The RCNP Cyclotron Facility; Activities of the Experimental Group in 2017

MAIKo; active target system for nueclear reaction measurements in inverse kinematics

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The Kyoto University group has performed alpha inelastic scattering off ^{10}C using the MAIKo active target [1] (Figs. 1, 2) to search for alpha cluster states in ^{10}C.

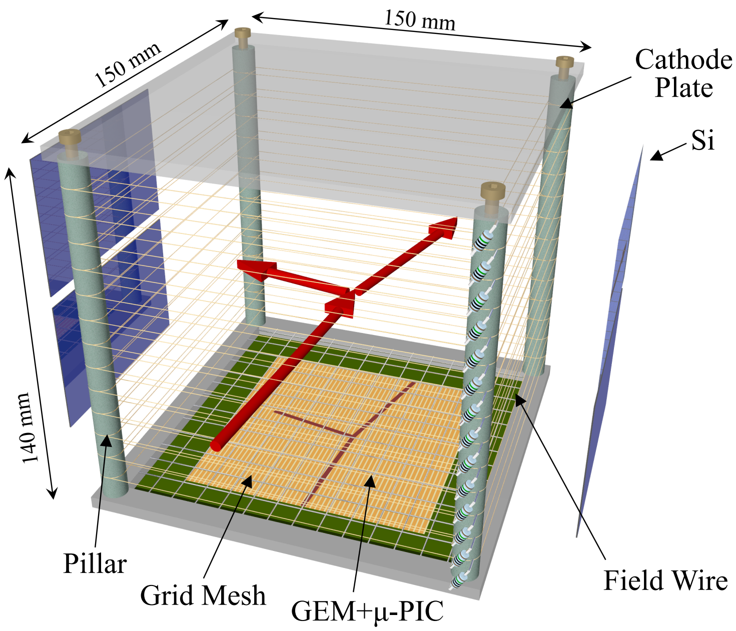

Figure 1: Structure of the effective region of MAIKo.

A ^{10}C secondary beam at 75 MeV/u was produced from a ^{12}C primary beam at 96 MeV/u on 508-mg/cm^2 ^{9}Be target and the fragmentation separator at the EN beam line [2]. The intensities of the primary and the secondary beams were 50 pnA and 80 kcps, respectively. The purity of ^{10}C was 95% at F3 focal plane. The position of the incident beam at F3 was measured by the two low-pressure MWDCs which were newly developed at RCNP (Fig. 3).

The MAIKo time projection chamber (TPC) was operated with He(96%) + CO$_2$(4%) mixture gas at 500 hPa. The sensitive volume of the MAIKo TPC is 10 × 10 × 14 cm^3. The TPC gas was used also as the ^{4}He target. MAIKo active target enabled us to detect low-energy recoil alpha particles around $E_\alpha \sim 500$ keV.

References

[1] T. Furuno *et al.*, J. Phys.: Conf. Ser. **863** (2017) 012076.

[2] T. Shimoda *et al.*, Nucl. Inst. and Meth. in Phys. Res. B **70** (1992) 320–330.

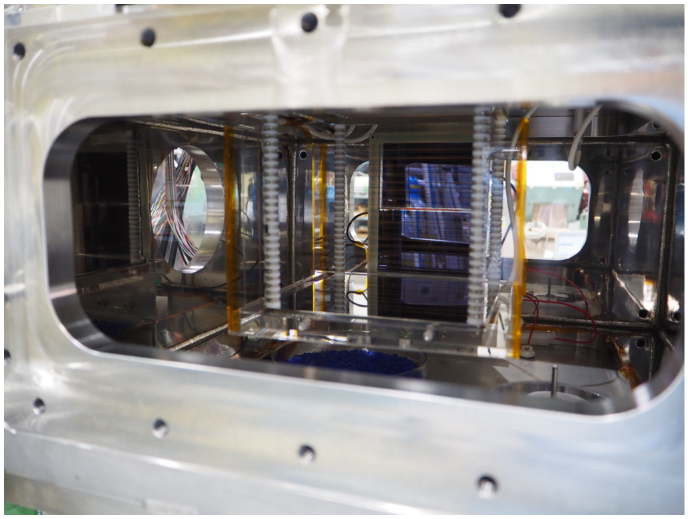

Figure 2: Photograph of the interior of the vacuum chamber.

