Ultraslow Positive-Muon Generation by Laser Ionization of Thermal Muonium from Hot Tungsten at Primary Proton Beam

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Thermal muonium (positive muon μ^+ and electron e^-) atoms were produced from the surface of a hot (2300 K) and high purity tungsten foil placed at the primary beam of 500 MeV pulsed protons. Resonant ionization ($1s \rightarrow 2p \rightarrow$ unbound) of the thermal muonium with pulsed laser sources was achieved with reference to thermal hydrogen isotopes (D and T) so as to produce a potentially intense ultraslow (as low as 0.2 eV) positive muon beam with an extremely narrow phase-space volume and high stopping density.

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So far, at all accelerator laboratories, muons are obtained by either pion decay in flight (decay μ^+/μ^-) or π^+ decay at the surface skin of a pion production target (surface μ^+). There, even after a careful design of the beam channel, the range width of the stopping muons is larger than 10 mg/cm^2 and the size of the muon beam spot is typically a few cm^2. A significant intensity decrease is inevitable when we wish to study samples with smaller dimensions. If we could establish a method to increase the slow μ^+ intensity, many new types of muon science experiments would be realized.

There have been three proposals up to now concerning how to achieve such slow muon beam production: (a) the thermal muonium (designated as Mu) ionization method by adopting the phenomena of the thermal Mu emission after stopping conventional (MeV) muons inside specially selected materials followed by ionization of the Mu [1]; (b) the beam cooling method by using electromagnetic confinement as well as acceleration or deceleration after detecting the phase space of each injected conventional muon [2]; (c) the degrader method by adopting a stopping material with a large energy gap, such as a solid layer of a rare gas element (Ne, Ar, etc.) [3,4].

In this Letter, we report the first successful experiment on ultraslow μ^+ production by the thermal Mu ionization method which had originally been proposed as the third step following two achievements at the pulsed muon facility of UT-MSL located at KEK (National Laboratory for High Energy Physics), namely: (a) the production of thermal Mu in vacuum [5] and (b) the laser ionization of the thermal Mu using a pulsed laser and a pulsed muon beam [6]. Once we can accommodate these two steps right at the primary pulsed proton beam line, as shown in Fig. 1, a significant increase in the ultraslow μ^+ intensity can be expected; compared to the case starting with a few MeV muon beams available at the end of the muon-producing beam channel, an intensity increase can be expected by a factor corresponding to the inverse of the solid angle of the beam channel (10^2–10^3) [1].

In order to realize this ultraslow μ^+ production idea, a laboratory space with a dedicated pulsed (50 ns width and 20 Hz repetition rate) proton beam line from the 500 MeV Booster synchrotron at KEK was constructed. Hot tungsten (W) was adopted as the thermal Mu producing target. All the target area as well as the following ion optics of slow μ^+ transport was maintained at a pressure below 10^{-8} Torr under the conditions of proton beam delivery and target heating. The actual target is composed of 2 mm thick boron nitride (BN) and 50 μm thick W. The BN, beside the 2300 K hot W foil, was for efficient π^+ production with the minimum allowable divergence of the proton beam. Thus, as seen in the inset of Fig. 1, the intended scenario is the following: low energy π^+ produced in the BN stops in the hot W, where, after the π^+ conversion to μ^+ and the μ^+ slowing down or stopping and diffusion inside the W foil, the thermal Mu is emitted from the W surface. The dependence of μ^+ stopping in 50 μm W on the BN thickness was found to be almost saturated at 1 mm using a Monte Carlo calculation [7].

For an efficient ionization method of the thermal Mu produced by the pulsed primary protons, we adopted a resonant ionization scheme using pulsed lasers, namely, the single photon resonant transition of $1s \rightarrow 2p$ (122 nm) followed by the photoionization transition $2p \rightarrow$ unbound (<366 nm) (see the inset of Fig. 1). For this purpose, a laser system was constructed for an intense 122 nm VUV light with a 200 GHz frequency width (FWHM), which was matched to the Doppler broadening

