Generation of Thermal Muonium in Vacuum

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We find that thermal-energy muonium atoms are emitted from a clean hot tungsten foil in which positive muons are stopping near the surface. The temperature dependence of the thermal-muonium signal yields a surprisingly low activation energy of 0.66(4) eV, suggesting that we are observing the thermionic emission of muonium from the solid. The total muonium yield at 2300 K is about 0.04 per stopped muon of 23 MeV/c initial muon momentum. A number of new experiments should be possible using this unique source of thermal muonium in vacuum.

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Positive muons (μ^+), after slowing down in a sample material, are very useful for probing various magnetic and chemical effects.[1] Many years ago, it was shown that μ^+ stopping in a gas form hydrogenlike atoms of muonium (Mu),[2] and many elegant atomic physics experiments have used this method.[3] With a view to removing the perturbing collisions of the gas molecules, there have been several attempts at forming Mu in vacuum using powders[4] and beam-foil techniques.[5] To date, either the Mu thus formed suffers many atomic collisions inside the stopping materials, or it is formed with a relatively high velocity, both of which limit its utility.

A more promising approach was suggested by the early attempts of Kendall and co-workers to obtain Mu in vacuum from heated Pt foils.[6] Possibly because of poor vacuum conditions or an unlucky choice of sample material, these experiments did not succeed. However, in the pursuit of Mu in vacuum, the "surface" muon beam was discovered that provides the μ^+ source for many experiments including the present one. In this Letter we show that thermal-energy Mu can indeed be formed in vacuum by the heating of a suitable solid target in which μ^+ are stopping. This experiment has already yielded much information about the energetics and surface dynamics of Mu. The relatively high Mu yield (of the order of 10^{-2} Mu per incident μ^+) should make possible many other interesting atomic and solid-state physics experiments. For example, thermal-energy Mu in vacuum is essential for a search for muonium to antimuonium conversion, a measurement of the $1s$-$2s$ interval by optical excitation, and resonant three-photon ionization of Mu to make a source of slow μ^+.

The way in which we expected to make thermal Mu was to stop μ^+ near the exit surface of a hot W target and to desorb in the form of Mu any μ^+ that might diffuse to the surface. The process would thus be analogous to the production of atomic hydrogen[7] and thermal positronium.[8]

Our experiment was performed at the $\pi 1$ channel of the Booster Meson Facility, Meson Science Laboratory, University of Tokyo, located at the National Laboratory for High Energy Physics (KEK), Tsukuba, Japan.[9] This channel provides a pulsed surface μ^+ beam produced at a Be target by bombardment of it with proton pulses from the 500-MeV booster synchrotron. The μ^+ arrived at the target in pulses 50 nsec wide and 50 msec apart, with an average momentum tunable from 20 to 30 MeV/c. The $\pi 1$ channel is equipped with an electrostatic separator to remove e^+ contaminants from the beam. This pulsed muon beam allows us to observe events at long time delays with very low background. In the present experiment, the muons passed through the last focusing magnet of the beam line and stopped in a 99.99%-pure W foil target in an ultrahigh vacuum (UHV) chamber depicted in Fig. 1. The W foil had dimensions of $25\times30\times0.050$ mm^3. Before striking the target, the μ^+ beam was shaped by a 200-mm-long collimator to eliminate μ^+ not aimed at the target. The final μ^+ intensity was about 60 per pulse. The collimator section of the beam line (10^{-6} Torr) was separated from the UHV chamber by a $20\times25\times0.050$-mm^3 Be window placed 60 mm in front of the target. The collimator was separated from the rest of the beam line by a 0.040-mm-thick Mylar window. The UHV target chamber was constructed of stainless steel except for two 200-mm-diam, 0.30-mm-thick Al windows that allowed decay positrons to pass through towards the counters without considerable scattering. The chamber was equipped with a cryopump and after bakeout attained an ultimate pressure of 2.5×10^{-10} Torr.