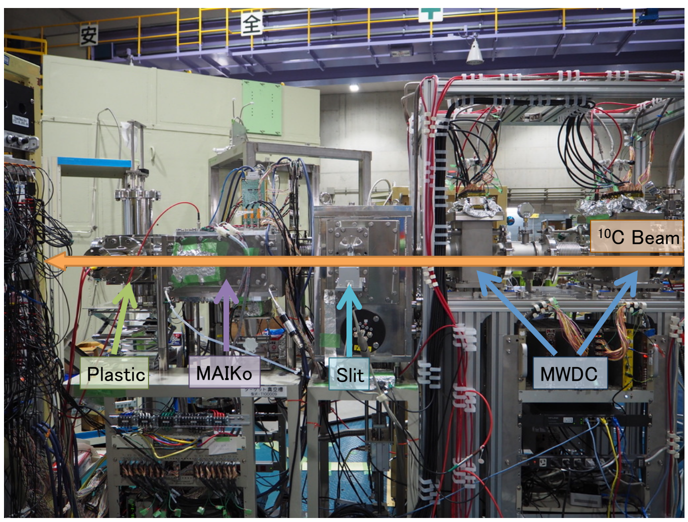

Figure 3: Experimental setup of the E463 experiment..

Full beam current operation of the new DC muon beam line, MuSIC

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This year has been one of major milestones of the MuSIC project. The DC muon beam facility, MuSIC [1], started full current operations with a 1.1 μA proton beam from the beginning of this year. Six user experiments were performed with the full intensity operation in this year, while many new proposals for MuSIC were submitted to the B-PAC. The muon science program of RCNP has successfully launched.

In order to upgrade the proton beam current to the pion production target from 20 nA to 1.1 μA, intense works were made from 2016 to January 2017. The radiation shields around the pion capture system were reinforced with additional concrete blocks, and some parts were replaced with new one made from radiation harder materials. A new target support system was installed so as to maintain the radiation-activated target remotely.

The first beam of 1.1 μA protons was injected to the Graphite target of the pion capture system on 18th February, 2017. The target temperature, vacuum pressure inside the beam ducts, and muon yields at the exit of the MuSIC-M1 beamline were carefully checked in the high intensity operation. All systems worked as designed. MuSIC has started high intensity operations. The beamline can provide both positively and negatively charged muon beams with its maximum intensity of 10^5-10^6 counts/s and 10^4-10^5 counts/s, respectively. The maximum momentum of the beams is 110 MeV/c. The Wien filter of the beamline was also well conditioned to work as a DC separator for up to 60 MeV/c.

The MuSIC-M1 beamline commenced to provide the intense muon beam to user experiments from February, 2017. Table 1 summarizes a list of user experiments, which use the muon beam. The first experiment with 1.1 μA operation was the G02 experiment conducted by Prof. Sakurai (RIKEN) to study reaction mechanism of the muon nuclear capture process. The beam time started at 23rd February, 2017, just after the shake-down operation. The G02 and E475 are parts of a series of experiments of an ImPACT program, Impulsing Paradigm Change through Disruptive Technologies Program, entitled "Reduction and Resource Recycling of High-level Radioactive Wastes through Nuclear Transmutation" managed by Dr. Fujita [2]. Pd isotopes, which are one of crucial isotopes in high-level radioactive wastes from spent fuel of nuclear power plants, were irradiated by negative muons to study the muon capture reaction. The successful measurement of the G02 experiment was followed by five user experiments in this year. In addition, another four proposals were approved at B-PAC held in this summer. These experiments aim for fundamental science in a variety of fields: nuclear and particle physics, material science, chemistry and earth and planetary sciences and so on. There has been great progress in these experiments. RCNP-MuSIC expands opportunities for scientists to utilize new research methods with muon beams for their research activities in a wide range of studies.

The μSR program for material science is one of key subjects of the MuSIC activity. A μSR spectrometer, which was built for the Tokyo/KEK muon facility (BOOM) in the 1980's, was rejuvenated with new scintillation counters and DAQ system designed for a DC muon beam. A mini-cryostat and a cooling system are ready to cool down a sample to about 4 K. Much of the MuSIC working group's effort has been focused on preparations and feasibility studies of the μSR measurement. We plan to carry out the first μSR user experiment, E517, in the coming year.

