Formation of Muonium in the 2*S* State and Observation of the Lamb Shift Transition

A. Badertscher, S. Dhawan, P. O. Egan, V. W. Hughes, D. C. Lu, M. W. Ritter, and K. A. Woodle
Gibbs Laboratory, Physics Department, Yale University, New Haven, Connecticut 06520

and

M. Gladisch, H. Orth, and G. zu Putlitz
Physikalisches Institut der Universitat Heidelberg, D-6900 Heidelberg, Federal Republic of Germany

and

M. Eckhause and J. Kane
College of William and Mary, Williamsburg, Virginia 23185

and

F. G. Mariam
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

and

J. Reidy
University of Mississippi, University, Mississippi 38677
(Received 2 November 1983; revised manuscript received 19 December 1983)

Muonium in the $2S$ state has been produced by the beam-foil method with a μ^+ beam of 10 MeV/c. The metastable $2S$ state of muonium has been detected by a static electric field quenching method, and the transition $2S_{1/2}, F=1 \rightarrow 2P_{1/2}, F=1$ induced by a radio-frequency electric field has been observed with an event rate of about 4/h.

PACS numbers: 36.10.Dr, 12.20.Fv

Muonium (M) is an atom consisting of a positive muon and an electron and is an ideal system to test quantum electrodynamics (QED).[1] High precision measurements of the hyperfine structure interval $\Delta\nu$ and of the Zeeman effect in its ground state have provided very sensitive tests of QED, as well as precise values of the fine structure constant α and the ratio of the muon and proton magnetic moments.[2,3] In these experiments muonium was formed by stopping μ^+ in gaseous targets.

Another important QED test would be a precise measurement of the Lamb shift in muonium in the $n=2$ state, since it would be free of the effects of proton structure which complicate the interpretation of the Lamb shift in hydrogen.[4] For this measurement muonium in the $2S$ state must be obtained in vacuum to avoid collisional quenching of M($2S$) atoms. With a method similar to beam neutralization in proton-beam-foil spectroscopy[5] we have shown that muonium in its ground state is formed by passing a μ^+ beam through a thin foil in vacuum.[6] From proton data[7] we expect that metastable M($2S$) atoms will be formed as well, and that M($2S$)/M($1S$) will be about 0.1. Higher excited states will also be formed but their formation probabilities are lower and most of these excited state atoms will decay rapidly. This paper reports on further developments for producing muonium in vacuum, the detection of M($2S$) by a static electric field quenching method, and the observation of the Lamb shift transition $2S \rightarrow 2P$ induced by an rf electric field of about 1140 MHz.

Our experiment was done at the Stopped Muon Channel at the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF). In our previous experiment to obtain muonium in vacuum,[6] the surface muon beam[8] of 28 MeV/c was degraded so that about one half of the muons were stopped in the production foil. Monte Carlo calculations of the energy spectrum of μ^+ emerging from the foil showed that this spectrum is rather flat and extends up to a kinetic energy of 2.5 MeV. Thus, only a small fraction of about 10^{-3} of the muons passing through the foil could capture an electron due to

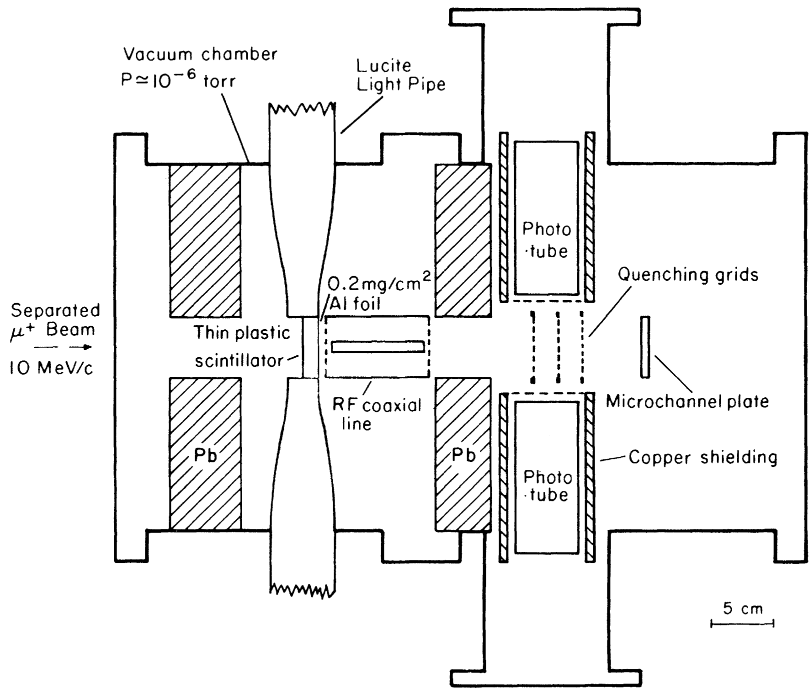

FIG. 1. Schematic diagram of the apparatus.

