Muon density enhancement with a tapered capillary method

D. Tomono*, T.M. Kojima†, K. Ishida*, T. Ikeda†, Y. Iwai†, M. Tokuda**,*, Y. Kanazawa‡, Y. Matsuda§, T. Matsuzaki*, M. Iwasaki*,** and Y. Yamazaki†,§

*Advanced Meson Science Laboratory, RIKEN Nishina Center for Accelerator Based Science, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0193, Japan
†Atomic Physics Laboratory, RIKEN Advanced Science Institute, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0193, Japan
**Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8551, Japan
‡Department of Physics, Sophia University, 7-1 Kioicho, Chiyoda, Tokyo 102-8554, Japan
§Graduate School of Arts and Sciences, University of Tokyo, Komaba, Meguro, Tokyo 153-8902, Japan

Abstract. Focusing effect of muon beam with a tapered capillary method has been investigated in a range from 4.2 MeV to 9.2 MeV (i.e. from 30 MeV/*c* to 45 MeV/*c* in momentum). We injected the muon beam into a pair of narrowing (tapered) plates and tubes made of glass, copper and gold-coated copper, and measured the energy distribution of the muon outgoing from the outlet. The plates were tilted from an inlet of 40 mm to an outlet of 20 mm. The density enhancement was more prominent with the plates made of heavier elements. The largest beam density enhancement at 10 mm downstream of the outlet was 1.3 with the gold-coated copper narrowing plates. The enhancement was composed of muons scattered with a small angle. Their energy was slightly lost less than that of the initial beam. This effect did not depend on the surface roughness. The result strongly suggests a simple and effective way to increase the muon beam density for a small target.

Keywords: muon, beam focus, density enhancement, glass capillary, μSR
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INTRODUCTION

Generation of a high density muon beam is currently an important issue in μSR studies [1, 2] and muonium formation [3] at the RIKEN-RAL muon facility [4]. Since the sample or target used in these studies is usually very small compared to the muon beam size of approximately 40 mm (full width at half maximum, FWHM), most of muons in the beam do not hit the target. The beam is usually cut into the target size by a collimator at the end of the beamline. For focusing the muon beam in the target size, a tapered capillary method was employed.

In this method, the charged particle beam can be effectively focused by a single tapered glass capillary. Nebiki *et al.* [5] reported the focusing effect for 2 MeV He^{+} ion beam by the tapered glass capillary. Our recent experiment at RIKEN-RAL [6] demonstrated that when a tapered glass tube was aligned coaxially with the muon beam, a certain fraction of the 54 MeV/*c* (13.0 MeV) pulsed muon beam (μ^{+} and μ^{-}) was scattered at the inner wall surface and was directed to the outlet; as a result, the number of available muons at the target was almost twice as that without the tube. In this experiment, however, only the total energy deposit of outgoing muons in a pulse was measured with a thin scintillation counter due to the pulsed nature of the muon beam at RAL. For detailed particle-by-particle study, a new experiment was performed at TRIUMF, Canada, using a continuous muon beam.

In this study, we investigated the followings: 1) beam kinematics such as energy distribution and profile, 2) muon beam density enhancement with a tube made of heavy elements instead of glass. The enhancement is expected to be more prominent when heavy elements such as copper or gold are used if the enhancement is composed of muons scattered with a small angle. 3) conservation of the muon spin polarization between incoming and outgoing muons. For simplicity, narrowing (tapered) metal and glass plates were firstly inserted instead of narrowing (tapered) tubes. Additionally, a metal and glass tube were installed to compare the focusing effect between plates and tubes. This article concentrates on the result for the density enhancement with the various narrowing plates at a initial momentum $p_{\mu} = 35$ MeV/*c*.

EXPERIMENTAL

Figure 1 (a) shows a schematic view of the setup at the M9B muon beamline, TRIUMF. All components were placed in a vacuum chamber so that even for low energy muons scattering or stopping by residual gases were negligible. Muons (μ^{+}s) from in-flight decay of pions were used from p_{μ} =30 MeV/*c* (4.2 MeV) to 45 MeV/*c* (9.2 MeV).($\Delta p_{\mu}/p_{\mu}$ ∼10%) The muon beam was almost in parallel. The incoming muon beam