The first scientific paper of the MuSIC user experiments was published by the E411 group in November, 2017 [3]. The experiment is the very first official user experiment of the MuSIC-M1 beamline, although it was performed with a 20 nA proton beam in 2015. They have successfully demonstrated a non-destructive muonic X-ray analysis method for determining the composition of carbon-containing asteroid samples. This achievement was also reported in the newspapers and on NHK TV.

The remarkable and successful milestone of this year is just reward for many people who have been working so hard with the MuSIC group over several years. We would like to thank all of these people for their efforts because the milestone was not achieved without their dedication and devoted supports.

Table 1: A list of user experiments, which use the MuSIC muon beams.

Exp. Number	Title	Beam time (days)	Status
E411	Development on non-destructive elemental analysis of planetary materials by using high intensity μ^- beam	3	Done 11/2015
E475	Reaction Mechanism of Muon Nuclear Capture on Pd Isotopes	2	Done 05/2016
G02	Reaction Mechanism of Muon Nuclear Capture on Pd Isotopes	3	Done 02,03/2017
E467	Development of muonic X-ray measuring system and precise determination of muon capture probabilities for iron compounds	2	Done 06/2017
E476	Measurement of the muon capture on ^{3}He by using of the high intensity continuous μ^- beam		Partially done 03/2017
E489	Muon-gamma spectroscopy for neutrino nuclear responses	1.5	Done 02/2018
G02-2	Reaction Mechanism of Muon Nuclear Capture on Pd Isotopes	3	Done 01/2018
E490	Muonic X-ray analysis of planetary materials: Development on Isotopic measurement and Muonic X-ray imaging	3	Done 06/2017
E517	Study of Novel Superconductivity in Layered Structural Superconductor by Means of μSR Technique at MuSIC	3	Approved
E527	Measurement of the lifetime of hyperfine excited state in muonic hydrogen atom	3	Approved
E528	Non-destructive elemental analysis of carbonaceous, ordinary and enstatite chondrites using DC Muon beam: Application to chemical classification of extraterrestrial materials	3	Approved
E529	Development of a new analytical method by muonic X-ray measurement; identification of chemical formula without contact	3	Approved

References

[1] S. Cook *et al.*, Phys. Rev. Accel. Beams **20**, 030101 (2017), doi:10.1103/PhysRevAccelBeams.20.030101.

[2] Reduction and Resource Recycling of High-level Radioactive Wastes through Nuclear Transmutation: `http://www.jst.go.jp/impact/hp_fjt/en/index.html`

[3] K. Terada, A. Sato, K. Ninomiya, Y. Kawashima, K. Shimomura, G. Yoshida, Y. Kawai, T. Osawa and S. Tachibana, Scientific Reports **7**, 15478 (2017), doi:10.1038/s41598-017-15719-5.

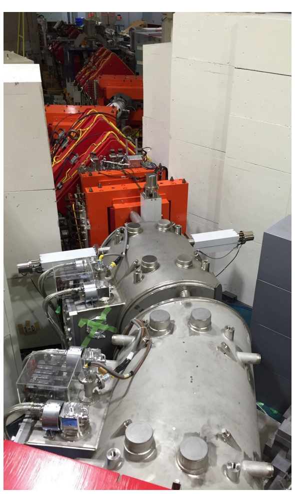

Figure 1: The MuSIC-M1 beamline during the enforcement of the radiation shielding blocks. The photo was taken from a top of the pion capture solenoid.

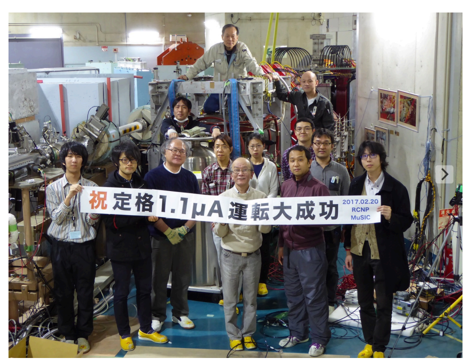

Figure 2: The MuSIC working team together with many collaborators as a commemorative photo for the successful operation with the 1.1 μA proton beam.