the rapid decrease of the capture cross section with increasing kinetic energy.[9,10] Our calculations also showed that the absolute yield of muonium atoms is roughly independent of the incident muon beam momentum p whereas the muon flux was measured to be proportional to $p^{3.5}$. Hence for lower beam momenta the signal-to-noise ratio for any muonium experiment should be improved. Our calculations indicate that muonium atoms emerge approximately isotropically from the foil and that the velocity distribution of M(1S) or M(2S) is determined by the charge capture cross section and is not dependent on p.

Figure 1 shows a diagram of our apparatus. The 20-μm-thick muon scintillation counter (NE 102A) served as a degrader, and muonium was formed in a thin Al foil (0.2 mg/cm^2) at ground potential immediately downstream of the scintillator. With a parasitic apparatus mounted downstream of the apparatus shown in Fig. 1 (with microchannel plate removed) and similar to the apparatus of Ref. 6, we optimized the beam momentum for maximal M(1S) yield per incoming muon. In the search for M(2S) we were limited to accept an average muon rate of 70 kHz at a duty factor of 9% because of pile-up considerations. Figure 2 shows that at 9.75 MeV/c the M(1S) flux is about 4% of the muon flux measured with the scintillation counter. The muonium flux from the downstream side of the foils is obtained from the measured rate with the parasitic apparatus assuming isotropic distribution of M(1S) from the foil. This "subsurface" muon beam was obtained by tuning the muon channel to transport muons of about 10 MeV/c; an electrostatic separator was used in our beam line to suppress the very high positron contamination ($e^+/\mu^+ \simeq 10^3$ at 5 MeV/c).

Figure 3 gives the energy level diagram for

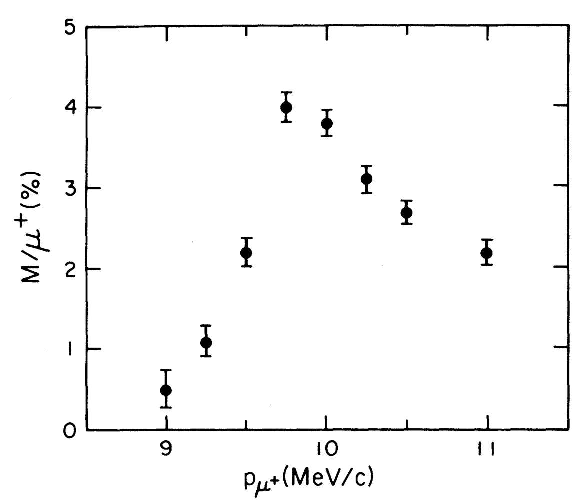

FIG. 2. Muonium yield at the foil as a function of the μ^+ beam momentum.

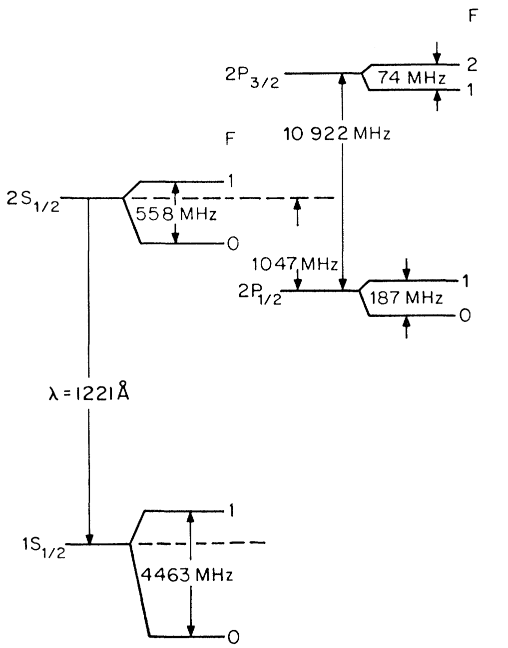

FIG. 3. Energy level diagram of the $n=1$ and $n=2$ states of muonium.

muonium in its $n=1$ and $n=2$ states including fine structure, Lamb shift, and hyperfine structure. The value of the Lamb shift interval of $2S_{1/2}$ to $2P_{1/2}$ for muonium has been calculated from QED.[11] The $2S$ atomic state is metastable with the mean lifetime of $\frac{1}{7}$ s for two-photon decay to the $1S$ state; however, the mean life of 2.2 μs for μ^+ decay determines the lifetime of M($2S$). In muonium the $2P$ state decays to the $1S$ state with a mean lifetime of 1.6 ns through an electric dipole transition with emission of a Lyman α photon of 1221 Å. M($2S$) is quenched in an external static electric field[12] through admixture of the $2P$ state; a Lyman α photon is emitted, and the mean lifetime is about 2 ns in a field of 600 V/cm.

