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Density Enhancement of Muon Beams with Tapered Glass Tubes

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We have demonstrated that the beam density of 54 MeV/c muons can be increased almost by a factor of two when a tapered glass tube is inserted coaxially along the muon beam. The observations are compared with a multiple Coulomb scattering calculation, which reproduces the observation reasonably. This technique opens a new and simple way to increase the muon intensity effectively.

KEYWORDS: muon, beam density, glass capillary, enhancement, tapered glass tube
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Spin polarized muons have been used for several decades for material science study.[1)] Muons implanted into a sample are quickly thermalized and then localized at characteristic sites. These muons interact with the local magnetic field, resulting in muon spin precession and/or depolarization. This makes spin polarized muons very sensitive and versatile microscopic probes to study magnetic properties in various materials. One of the obstacles of this technique is that the size of the polarized muon beam from accelerator facilities is relatively large; typically a few tens of mm in full width at half maximum (FWHM) at the focal point. However, most of intriguing samples, such as newly synthesized chemical compounds and biological samples, are often much smaller in size than the beam diameter. Usually a collimator is installed in front of the sample, masking the muons which do not hit the sample. This method suppresses the noise but does not increase the number of muons which hit the sample. Any method to increase beam density on the sample will be of great interest and importance to the application of polarized muon beams.

Nebiki *et al.* injected 2 MeV He^+ ions into a tapered glass capillary with inlet and outlet diameters of 0.8 mm and 0.8 μm, respectively, and reported that the transmission efficiency was much larger than that expected from the inlet-to-outlet area ratio.[2)] Ikeda *et al.* also demonstrated that a slow highly-charged ions (8 keV Ar^{8+}) were guided through a similar tapered capillary with beam density enhancement of a factor of about 10 while keeping their initial charge.[3,4)] With these new findings in mind, we have studied the behavior of 54 MeV/c muon beams with tapered glass tubes having an inlet diameter of 46 mm and an outlet diameter of 3–20 mm.

The experiment was performed at Port 2 of RIKEN-RAL Muon Facility at Rutherford Appleton Laboratory, U.K.[5)] Figure 1 schematically shows the experimental setup. Muons with specified momentum are transported to the beam port, and extracted into atmosphere through a thin Mylar foil and an aluminum collimator of inner diameter 40 mm and length 85 mm. Beam divergence is $\sim 2^\circ$ in standard deviation. The beam has a pulsed structure with a repetition rate of 50 Hz, each pulse consists of two bunches of 70 ns FWHM separated by 320 ns. Typical beam intensity is about 10^4 muons per pulse for 54 MeV/c μ^+. Positron/electron contamination is negligible. The bottom of Fig. 1 shows the beam profile of 54 MeV/c μ^+ at 403 mm downstream from the end of the collimator. Considering the size of the muon beam, we used tapered glass tubes with an inlet diameter, $D_{\rm in}$, of 46 mm. The tubes were made of Pyrex. The lengths of the tubes, L, were 100–400 mm, the outlet diameters, $D_{\rm out}$, were 3–20 mm, and the thickness was 2 mm. A beam momentum of 54 MeV/c was used because muon loss in air of 400 mm is negligible, while muons stop completely in a 2 mm glass wall, so that it does not interfere with the muon intensity observation. We prepared plastic scintillation counters (EJ212) with thickness of 0.5 mm and diameters, $D_{\rm sci}$, of 5, 10, and 20 mm. One of the scintillators was placed 3 mm downstream of the tube to monitor the muon intensity. The pulsed muon signal from the photomultiplier tube (PMT) was averaged over 128 beam pulses with a digital storage oscilloscope.

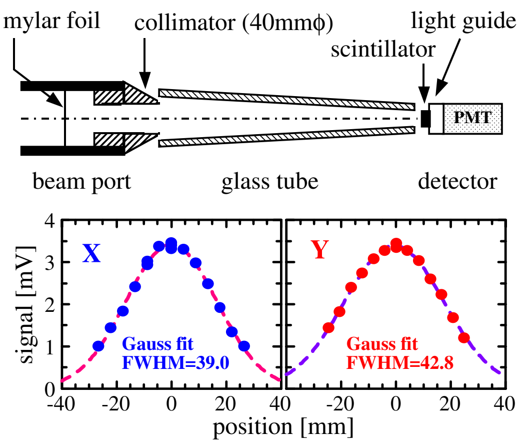

Fig. 1. (Color online) Top: a schematic view of the experimental setup (not to scale). Bottom: the beam profile of 54 MeV/c μ^+ measured with a 5 mmϕ scintillator positioned 403 mm downstream from the collimator.