Inside the vacuum chamber, the W sample was held by Mo clamps to two Mo high-current leads with a cross section of 1×10 mm^2. The W foil was heated by direct current, the maximum current of 310 A producing a temperature of 2800 K as read by an optical pyrometer. At 2300 K, the pressure in the chamber was 3×10^{-9} Torr. Before the experiment, the sample was

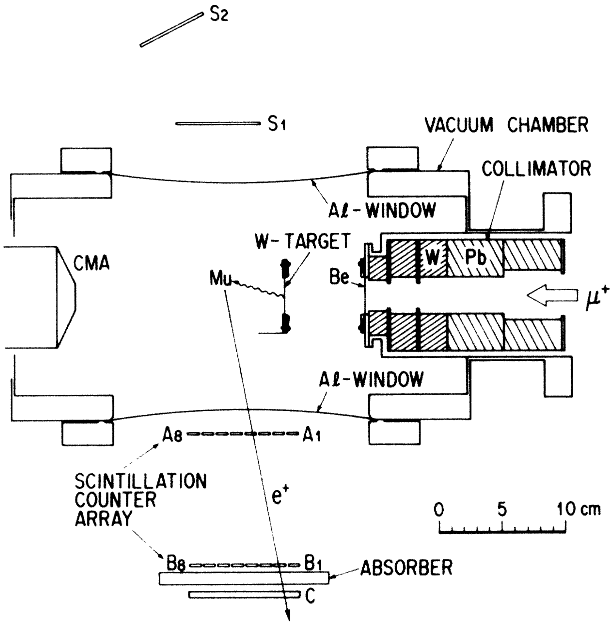

FIG. 1. Apparatus for observing muonium in vacuum. A_i, B_i, C, and S_i are scintillation counters.

purified[10] by heating it in 10^{-7} Torr O_2 for 7 h at 150 A (1860 K) and for 7 h at 220 A (2300 K) in order to remove C impurities from the surface. On the third day after the target was last heated and the eighth day after the last O_2 treatment, Auger analysis using a cylindrical-mirror analyzer (CMA) showed less than 10% of a monolayer each of O and C. When the target was then heated briefly, the C and O levels were respectively 12% and 3% of a monolayer.

Decay positrons were detected by an array of small plastic-scintillation-counter telescopes directed either at the W target or at the vacuum space in front of the target. The telescope array consisted of eight $1\times10\times100$-mm^3 counters (A_i) next to one of the Al windows and at 110(5) mm from the beam axis, eight $5\times10\times300$-mm^3 counters (B_i) at 220 mm from the axis, and one large $10\times100\times350$-mm^3 counter (C) just behind the B counters and separated from them by a 10-mm-thick Al absorber. Using various triple-coincidence combinations $A_i\cdot B_j\cdot C$ (resolving time, 7 ns) we detected muon decays from the target and from three fiducial volumes centered at distances from the target of $z=26$, 38, and 49 mm. Including the effects of multiple scattering and counter misalignment, we estimate that the fidicial volume of each telescope was roughly Gaussian in shape with a full width at half maximum of 25 mm. The Al absorber rejects from our counting signal low-energy positrons that may have been scattered through a large angle. A Mo vane on the target holder reduced the number of scattered μ^+ landing on the Al window in front of the A_i counters.