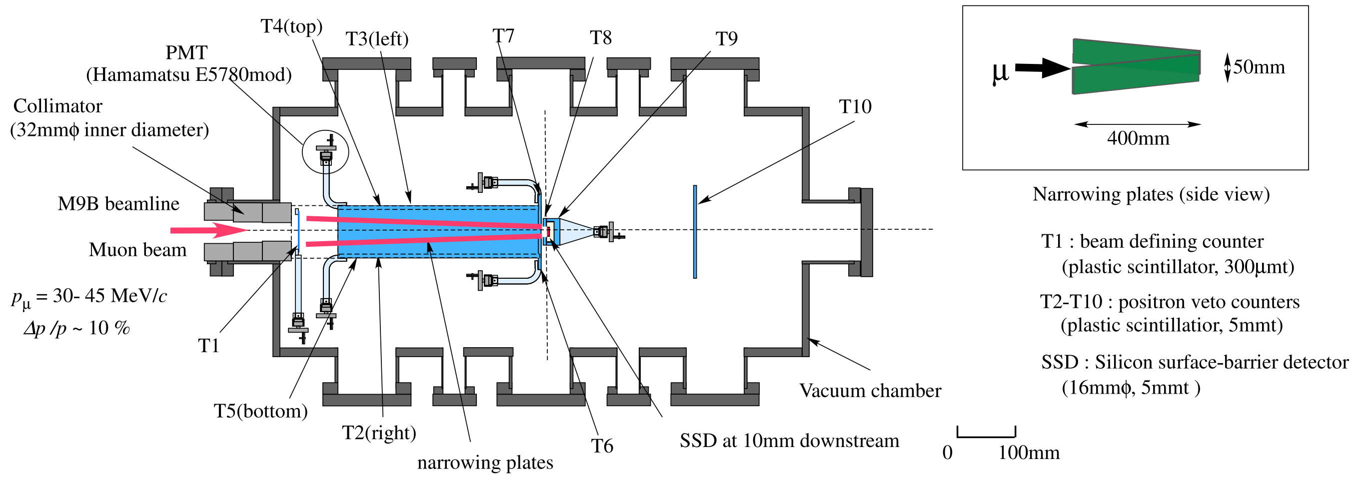

FIGURE 1. Schematic view of the setup at the M9B muon beamline (top view). All components when the SSD was installed at 10 mm downstream of the plates. A pair of vertical plates narrowing from a 40 mm inlet to a 20 mm outlet was mounted. A beam defining counter (T1), veto counters (T2-T7) for the plates, veto counters for the SSD (T8 and T9), a downstream veto counter (T10) in a vacuum chamber. A schematic illustration of the narrowing plates was shown in an inset.

passed through a plastic scintillation counter (T1, 0.3 mm thickness) for defining the beam. The narrowing (tapered) plates or tubes (400 mm length) were inserted coaxially with the muon beam. Some muons passed through the gap without hitting the narrowing plates. Some other muons were scattered by the narrowing plates, and guided downstream. The rest was stopped in the plates, and decayed into positrons. The positrons were detected with plastic scintillation counters (T2-T7) surrounding the plates. The energy of outgoing muons was measured with a silicon surface barrier detector (SSD, ORTEC TL-045-200-5, 16 mmϕ, 5 mm thickness, transmission type). Plastic scintillation counters (T8 and T9, 5 mm thickness) surrounded the SSD for monitoring positrons that came from the decay of muons having stopped in the SSD. A large plastic scintillation counter (T10, 200×200 mm^2, 5 mm thickness) was mounted at 200 mm downstream to catch muons that did not stop in the SSD, array or any other counters.

The surface roughness for the polished copper and gold-coated copper plates was measured for investigating influence on the density enhancement. An averaged surface gradient of the polished copper plate was estimated to be 0.51°, which was 18 times finer than that of the gold-coated copper plate of 9.2°. The surface of the glass was finer than that of metals used.

In order to estimate the muon density enhancement, a density enhancement factor ξ is defined as

$$\xi = \frac{\int_{\varepsilon_{min}}^{\varepsilon_{max}} N_{in}(\varepsilon')d\varepsilon'}{\int_{\varepsilon_{min}}^{\varepsilon_{max}} N_{slit}(\varepsilon')d\varepsilon'}, \tag{1}$$

where $N_{in}(\varepsilon)d\varepsilon$ denotes the number of muons at energies between ε and $\varepsilon+d\varepsilon$ in the distribution when the plates or tube are inserted, and $N_{slit}(\varepsilon)d\varepsilon$ denotes the number of muons when the corresponding slits are inserted. The ε_{max} and ε_{min} denote the maximum and minimum energies. In the present analysis, this energy integration region from ε_{min} to ε_{max} was set to three standard deviations ($\pm 3\sigma$) from the peak energy of the distribution of each slit data.

In the data analysis, an incoming muon associating with the initial hit timing in the T1 counter was chosen. When a muon decayed earlier than the shaping time of the SSD amplifier, positron energy deposit from the muon decay was mostly piled up to the muon energy. This component was removed in the SSD data analysis.