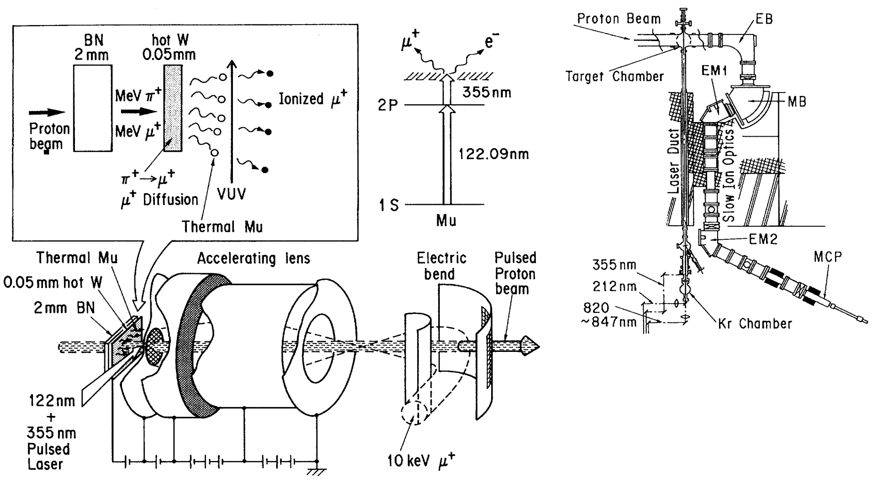

FIG. 1. Schematic view of the experimental arrangement for ultraslow μ^+ production by the laser resonant ionization of thermal Mu produced from a hot tungsten surface using pulsed 500 MeV protons. Insets show a schematic view of the mechanism for the ultraslow μ^+ production, an energy level diagram with the two transitions involved in ionizing the Mu, and a layout of ion extraction as well as laser lines.

of the thermal Mu. The laser light required for the VUV generation was produced by a system of Ti:sapphire (TiS) lasers consisting of exclusively solid-state oscillator and amplifier stages; the HRL, a TiS laser system pumped by a Nd:YAG laser to produce narrow-band 212 nm light and the LRL, a TiS laser system producing wide-band 820 nm light. As reported separately [8], these two different wavelength lasers are delivered to a satellite room where the 212 and 820 nm are combined by a dichroic mirror and introduced into a cell containing an optimized Kr/Ar gas mixture. There, coherent VUV light is generated by a four-wave sum-difference method developed at Imperial College [9]; the transition to $4P^5 5P$ [1/2, 0] of Kr levels is induced by two-photon absorption of the 212 nm light followed by the subsequent deexcitation by the 820 nm light, thus producing VUV at $\sim$122 nm. A precise frequency calibration of the generated VUV was made by measuring the resonance curve of the ionization of (1) H (D) atoms dissociated from residual H_2 (intentionally introduced D_2 gas) at the hot tungsten and (2) thermal D or T atoms produced by nuclear reactions by 500 MeV protons and tungsten as described later.

The VUV light pulse of a few μJ/(5 ns) generated synchronously with the proton beam pulse by the pulses given by the proton accelerator goes directly into the target region (10 mm gap between the hot W target and the front end of the ion extraction optics). The other laser light to ionize the $2p$ state of the Mu (355 nm) of (30 mJ)/(10 ns) is introduced into the target region through a path bypassing the Kr/Ar chamber.

The basic structure of the ion extraction optics for the ionized products of μ^+ is composed of a SOA immersion lens for 9.2 kV acceleration, as well as focusing (see Fig. 1) followed by an electric bend and a magnetic bend (MB) with axially focusing electric quadrupole lens. This front part of the ion optics is followed by two electric mirror bending systems with focusing electric Q lens (see the inset of Fig. 1). The system for detecting the ionized μ^+ consisted of a microchannel plate, as well as a decay-positron telescope placed at the end of the ion optics (8 m flight distance from the target). Thus, a twofold monitoring, namely, a mass analysis determined by the MB setting for a given acceleration voltage and a time-of-flight (TOF) spectrum with reference to either the proton pulse or the laser pulse can be used for the ionized μ^+.

After a series of trials, it was found that only tungsten material carefully chosen and correctly prepared was able to produce a successful result. The actual W material (35 mm high $\times$ 50 mm wide $\times$ 50 μm thick) was obtained from Metallwerk Plansee GmbH with a grade of 99.9999% purity. The material, after being heated up to 2300 K in a vacuum of 1.6×10^{-9} Torr, was then cooled down to 1600 K, where the surface treatment of a carbon removal was carried out under oxygen gas of 10^{-7} Torr for about 14 h. Then, the material was heated up to 2300 K and used for the thermal Mu ionization experiment after being maintained at the same temperature for 30 h. The W target was heated by a pulsed dc current; it was turned off for 1 ms around the proton pulse arrival times.

The resonant ionization measurements on thermal Mu were preceded by those of thermal D and T. By setting the correct VUV wavelength at 121.53 nm (121.52 nm) and selecting the mass/charge value in the ion optics for 2 (3), the laser resonant ionization was successfully observed for thermal D (T) atoms which were produced by nuclear reaction between the target materials (mostly BN) and the 500 MeV protons, followed by thermalization inside the hot W and evaporation from the W surface.