Muon signal intensities, $V_{\rm with}$ and $V_{\rm without}$ were measured with and without the glass tube, respectively, keeping all other experimental conditions the same. The muon signal enhancement factor, η, is defined as

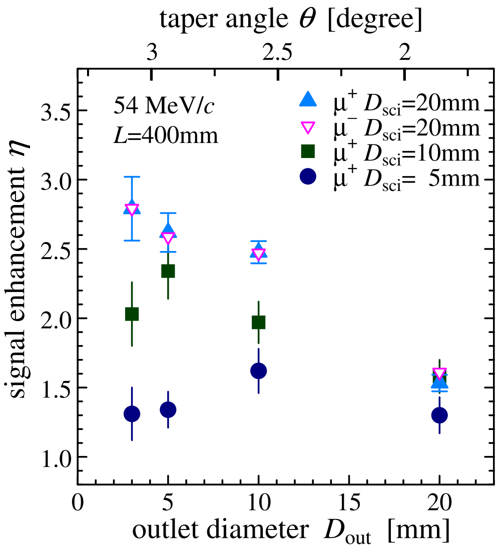

Fig. 2. (Color online) The signal enhancement factor η as a function of outlet diameter D_{out} for 54 MeV/c muons with $L = 400$ mm tubes for $D_{sci} = 5$, 10, and 20 mm. The error bar includes statistical and systematic errors (see text). Data points with "T" shape error bar are the mean of multiple measurements and those with "|" shape error bar are measured only once. Error bars of μ^- data are omitted for clarity.

$$\eta = \begin{cases} V_{with}/V_{without} & \text{for } D_{sci} \le D_{out}, \quad (1a) \\ V_{with}/V_{without,\, d \le D_{out}} & \text{for } D_{sci} > D_{out}, \quad (1b) \end{cases}$$

where the suffix "$d \le D_{out}$" stands for the muon signal integrated within the area of D_{out} using muon beam profile.

Figure 2 shows η as a function of D_{out} for $D_{sci} = 5$, 10, and 20 mm, and $L = 400$ mm. The error bars were evaluated from the deviation of the measured values to be about 5%. Taking this fact into account, we also included error bars of 5% for data points measured only once. In addition, for all data points, we added a systematic error of a few percent due to the finite resolution of the oscilloscope. It is worth noting that the signal enhancement for μ^- was almost identical to that of μ^+.

Because the energy deposition of each muon to the scintillator depends on its kinetic energy and pass length in the scintillator, η does not directly correspond to the density enhancement of the muon beam. Energy and angular distributions of muons at the position of the scintillator were calculated with a Monte Carlo simulation, and a pair of average deposition energies ε_{with} and $\varepsilon_{without}$ was evaluated for each experimental condition. The number of muons N_{with} and $N_{without}$ are proportional to $V_{with}/\varepsilon_{with}$ and $V_{without}/\varepsilon_{without}$, respectively. In the simulation; 1) the energy loss is scaled from proton data using a semi-empirical formula, 2) the energy straggling is given by the Vavilov distribution, and 3) the angular distribution is given by the Moliere expression for multiple scattering.[6] For simplicity, a parallel muon beam is generated having a 4% momentum dispersion and the Gaussian position distribution shown in Fig. 1. The beam density enhancement factor, ξ, is given as

$$\xi = \begin{cases} N_{with}/N_{without} & \text{for } D_{sci} \le D_{out}, \quad (2a) \\ N_{with}/N_{without,\, d \le D_{out}} & \text{for } D_{sci} > D_{out}. \quad (2b) \end{cases}$$

Figure 3 shows ξ as a function of D_{out} for $D_{sci} = 20$ mm and $D_{sci} = D_{out}$ together with the results of the numerical