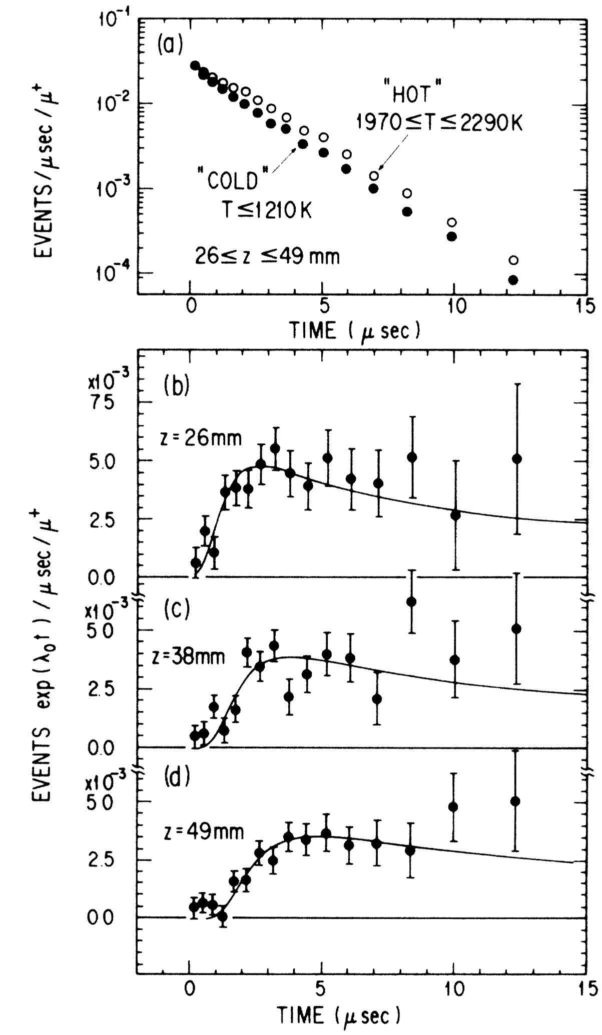

FIG. 2. Time spectra of μ^+ decay events. (a) Raw spectra, binned and normalized, obtained with the W target hot and cold; (b)–(d) "hot" – "cold" difference spectra for three z positions of the counter telescopes. See text.

At the beginning of the experiment the μ^+ momentum was adjusted to a value (23 MeV/c) at which half of them were transmitted through the W target in order to maximize the μ^+ density near the exit surface of the target. Figure 2(a) shows two time histograms of the decay event rate recorded by nine telescopes aimed at $z=26$, 38, and 49 mm and corrected for counter solid angle and efficiencies. The two histograms were obtained with the W sample cold (300 K $< T <$ 1210 K) and hot (1970 K $< T <$ 2290 K). The main features of the histograms are the exponential slopes due to μ^+ decay, the lack of constant background counts, and the obvious excess of counts in the "hot" spectrum. Figures 2(b)–2(d) show the differences between the hot and cold spectra for the $z=26$, 38, and 49 mm telescopes individually. These spectra have been multiplied by $\exp(\lambda_0 t)$ to remove the effects of the μ^+ decay rate λ_0. The zero of time is the arrival time of the μ^+ pulse at the target and the spectra have been normalized to the total number of μ^+ stopping in the target as determined by an additional large telescope $S_1 \cdot S_2$. Since the excess delayed counts in the hot spectra peak at about 2 μsec, they can be attributed to the decay of Mu having a velocity of 2×10^6 cm/sec, roughly what we expect for $T=2000$ K. We exclude the possibility that we are observing thermal-energy μ^+ because such slow charged particles would be prevented from leaving the target region by the magnetic field produced by the large heater current.[11] The direction of the target current was reversed for half the runs to eliminate any effect due to μ^+ spin rotation. There was no significant difference between the signals obtained with the two directions of the current.

The three difference spectra in Figs. 2(b)–2(d) exhibit counting rates that increase with time after $t=0$ and reach a maximum at a time that appears to be later for larger values of the distance z. This behavior is also what we expect from slow Mu moving into the fiducial volumes of the three telescopes at different times. We have fitted these three spectra by a time-of-flight expression that includes the diffusion-limited time-dependent one-dimensional flux of particles from the surface and a beam-Maxwellian time-of-flight distribution for Mu atoms at a temperature $T_{\rm Mu}$.[12] The χ^2 per degree of freedom for the simultaneous fit to the three spectra is 57/49. The free parameters for the fit were the total yield of Mu per μ^+ stopping in the target, $y=0.04(2)$, and the Mu temperature, $T_{\rm Mu}=2320(300)$ K. The error estimate quoted for y includes the uncertainties in the counter efficiencies. The Mu temperature $T_{\rm Mu}$ is in good agreement with the average temperature of the hot W target, 2130 K. The excess-delayed-counting-rate signal is thus in quantitative agreement with the thermal-Mu-emission hypothesis.

