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Ultra slow muon microscopy by laser resonant ionization at J-PARC, MUSE

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Abstract As one of the principal muon beam line at the J-PARC muon facility (MUSE), we are now constructing a Muon beam line (U-Line), which consists of a large acceptance solenoid made of mineral insulation cables (MIC), a superconducting curved transport solenoid and superconducting axial focusing magnets. There, we can extract 2×10^8/s surface muons towards a hot tungsten target. At the U-Line, we are now establishing a new type of muon microscopy; a new technique with use of the intense ultra-slow muon source generated by resonant ionization of thermal

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Muonium (designated as Mu; consisting of a μ^+ and an e^-) atoms generated from the surface of the tungsten target. In this contribution, the latest status of the Ultra Slow Muon Microscopy project, fully funded, is reported.

Keywords J-PARC · Muon · Ultra slow muon · VUV · Pulsed laser · Resonant ionization

1 Introduction

The surface muon beam (μ^+, 30 MeV/c) which has been used for the studies of condensed matter physics or chemistry is conventionally obtained from the decay of positive pions (π^+) stopped near the surface of the pion production target in the proton beam line and has large energy broadening with an implantation depth of 0.1 to 1 mm. Despite the name of surface muon, it has been used as a probe for bulk phenomena rather than surface phenomena. In these two decades, a new method to generate ultra-slow muon beam with energy 0.2 eV has been developed at KEK and RIKEN-RAL, utilizing the resonant ionization technique [1]. However, its yield of 20/s maximally obtained [2] was not even enough for the researches in material science. In order to obtain a sufficient yield for the variety of surface, and nano-science, it was essential to embark on a new project at J-PARC MUSE (Muon Science Establishment), where the world strongest pulse muon source is available.

2 D-Line, the strongest pulsed muon beamline

For Phase 1 at J-PARC MUSE, we managed to install a superconducting decay/surface beam line, so called, D-Line, with a modest-acceptance pion injector of about 45 mSr, where either surface muons, or decay muons (5–120 MeV/c, μ^+ and μ^-) that are obtained through the in-flight decay of π^+/π^- confined by a strong longitudinal magnetic field of several tesla from a superconducting decay solenoid magnet, can be extracted. Since the first delivery of the surface muon beam to the experimental area on September 26th, 2008, the muon beam commissioning had been continued. In November 2009, the surface muon extraction rate was significantly increased up to 1.8×10^6/s with a 120 kW proton beam from the 3 GeV synchrotron (RCS). The achieved intensity was equivalent or even larger than that (1.2×10^6/s) at the RIKEN-RAL muon facility [3]. This is the reason why the world strongest pulsed muon source was claimed to be achieved at MUSE even by using only a 120 kW proton beam. This intensity would correspond to 1.5×10^7/s surface muons when in the future the proton beam power will reach 1 MW [4]. Since November 26th, 2010, the proton beam power from the RCS has steadily increased up to 220 kW, consequently delivering 3.2×10^6/s of intense surface muon or several 10^6/s of decay muon beam, until the earthquake on March 11th, 2011.

3 U-Line, dedicated for the ultra slow muon

In addition to D-Line, we were funded to install the second muon beamline, so called U-Line, which consists of a large acceptance solenoid made of mineral

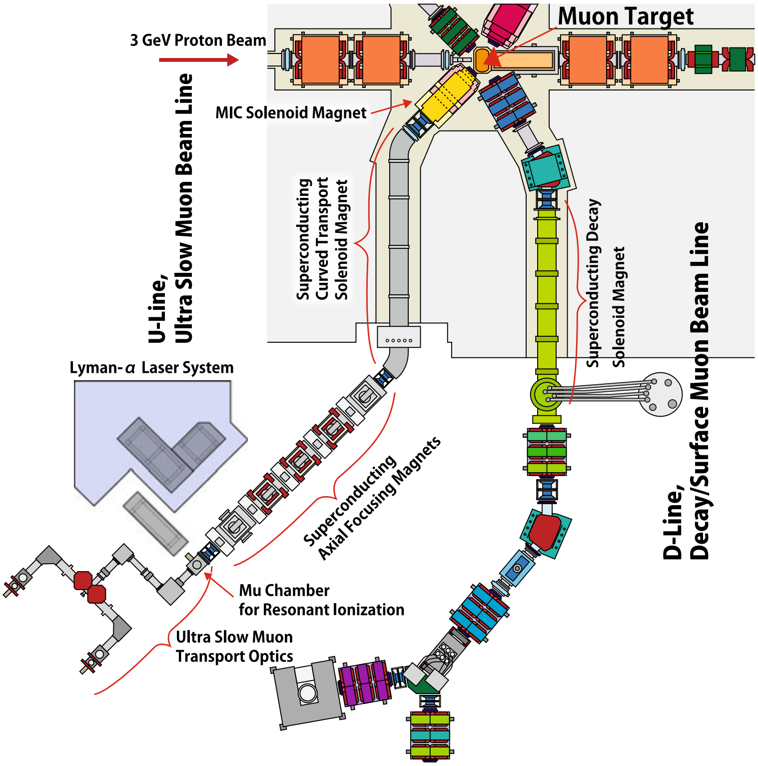

Fig. 1 A layout of J-PARC MUSE, D-Line and U-Line in the Materials and Life science experimental Facility (MLF) for neutron and muon

insulation cables (MIC), a superconducting curved transport solenoid magnet and a superconducting axial focusing magnets system. There, we can collect surface muons with a large acceptance of 400 mSr. Compared to the conventional beamlines such as D-Line, the large acceptance of the front-end solenoid will allow for the capture of more than 10 times intensity pulsed muons [5]. With a muon capture of 5×10^8/s surface muons, we can collect 2×10^8/s surface muons on the W target in the Mu chamber, with an approximate transport efficiency of 40 %. The U-Line components of the superconducting curved and axial focusing magnets were already fabricated and those commissioning will be performed in the autumn of 2012 (Fig. 1).