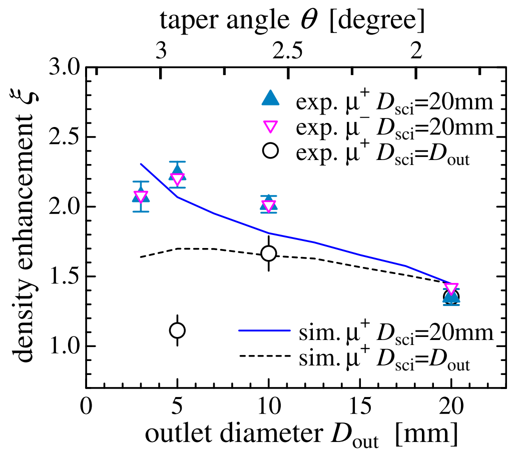

Fig. 3. (Color online) The beam density enhancement ξ for 54 MeV/c muons as a function of D_{out} for $D_{sci} = 20$ mm and $D_{sci} = D_{out}$. The solid and dashed lines show the results of the simulation for $D_{sci} = 20$ mm and $D_{sci} = D_{out}$, respectively.

simulation. As seen in the figure, beam density enhancements were observed for all the conditions studied, and furthermore the simulation successfully reproduced the overall behavior of the experimental results. This enhancement occurs because a certain fraction of muons incident on the inner wall is reflected via small angle scattering and transported to the outlet of the tube. For $D_{sci} = 20$ mm, ξ increases from $\sim$1.5 to $\sim$2.3 as D_{out} decreases from 20 to 3 mm, whereas ξ stays almost constant for $D_{sci} = D_{out}$. This difference is due to muons with large angle at the outlet of the tube. Since the counter is placed 3 mm downstream from the outlet, such muons miss the counter if $D_{sci} = D_{out}$. Although we do not know the real reason why the observed ξ for $D_{sci} = D_{out} = 5$ mm was much smaller than the result of the simulation, one possibility is slight misalignment of the 5 mm scitillator from the tube axis.

Figure 4 shows ξ as a function of L with $D_{out} = D_{sci} = 20$ mm and its Monte Carlo simulation. It is clearly seen that ξ increases monotonically with L. When the length L varies from 100 to 400 mm, the taper angle, $\theta = \tan^{-1}[(D_{in} - D_{out})/2L]$, changes from 7.4 to 1.9°. As the incident angle

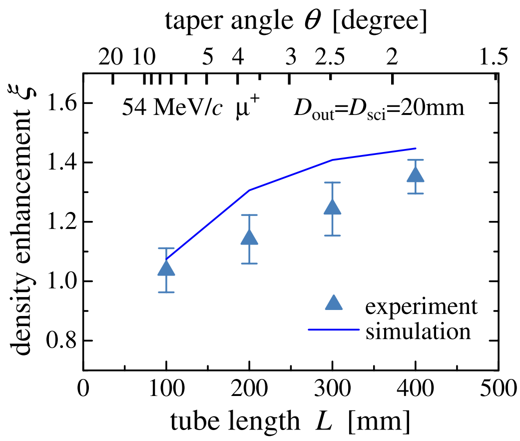

Fig. 4. (Color online) The beam density enhancement ξ for 54 MeV/c μ^+ as a function of the tube length L for $D_{out} = D_{sci} = 20$ mm. The solid line shows the simulation.

with respect to the inner wall increases, the probability of muons coming back to the inner side of the tube by a small angle scattering decreases steeply.

We simulated the density enhancement under vacuum condition for 27–81 MeV/c. The simulation shows the enhancement factor is about 2 and almost constant all over the momentum region, including commonly used surface muon of 27 MeV/c. The simulation also suggests that the density enhancement factor improves further when the tube is made of heavy material like copper, lead, or gold. Preparations in this direction are in progress.

In summary, we have observed a beam density enhancement of around two with tapered glass tubes for 54 MeV/c μ^+ and also μ^- beams in atmosphere. This enhancement is considered to be due to scattering of muons at the surface of the inner wall with small incident angles. A computer simulation with a multiple Coulomb scattering model reproduces the behavior of the experimental findings. The simulation also suggests that a similar density enhancement is expected for a broad momentum range of muons with a tapered tube placed in vacuum, and that the enhancement increases when a heavier material is used for the tube.

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