Then, after setting the VUV wavelength for Mu ionization (122.09 nm), the laser ionized μ^+ events were seen in a two-dimensional "mass-TOF" plot obtained with the ion optics scanning around the mass region corresponding to the muon mass (mass/charge $\approx 1/9$) (see Fig. 2). It should be noted that the ionized μ^+ had a sharply pulsed time structure (49 ns FWHM) even after a long-distance transportation towards the MCP. As a further confirmation of the resonant ionization signal, the VUV wavelength was varied so as to obtain the resonance curve shown in the inset of Fig. 2, where, as a reference, calibration data of the resonance curves for H, D, and T are also presented. The observed resonance peak wavelength [122.087(3) nm] agrees well with the value expected for Mu (122.088 nm).

A time-dependent change in the ionized μ^+ yield was obtained by changing the timing between the incoming proton pulse and the laser pulse. Similar measurements were carried out for thermal D and T which are produced by nuclear reactions of 500 MeV proton and the target. As shown in Fig. 3, the time evolution of the ionized μ^+ reflecting that of the thermal Mu emission into vacuum was observed where the muon lifetime was corrected. The main characteristics of the obtained result were reproduced by a formula describing a one-dimensional diffusion-limited time-dependent flux of particles in the target and a beam Maxwellian TOF distribution from the surface [5], including a loss rate of the particle flux due to the vacancy trapping, etc. (see Fig. 3). There the loss rates were obtained for Mu (0.03 μs^{-1}), D (0.007 μs^{-1}), and T (0.006 μs^{-1}). A detailed description will be reported elsewhere.

All of these results shown in Figs. 1, 2, and 3 demonstrate the first successful production of ultraslow μ^+ by laser resonant ionization of a thermal (0.2 eV) muonium produced from the surface of a hot W target placed at the primary proton line.

The yield of thermal Mu from W (N_{Mu}) can be written as $N_{\mathrm{Mu}} = I_p N_{\pi^+} N_{\mathrm{stop}\mu} \varepsilon_{\mathrm{Mu}}$, where I_p is the proton number per second, N_{π^+} the positive-pion production yield in 2 mm BN per incoming proton, $N_{\mathrm{stop}\mu}$ the yield of μ^+ stopping in 50 μm thick W foil per produced positive pion, and $\varepsilon_{\mathrm{Mu}}$ the thermal Mu production yield from the 50 μm thick hot W per stopped μ^+. The I_p used for the present experiment was 2.4×10^{13} protons/s (3.8 μA). N_{π^+} is given by a pion production cross section of 8.7 mb, taken from the value for 500 MeV protons on carbon, yielding $2.0 \times 10^{-4} \pi^+$/proton. The estimation of $N_{\mathrm{stop}\mu}$ was made by a Monte Carlo calculation, yielding $2.2 \times 10^{-3} \mu^+/\pi^+$ [7]. The value of $\varepsilon_{\mathrm{Mu}}$ is given by the μ^+ diffusion length divided by the target thickness as consistent with the experiment [5], $\varepsilon_{\mathrm{Mu}} \approx 10^{-2}$. Thus, N_{Mu} is estimated to be 1.1×10^5/s.

The yield of ultraslow μ^+ (N_{μ^+}) by laser ionization can be obtained by using $N_{\mu^+} = N_{\mathrm{Mu}} \varepsilon_{\mathrm{ioni}} \varepsilon_{\mathrm{coll}}$, where $\varepsilon_{\mathrm{ioni}}$ is the laser ionization efficiency and $\varepsilon_{\mathrm{coll}}$ the collection efficiency of the ionized μ^+ by the ion extraction optics. Originally, we intended to achieve the $\varepsilon_{\mathrm{ioni}}$ of 0.1 and the $\varepsilon_{\mathrm{coll}}$ of 0.3. At the present stage in the development of the laser and the ion optics, these values are far below the designed values. In our separate measurements concerning laser resonant ionization of H atoms dissociated from

