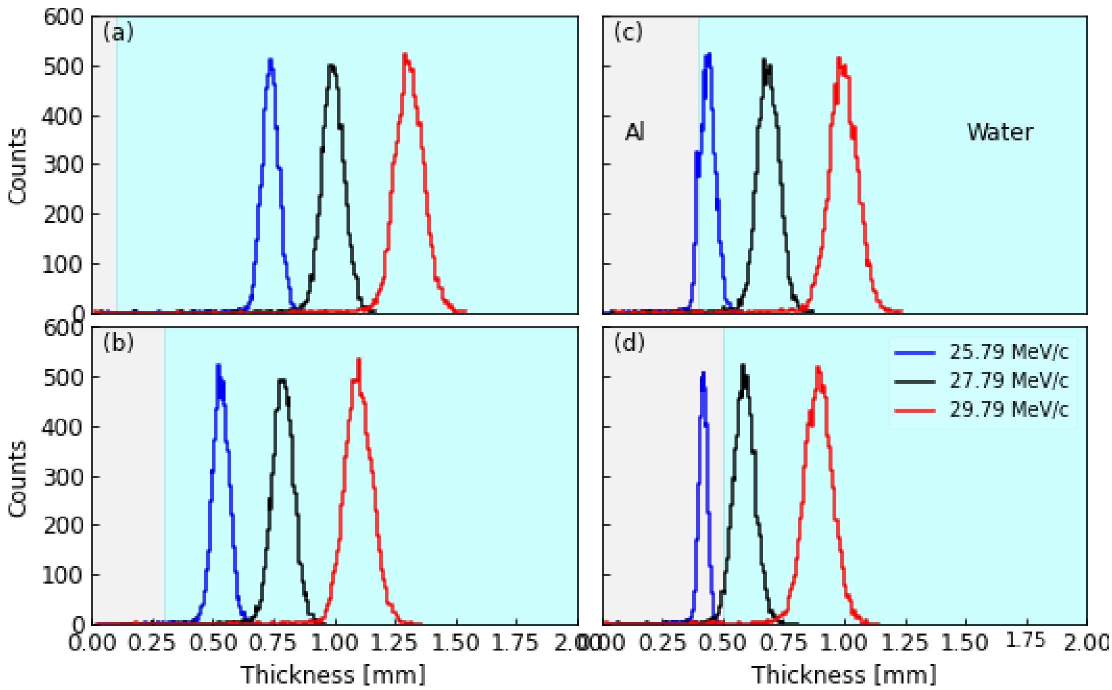

Fig. 2. Stopping range of muon beam of different momentum passed through the Al window in water (a) Al windows thickness, t = 0.1 mm, (b) t = 0.3 mm, (c) t = 0.4 mm and (d) t = 0.5 mm. The light blue color for water and light silver color for Al are used. The line colors blue, black and red are used for momentum of muon beam 25.79 MeV/c, 27.79 MeV/c and 29.79 MeV/c, respectively.

With regard to monoenergetic muon beam,

the stopping range difference for particular thickness is smaller (full width at half maximum is smaller) however in real beamline there is certain distribution of muon energy. In such cases low energy muon may stop in the window materials. For this reason, the selection of cell-window is quite important. If the muon stopped in window material, there is possibility of background or noise signal from the charge states of muon stopped in the windows materials. For example, muon stopped in Kapton (unsaturated organic material) may form radical or muonium state however in Al there will be muon in diamagnetic state.

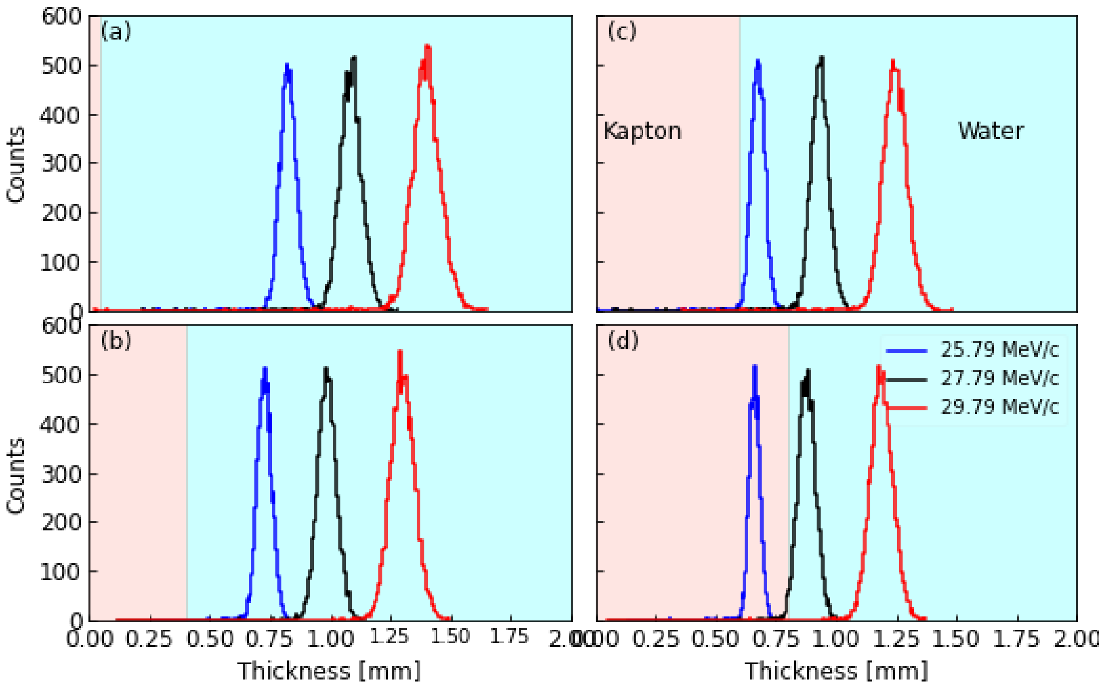

Fig. 3. Stopping range of muon beam of different momentum passed through the Kapton window in water (a) Kapton windows thickness, t = 0.05 mm, (b) t = 0.4 mm, (c) t = 0.6 mm and (d) t = 0.8 mm. The light blue color for water and light pink for Kapton are used. The line colors blue, black and red are used for momentum of muon beam 25.79 MeV/c, 27.79 MeV/c and 29.79 MeV/c, respectively.

For the selection of windows material, we also need to consider about the visualization of sample for example during experiments using light/laser or if we use other visual spectroscopic detectors during μSR experiment. For such purpose, the window of Kapton or glass will be better than Al. In addition, the chemical reaction of bio-sample with those window material should also be considered. For real bio-sample, the density will be different than the water used in this study. So, the density of particular sample also should be taken into account before selection of the cell window.

Conclusion

The stopping range of surface muon in different thickness of Al and Kapton window of sample cell for μSR experiment in bio-sample cell have been studied using Monte Carlo simulation. Optimization of thickness of the window and momentum of muon beam shows that the thickness of Al or Kapton window within 0.3 mm will suitable to pass the muon beam of momentum between 25.79 MeV/c and 29.79 MeV/c. The thickness of windows suggested by this study will be used in the experiments to be performed in future μSR experiments in aqueous biological samples.

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