PROCEEDINGS OF SCIENCE

Construction of new DC muon beamline RCNP-MuSIC for muon applied science

---

D. Tomono[*a], M. Fukuda[a], K. Hatanaka[a], W. Higemoto[b], M. Ieiri[c], Y. Kawashima[a], Y. Kuno[d], T. Matsuzaki[e], M. Minakawa[3], Y. Miyake[c], Y. Nakazawa[d], K. Ninomiya[f], Y. Mori[g], S. Morinobu[a], A. Sato[d], K. Shimomura[c,a], K. Takahisa[a], A. Taniguchi[g] Y. Weichao[d] and M. L. Wong[d]

[a]*Research Center for Nuclear Physics (RCNP), Osaka University*
Ibaraki, Osaka 567-0047, Japan
[b]*Japan Atomic Energy Agency (JAEA)*
Tokai, Ibaraki 319-1195, Japan
[c]*High Energy Accelerator Research Organization (KEK)*
Tsukuba, Ibaraki 305-0801, Japan
[d]*Department of Physics, Osaka University*
Toyonaka, Osaka 560-0043, Japan
[e] *RIKEN Nishina Center, RIKEN*
Wako, Saitama 351-0198, Japan
[f]*Department of Chemistry, Osaka University*
Toyonaka, Osaka 560-0043, Japan
[g] *Kyoto University Research Reactor Institute (KURRI)*
Kumatori, Osaka 590-0494, Japan
E-mail: `tomono@rcnp.osaka-u.ac.jp`

A new DC muon beamline MuSIC was set up at the Research Centre for Nuclear Physics (RCNP), Osaka University. The MuSIC beamline provides an high-intensity and low-energy muon beam with distinctive devices of superconducting solenoid magnets. A beamline commissioning and a feasibility study for μSR (Muon spin rotation, relaxation and resonance) are in progress. In the commissioning, $\sim 10^5$ count/(sec$\cdot 1\mu$A-proton) of negative muons and $\sim 10^6$ count/(sec$\cdot 1\mu$A-proton) of positive muons were measured with TOF setup in the experimental port using 60 MeV/c muon beam. The non-destructive elemental analyses and nuclear physics experiments with a negative muon beam have been recently started. In a feasibility study for μSR with a positive muon beam, we observed spin asymmetry spectra with a test sample in a magnetic field of 0.004 Tesla using a newly constructed μSR spectrometer.

The 19th International Workshop on Neutrinos from Accelerators-NUFACT2017
25-30 September, 2017
Uppsala University, Uppsala, Sweden

---

[*] Speaker.

PoS(NuFact2017)111

1. Introduction

In recent years, there has been an increasing sdemand for the high-intensity and low-energy muon beam. The low energy muon beam is implanted to explore various kind of materials as an analyzing probe for sample materials. A negative muon can be utilized for non-destructive elemental analyses: the implanted negative muon is captured by the nuclei in the sample material and then, it induces muonic X-rays, which is characteristic to the atomic number of the nucleus. They transfer lots of information about the elemental composition of the sample inside. On the other hand, a positive muon is often utilized as a magnetic probe of the materials by the μSR (Muon spin rotation, relaxation and resonance) technique. The polarized positive muon stopped inside the target and interacts with the internal magnetic field. A positron decayed from the muon emitted preferably to the muon spin and therefore the spin asymmetry has information about the magnetic property inside the material. Furthermore, the high-intensisty and low-energy muon beam has another potential to serve as probes for a fundamental physics, nuclear physics and chemistry. The beam intensity is a key to reduce the statistical error especially for the fundamental physics. Since the potential impacts of the capability on non-destructive analysis, μSR and other muon experiments have been recently recognized to be larger, a new muon beamline to produce the high-intensity and low-energy muon beam is highly expected for these purposes.

A new continuous (DC) muon beamlines, MuSIC (MUon Science Innovative Channel) was constructed at the Research Center for Nuclear Physics (RCNP), Osaka University [1]. The MuSIC provides intense positive and negative muon beams from 28 to 110 MeV/c. It is a versatile beamline for various experiments by changing the setup for the experimental purposes. The distinctive feature of the MuSIC is a novel muon production method. A pion capture superconducting solenoid magnets enabled us to collect pion very efficiently with its large acceptance. At full proton beam power of 0.4 kW, (4.2± 1.1) $\times 10^8$ counts/sec positive muons were measured at the solenoid exit [2]. The number of negative muon measured was about one order lower. This indicates that the MuSIC beamline has a better muon-production efficiency than that of the conventional beamline. In 2017, by increasing the radiation shields around the muon production target, we could use 1.1 μA primary proton beam for the muon production. At present, the intense muon beam is available for all experiments at MuSIC. The non-destructive elemental analyses with the negative muon beam [3] were reported prior to other experiments. With the positive muon beam, feasibility studies of the μSR in the condensed matter physics were started to construct a new spectrometer [4].