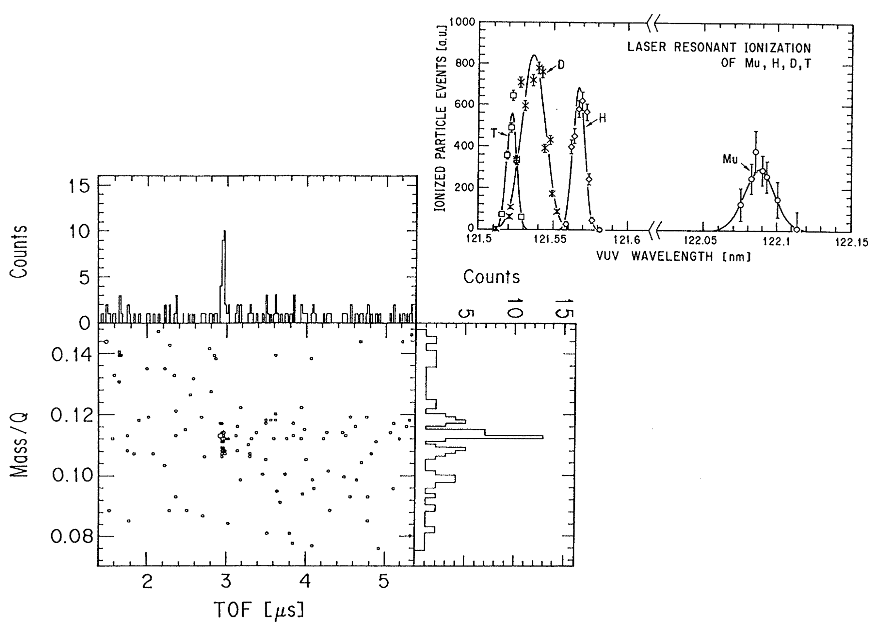

FIG. 2. Evidence for the ultraslow μ^+ production seen in the mass-TOF two-dimensional histogram and a resonance curve for the laser ionization of thermal Mu obtained by changing the VUV frequency. The inset shows resonance curves for the laser ionization of thermal Mu with reference to those of thermal H from residual H_2 gas, thermal D from introduced D_2 gas, and from thermal T of reaction products.

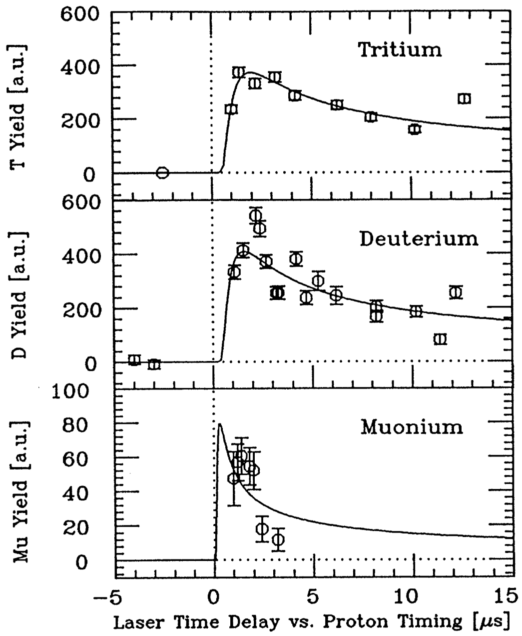

FIG. 3. Time evolution of the laser ionization of the thermal Mu as a function of the time delay between the laser pulse and the proton beam pulse. As a reference, results of similar measurements are shown for thermal D and T which are produced by nuclear reactions induced by a 500 MeV proton beam. The solid lines are the calculated curve described in the text. The yield has been corrected for the μ^+ lifetime (2.2 μs).

H_2 molecules, we obtained a value of $\varepsilon_{\text{ioni}}\varepsilon_{\text{coll}}$ of 0.6×10^{-6}. Thus, N_{μ^+} becomes $0.07\mu^+/\text{s}$, which is almost consistent with the ultraslow μ^+ events observed in the present experiment ($0.2\mu^+/\text{s}$). A straightforward increase up to $12\mu^+/\text{s}$ can be expected for the 5 μA pulsed proton intensity and for the already achieved value of the $\varepsilon_{\text{ioni}}\varepsilon_{\text{coll}}$ (4×10^{-5}).

A significant increase in the ultraslow μ^+ intensity towards the designed value of $10^4\mu^+/\text{s}$ for a 5 μA proton beam can be expected by a careful optimization of the ion optics, including a further elimination of the charge-up effects, a further upgrading of the VUV laser power by increasing the HRL power, and a further optimization in the surface treatment of the tungsten material.

During the course of several days of measurements, it was found that the yield of the ultraslow positive muons from hot tungsten was not significantly affected by irradiation of the proton beam. Assuming that the present method is free from any primary-beam-associated radiation effects at higher proton intensities, we can expect a straightforward increase in the ultraslow μ^+ intensity (up to $10^6/\text{s}$) by installing the present system at a higher intensity pulsed proton source. This excellent feature has a really significant advantage compared to the other methods of slow μ^+ production [2–4].

The intense ultraslow μ^+ beam with an extremely narrow phase-space volume of the order of 0.2 eV $\times$ (cm)^3 and a high stopping density realized by the present method should open new types of muon science experiments in the fields of basic atomic physics, surface physics, and materials research. Also, it should be emphasized that the present method of ultraslow μ^+ production can be used as an ion source for further accelerations, thus producing high intensity and low emittance muon beams.

For the polarization of the ultraslow μ^+, we have to expect 50% polarization in the present method, since we ionize both of the two hyperfine states of the $1s$ state of Mu. In order to recover the polarization one might (a) use the $1s \rightarrow 2s$ transition for laser ionization [6] or (b) use ultraslow μ^+ collisions with optically pumped polarized atoms.

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