4 Ultra slow muon microscopy

Ultra slow muons are generated by resonant ionization of thermal Mu atoms generated from the surface of a hot tungsten foil, placed at the intense surface muon beam line. In order to efficiently ionize the Mu near the W surface, we adopted a resonant ionization scheme via the {1S-2P-unbound} transition. In order to induce 1s-2p transitions, Lyman-α light of 122.088 nm is needed. To generate such Lyman-α (VUV;Vacuum Ultra Violet) laser, we have been adopting the resonant four-wave

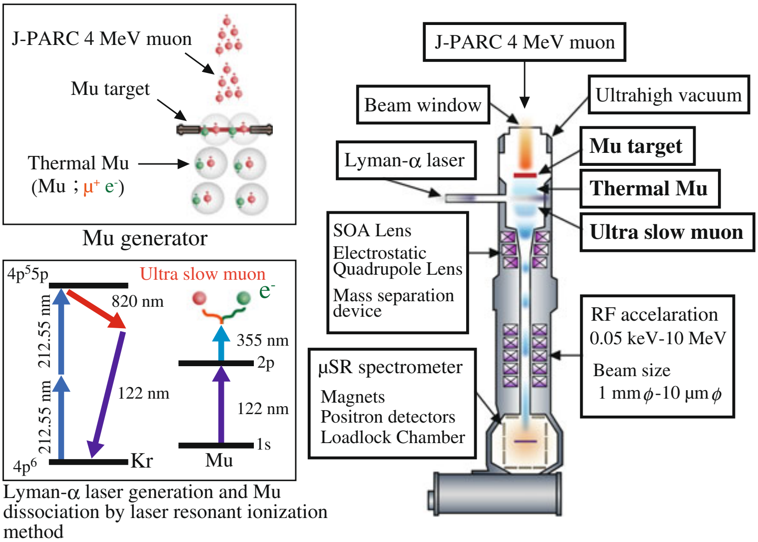

Fig. 2 A concept of the ultra low muon microscopy

frequency mixing ($\omega_{VUV} = 2\,\omega_r - \omega_t$) where two 212.5 nm photons(ω_r) are used for two-photon resonant excitation of the 4P^{5}5P[5/2] state in Kr, subtracted by a photon with a tunable difference wavelength (ω_t; 820 nm), rather than the frequency tripling (non-resonant) of 366 nm photons, of which conversion efficiency is in the order of 10^{-5-6}. In our new laser system developed by Wada et al. [6], ω_r(100 mJ/p, 2ns) is generated as the 5th harmonics of 1062 nm (1 J/p), which consists of all solid state laser system, such as diode laser, fiber amplifier, regeneration amplifier, OPA, OPG etc., generating expectedly more than 71 μJ/cm^2 Lyman-α light of the saturation intensity for the Doppler broadened Mu at 2000 K.

Comparing the surface muon intensity between RIKEN-RAL (1.2×10^6/s) and U-Line (2×10^8/s), we can gain a factor of 160. Taking into account the repetition rate of the pulsed laser system and the muon beam, we can also gain a factor of two, since both the laser and the muon beam can be synchronized to 25 Hz at MUSE, whereas the muon beam (50 Hz) is synchronized to every second laser pulse at the RIKEN-RAL facility. Moreover, the new solid state laser system is designed to generate an intense Lyman-α light of more than 100 μJ/cm^2 needed to saturate the transition of Mu from the 1S state to the 2P state [6], whereas only about 1 μJ/cm^2 of the Lyman-α light was produced at RIKEN-RAL. Consequently, we may expect, as a maximum, 0.6×10^6/s of the ultra-slow μ^+/s at MUSE (Fig. 2). This work was supported by a Grant-in-Aid for Scientific Research on Innovative Areas "Ultra Slow Muon" (No. 23108002) of the Ministry of Education, Culture, Sports, Science, and Technology, Japan and its commissioning will be performed in the winter of 2012.

5 Summary

At J-PARC MUSE, we are installing the U-Line which consists of a large acceptance solenoid made of mineral insulation cables (MIC) and a superconducting curved transport solenoid and 6 sets of superconducting axial focusing magnets. There, we can collect surface muons with a large acceptance of 400 mSr. Finally, we are expecting a rate of 0.6×10^6 ultra slow muons/s out of the 2×10^8 surface muons/s. When the production of intense ultra-slow muon source is realized, the use of its short-range penetration depth (eg. 1 nm resolution at a penetration of 1 nm, and 10 nm at a penetration of 6 nm in Gold) will allow muon science to be expanded towards a variety of new scientific fields such as,

1) Surface/boundary magnetism utilizing its spin polarization and unique time-window.
2) Surface chemistry, utilizing a feature of a light isotope of hydrogen; such as catalysis reactions.
3) Precise atomic physics such as QED,
4) Ion sources towards $\mu^+\mu^-$ collider experiments in high-energy physics.

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