In this paper, we will briefly explain the MuSIC beamline, report measurements of the muon beam intensity and momentum spread, and show a current status of μSR feasibility study.

2. Muon Beamline

Figure 1 shows a layout of the MuSIC production solenoids and transport beamline at RCNP. A pion capture solenoid magnet and a muon transport solenoid magnet, and a muon production target made of graphite are also shown schematically. The Ring Cyclotron accelerator provides protons and heavy ions from accelerator with a variable energy. For muon production, a proton beam with the energy of 392 MeV and a beam current of 1.1 μA is provided at 16.8 MHz repetition rate.

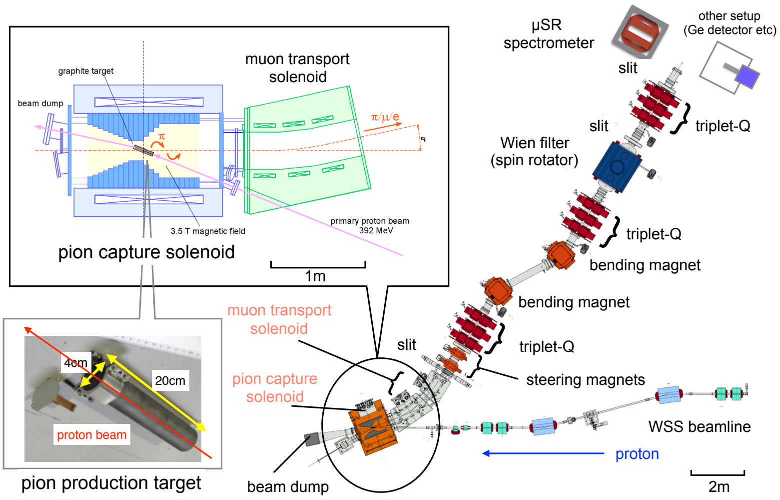

Figure 1: Layout of the new DC muon beamline, MuSIC. The MuSIC beamline is located in the west experimental hall in RCNP, Osaka University. Enlarged detail view of the pion capture solenoid and the first muon transport solenoid are shown in the inset. A photograph of thick muon production target (made of graphite) is additionally shown in the inset.

There are some characteristic devices to produce the large number of muons with the MuSIC beamline. One is to employ a very thick 200 mm-long graphite target for muon production. Its photograph is shown in Fig. 1 inset. The proton beam deposits an energy which is larger than the minimum muon production energy of 290 MeV. Although the proton beam current of 1.1 μA is not high compared with other facilities, the number of pions can be emitted owing to the thick target. The other is to collect the muon with the large-acceptance capture solenoid magnet with 3.5 Tesla magnetic field. The transport solenoid magnets with a 2.5 Tesla magnetic field, transport the muon beam to the downstream with a dipole field which can focus the muon beam at the center to cancel the centrifugal force. A schematic figure is also shown in Fig. 1 inset. The both solenoid fields are carefully optimized to maximize the muon yield in the construction (Ref. [5] in detail). The pion and muon beams are captured in the pion capture solenoid and then, transported through the muon transport solenoid. The beams are subsequently transported to an experimental port with conventional beamline components of triplet-quadrupole magnets, bending magnets, and Wien filer. The Wien filter is installed to rotate a muon spin by 74 ° at 28 MeV/c with a 400 kV electric field in a 15 cm gap, or to eliminate contaminated positrons as an electrostatic separator (DC separator) with a $\sim$100 kV electric field. Four sets of beam slit were mounted to improve the momentum spread or the beam size.

3. Muon beam commissioning by TOF

The muon beam intensity was measured by the time-of-flight (TOF) method. A schematic view of its experimental setup is shown in Fig. 2 (a). A start counter was installed at the end of the beamline. The time difference between the start counter ($t = t_{\rm start}$) and the beam extraction RF timing ($t = t_{\rm RF}$) was measured for separating $\mu^{\pm}$ from $e^{\pm}$ and $\pi^{\pm}$. The proton beam intensity was