RESULTS

Figure 2 shows an energy spectrum when a central momentum of the muon beamline is set at p_μ = 35 MeV/c (5.6 MeV). These spectra were observed with the SSD fixed at 10 mm downstream of the outlet when the polished copper plates, rough copper plates, gold-coated copper plates, glass plates and corresponding slits were inserted. Entries of each spectrum are normalized by the number of muons incoming to T1 counter for comparing the yield in the above conditions. Each vertical axis is scaled to a relative yield to the slit data, namely the peak value of the slit data was set to 1.0. These spectra indicate that the beam was focused with the narrowing plates. The muon yield at the SSD increased with the plates when the same number of the initial muons was injected. The increase component included slightly lower energy muons than that of initial muons when compared to the slit data. Some muons were scattered downstream at the surface of the plates, losing their kinetic energy.

The largest density enhancement of ξ_{gold} $\sim$1.3 with the gold-coated copper plates was obtained. In addition, although a surface of gold-coated copper was approximately more than 10 times as rough as that of polished copper and glass, the enhancement with the glass plates was smaller than that with the plates made of metal. The spectrum of the polished copper plates was almost identical with that of the rough copper plates. These facts indicate that the focusing effect is independent of the surface roughness. It is noted that spectra for the rough copper are omitted in Fig. 2 for clarity. Although enhancement factors at different momenta could not compared strictly due to the difference of the initial beam condition and scattering at T1 counter, the largest enhancement factor was obtained with the gold-coated copper plates in all momentum region we measured. The averaged enhancement factor for gold-coated copper plates was also calculated to be $\bar{\xi}_{gold}$ $\sim$1.3 with an average of the factors in all momenta. Note that, for the tubes, the enhancement is expected to be almost the square of that with the narrowing plates since the focusing effect in the vertical direction was added to that in the horizontal direction.

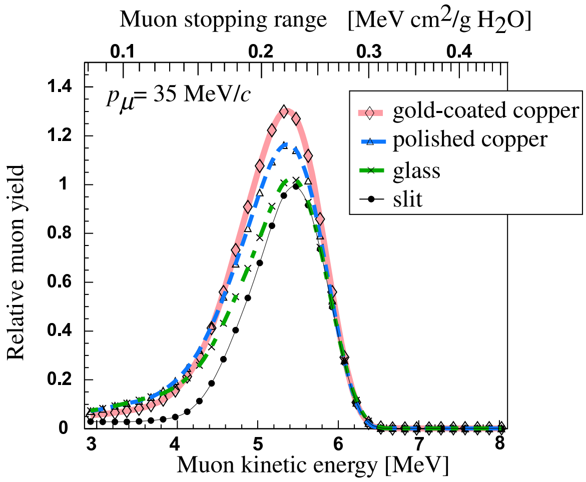

FIGURE 2. Energy distributions of the outgoing muons at p_μ = 35 MeV/c (5.6 MeV) when the gold-coated copper plates (open diamond, bold solid line), polished copper plates (open triangle, dashed line), glass plates (cross, chain line) and corresponding slit (closed circle, solid line) were inserted. Spectra for the rough copper are omitted for clarity. Entries of each spectrum are normalized by the number of incoming muons to T1 counter. Each vertical axis is scaled to a relative yield to the slit data.

SUMMARY AND OUTLOOK

We studied the muon beam focusing effect from T_k = 4.2 to 9.2 MeV (i.e. from p_μ =30 to 45 MeV/c in momentum) using several kinds of narrowing (tapered) plates with the tapered capillary method. The density enhancement is caused by the focusing effect through small-angle scatterings at the inner surface of the narrowing plates. The largest enhancement factor at p_μ = 35 MeV/c is 1.3 for the gold-coated copper plates with an average of the factors using low energy muon beam at 10 mm downstream of the outlet with the SSD. The focusing effect is more prominent with the plates or tubes made of heavier elements but is independent of the surface roughness. From these results, the tapered capillary method is effective to increase the muon density.

Assuming that this method was applied to the muonium formation in vacuum, we expect to increase the muonium density in a small spot. In this case, a muon stopping range is important as well as the muon yield because only muoniums formed near the target surface can come out into vacuum. The number of muoniums in vacuum increases if thickness of a muonium formation target is optimized for the muon stopping range which corresponds to the peak position in the enhanced muon energy distribution. As shown in Fig. 2, at p_μ = 35 MeV/c, the peak energy of the enhanced muon energy distribution was 5.1 MeV, corresponding to a stopping range of 0.22 MeV·cm^2/g H_2O. If this condition is used, the muonium yield in vacuum is expected to increase by a factor of 1.3 at the gap between the narrowing plates of 20 mm outlet in width. Thus, this simple method will be a powerful tool for increasing muon yield in a small spot for the slow muon project at RIKEN-RAL [3] and for development of a new cold muon source in the precision measurement of muon g-2 project at J-Parc [7].

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