To examine the delayed-signal effect in more detail, we extract from our time spectra a delayed counting rate that is the sum of the counts recorded by the nine telescopes of Fig. 2(a) between 2 and 6 μsec. Figure 3 shows these delayed counting rates versus target temperature at a μ^+ momentum of 23.2 MeV/c. The delayed counting rate starts to increase above 1200 K, peaks at 2300 K, and then decreases at higher temperatures. We attribute the increase with temperature to the thermal activation of the Mu emission. The decrease at the highest temperatures is consistent with the reduction of the thermal Mu emission due to the increase in μ^+ trapping at thermally generated vacancies in the W. The slowness of the increase means that the Mu activation energy E_μ is very low. A least-squares fit of an Arrhenius-type activation curve to the data implies that $E_\mu=0.66(4)$ eV. Hydrogen atoms are bound to the W surface by about 3.0 eV,[13] and to the solid by about 1.5 eV.[14] We conclude that the Mu is probably being thermionically emitted from the bulk and possibly also desorbed from the surface. Caution must therefore be exercised in interpreting the fitted value of E_μ quantitatively. The high-temperature behavior of the Mu signal in Fig. 3 (shown by the dashed portion of the curve) indicates that the μ^+ may be sensitive to trapping at thermally generated vacancies.[15]

Figure 4 shows the difference in delayed counting rates between 2300 and 300 K as a function of μ^+ beam momentum. The data have been multiplied by $(23/p)^{3.5}$ to correct for the expected momentum dependence of the intensity of the surface μ^+ beam. At low p, the μ^+ stop deep inside the sample, and the delayed-counting-rate signal is reduced; at high momenta, the signal is reduced because the μ^+ are being transmitted through the sample and are stopping elsewhere in the vacuum chamber. These data thus show that our Mu signal is indeed associated with the W surface. The data have been fitted by a Gaussian function; the full width at half maximum is 4.2(5) MeV/c (almost the same as the momentum bite of the in-

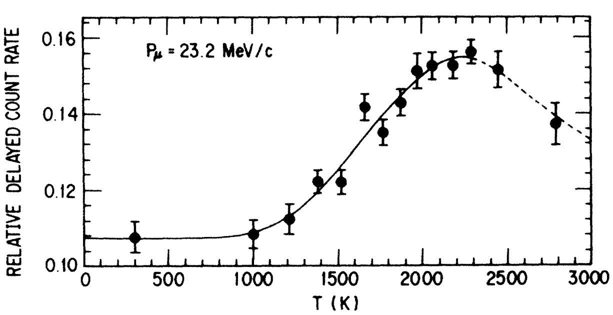

FIG. 3. Temperature dependence of the delayed events in Fig. 2(a) summed over the time interval from 2 to 6 μsec. The fitting curve represents an Arrhenius-type activation with a correction due to μ^+ trapping at thermal vacancies at high temperature.

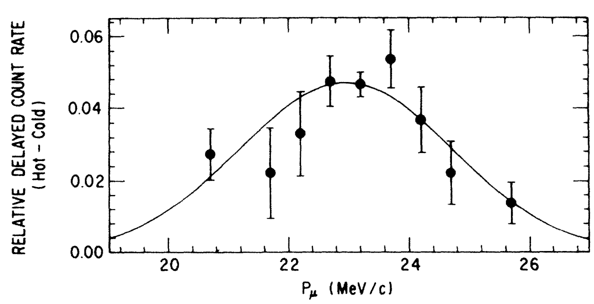

FIG. 4. Dependence of the delayed-event difference between "hot" (2300 K) and "cold" (300 K) data on the μ^+ incident momentum. The vertical scale has the same units as in Fig. 3.

cident μ^+ beam), and $\chi^2/\nu = 5.16/6$. We calculate that the μ^+ stopping in the target has a surface density per μ^+ of $\rho = 60$ mm^{-1}. At high temperatures the Mu yield per μ^+, y, is expected to be given by $y = \rho(D/\lambda_0)^{1/2}$, where D is the μ^+ diffusion constant. The latter is thus $D = \lambda_0(y/\rho)^2 = 2\times10^{-3}$ cm^2/sec, close to the value reported by Frauenfelder for H in W (5×10^{-4} cm^2/sec).[16]

In summary, we have observed a delayed-counting-rate signal associated with μ^+ stopping in a hot W target. The characteristics of this signal are (1) a time dependence that agrees with the expected Mu time-of-flight spectrum if the Mu are at the temperature of the hot W, (2) a temperature dependence that gives us an activation energy for the Mu emission similar to what we expect for the thermionic emission of H from W, and (3) a momentum dependence that indicates that our signal originates at the surface of the W sample. We conclude that we have produced thermal Mu atoms in vacuum.

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