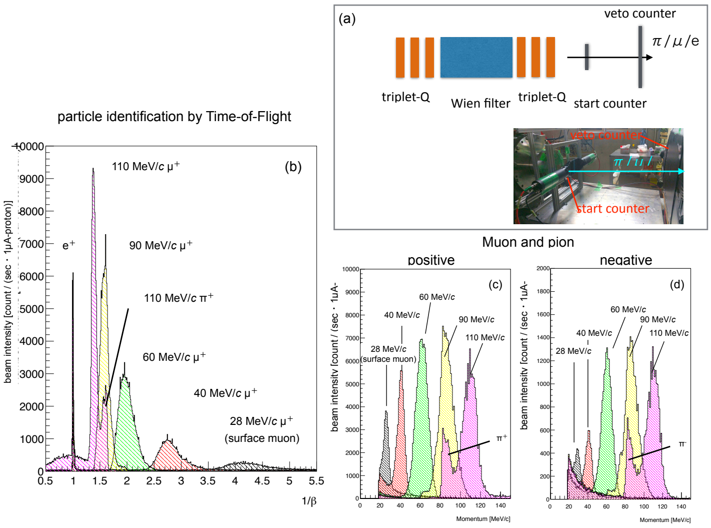

Figure 2: (a) Schematic view and photograph of the experimental setup in TOF measurement. (b) $1/\beta$ dependence of the beam intensity for e^+, μ^+ and π^+ at momenta of 28, 40, 60, 90, and 110 MeV/c. (c), (d) Momentum distribution for positive and negative muons, respectively. A momentum spread ($\Delta p_\mu/p_\mu$) is estimated to be approximately 10 % for each momentum. Note that vertical axes are scaled assuming that the 1 μA proton beam is used for the muon beam production.

reduced by 1/9 to avoid overlapping the muon beam within the same time window in the accelerator side.

Figure 2 (b) shows a $1/\beta$ dependence of the beam intensity for each particle at momenta of 20, 40, 60, 90, and 110 MeV/c. It shows that the $\mu^\pm$, $e^\pm$ and $\pi^\pm$ are clearly separated. Note that the measured muon beam intensity in the vertical axis is scaled assuming that the 1 μA proton beam is used to produce the muon beam considering a practical experimental condition. Figures 2 (c) and (d) show the positive and negative muon momentum spectra respectively, in which the muon momentum (p_μ) is calculated from

$$p_\mu = \frac{m_\mu \beta_\mu}{\sqrt{1-\beta_\mu^2}}, \tag{3.1}$$

where the m_μ denotes the muon mass. From each spectra, the momentum spread ($\Delta p_\mu/p_\mu$) was calculated to be approximately 10 % in each momentum when all beamline slits were fully opened. Further optimization of the momentum spread will be required by adjusting widths of the beamline slits.

Figure 3 shows momentum dependence of the muon beam intensity for negative (a) and positive (b) muons. At 60 MeV/c, 1×10^5 count/(sec·1μA-proton) of negative muons and 7×10^5 count/(sec·1μA-proton) of positive muons were obtained at the experimental port. In these measurement, beamline slits were fully opened and no beam-end collimator was attached. The beam intensity decreases above 60 MeV/c as the incident pion decreases. Note that beam intensity in the vertical axis is also scaled assuming that 1 μA primary proton beam is used to produce the muon beam. Recently, we have succeeded in transporting 3×10^4 count/(sec·1μA-proton) for surface muons by changing a proper surface-muon beamline setting.

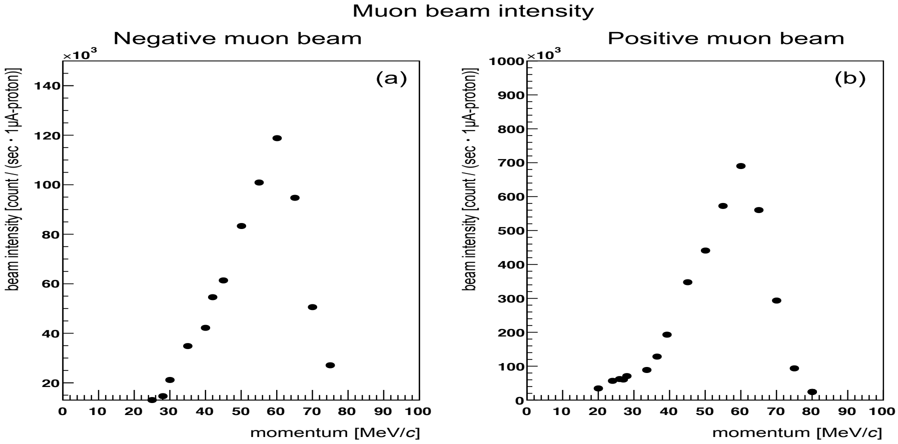

Figure 3: Momentum dependence of muon beam intensity for (a) negative and (b) positive muons.

4. μSR spectrometer and feasibility study

A new μSR spectrometer was newly installed at the experimental port. Figure 4 (a) shows a photograph of the μSR spectrometer [4]. Five pairs of Helmholtz coils were fabricated with the aluminum frames in the spectrometer. These coils and frames were refurbished from the old spectrometer used at KEK-MSL [6]. Figure 4 (b) shows the schematic view of counter configuration. Along with the muon beam, a beam defining counter was installed to separate muons from contaminated positrons, which was made of 0.5 mm-thick thin plastic scintillators viewed from two photo-multipliers. Just behind of the defining counters, large μ-e decay positron counters (20 cm × 20 cm and 0.5 cm-thickness with a 4 cmϕ hole at the center) were currently mounted in tandem to the upstream and downstream of a sample chamber. A helium flow cryostat (MicrostatHe, Oxford Instruments) was fabricated in the sample chamber. We have already succeeded a cooling test around 4 K with this setup.

A feasibility test was started with the present μSR spectrometer with 60 MeV/c muon beam. The spin polarization is naively estimated to be approximately 60 % at 28 and 60 MeV/c [7]. The beam is collimated at 30 mmϕ and effective intensity of approximately 2×10^4 counts/sec. From positron time spectra of upstream ($N_U(t)$) and downstream ($N_D(t)$) counters, we calculated the spin asymmetry as follows:

$$A(t) = \frac{N_U(t) - \alpha N_D(t)}{N_U(t) + \alpha N_D(t)}, \tag{4.1}$$

where α denotes a correction factor to cancel solid angle difference between two counters. We clearly observed the decay positron spectra and muon spin precession asymmetry in the transverse field of 0.004 Tesla in Fig. 4 (c). Since the constant background level is slightly high, we are now investigating background sources carefully to improve spectra.

5. Summary

At the MuSIC beamline, the beam commissioning is in progress. We measured the muon intensity typically $\sim 10^6$ counts/sec inflight-decay positive muons at 60 MeV/c. Parts of scientific

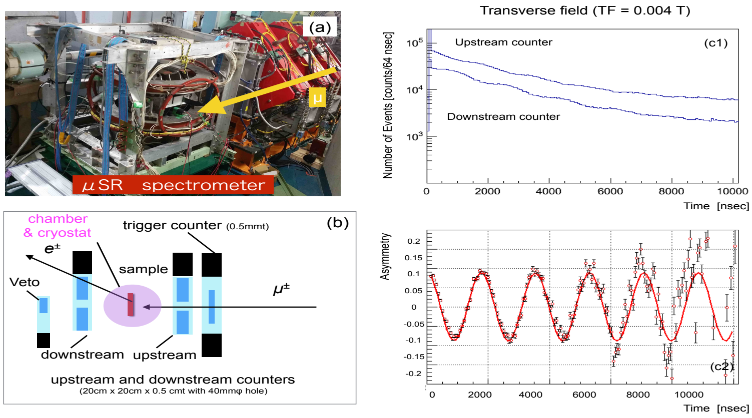

Figure 4: (a) Photograph of the μSR spectrometer installed at the end of the beamline. The experimental setup was easily interchanged with the other experimental setup. (b) Schematic view of the counter configuration from the top. A muon defining, muon decay and veto counters are schematically shown. (c1) Precession spectra of the muon decay positron observed with the upstream and downstream counters shown in Fig. (b). The magnetic field of 0.004 Tesla was applied transverse to the muon spin direction. (c2) Asymmetry spectrum in a transverse field of 0.004 Tesla. Red lines show a fitting results.

programs, especially non-destructive elemental analysis with the negative muon beam was started. The μSR feasibility study for the condensed matter physics was also started with the positive muon beam. Further beamline improvement and optimization will enable us to increase the muon intensity and to improve beam quality. By advancing commissioning test, feasibility test, and beamline improvement, we will be able to promote the muon science program with both negative and positive muon beams to provide the high-intensity and low-energy DC muon beam at MuSIC.

References

[1] http://www.rcnp.osaka-u.ac.jp/index_en.html

[2] S. Cook *et al.*, *Delivering the world's most intense muon beam*, Phys. Rev. Accel. Beams **20**, 030101 (2017).

[3] K. Terada *et al.*, *Non-destructive elemental analysis of a carbonaceous chondrite with direct current Muon beam at MuSIC*, Sci. Rep. **7**, 15478 (2017).

[4] D. Tomono *et al.*, *Muon Beamline Commissioning and Feasibility Study for μSR at a New DC Muon Beamline, MuSIC-RCNP, Osaka University*, Proc. of the 14th International Conference on Muon Spin Rotation, Relaxation and Resonance (μSR2017), JPS Conf. Proc. **21** 011057 (2018).

[5] M. Yoshida *et al.*, *Superconducting solenoid magnets for the MuSIC project*, IEEE Trans. Appl. Supercond. **21**, 1752 (2011).

[6] K. Nagamine, *Pulsed μSR facility at the KEK Booster*, Hyp. Int. **8**, 787 (1981).

[7] D. Tomono *et al.*, *New DC muon beamline, MuSIC : present status of beamline commissioning and prospects*, Proc. of 18th international workshop on neutrino factories and future neutrino facilities search (NuFact16), submitted.