Our first approach to observation of M($2S$) was to detect the static electric field quenching of M($2S$). Our apparatus (Fig. 1) includes four photomultiplier tubes for detection of Lyman α uv radiation. These are the Hamamatsu type R2050 photomultipliers with a MgF_2 window of 5 cm diameter and a quantum efficiency of 10% at 1221 Å including transmission through the window. The total solid angle of the four tubes is 30% of 4π. In addition, there is a microchannel plate just downstream of the phototubes to detect M($1S$) atoms and μ^+; in our first run the active plate diameter was 4 cm and in the second, 7.5 cm. Three quenching grids located at the axial position of the phototubes produced an axial static electric field of 600 V/cm. The center grid was at -1200 V and the two outer grids were grounded.

We searched for M($2S$) by modulating the static electric field between on (600 V/cm) and off and looking for a difference in the event rate due to Lyman α photons emitted during the field-on phase. An event required a triple coincidence between an incoming muon, a delayed Lyman α photon in one of the four uv phototubes, and a further delayed M($1S$) atom detected in the microchannel plate. The distance between the scintillator and the center plane of the uv phototubes is 20 cm and that between the scintillator and the microchannel plate 27.5 cm; the time gates were set to accept M($2S$) atoms with kinetic energies between 4 and 26 keV. The phototube pulse had to occur between 30 and 80 ns after an incoming muon, and the microchannel plate pulse between 10 and 40 ns after a phototube pulse was detected in the first gate. Combining about two days of data taking from our two runs, we observed 174 events with the quenching field on and 72 events with the field off. Assigning the difference between grid on and grid off to events due to Lyman α photons from quenched M($2S$) gives a Lyman α event rate induced by the static electric field of (4.7 ± 0.7)/h. Within the uncertainties of our detection efficiencies this value agrees with the expected rate of M($2S$). For the normalized difference signal (S) between quenching field on and field off defined with the events (E) normalized to the number of incoming muons, $S=[(E/\mu)_{\rm on}-(E/\mu)_{\rm off}]/[(E/\mu)_{\rm on}+(E/\mu)_{\rm off}]$, we obtained $S=(41.5\pm5.8)\%$. For delayed coincidences with delay times outside the expected flight times of M($2S$) atoms, the signal is consistent with zero, namely $S=(-1.7\pm6.4)\%$. Formation and static electric field quenching of M($2S$) has also been reported from an experiment at TRIUMF.[13] However, the M($2S$) formation rate reported by them is in disagreement with ours, being about a factor of 10 higher when the different beam momenta are taken into account.

Our next step in establishing the formation of M($2S$) atoms was to search for the Lamb shift transition $2S_{1/2}$, $F=1\to 2P_{1/2}$, $F=1$ driven with an rf electric field. In Fig. 4 the solid curve shows the theoretical non-power-broadened resonance lines for two transitions between the hyperfine sublevels of the $2S_{1/2}$ and $2P_{1/2}$ states. The natural linewidth of 100 MHz (full width at half maximum) is due to the lifetime of the $2P_{1/2}$ state. Our rf interaction region (Fig. 1) consisted of a coaxial line. It was 8.3 cm long and had tungsten meshes with a

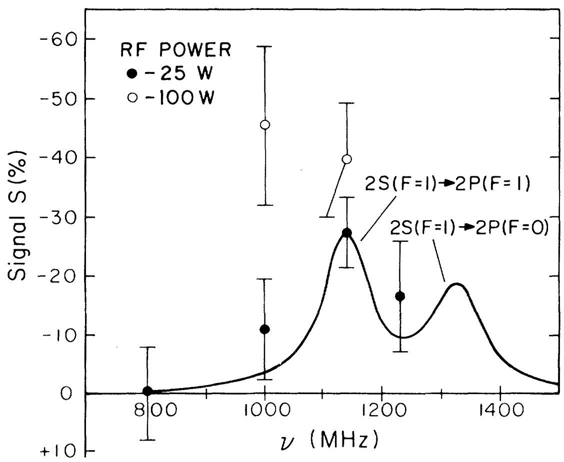

FIG. 4. Muonium $2S_{1/2}\rightarrow 2P_{1/2}$ resonance lines. The solid curve shows the theoretical non-power-broadened resonance line shape. The data points for 100- and 25-W rf input power are shown.

transmission of 80% each at the entrance and exit planes to allow the muon beam to pass through. The diameter of the inner conductor was 1 cm and the inner diameter of the outer conductor was 5.1 cm, which resulted in a variation of a factor of 25 in the power density between the inner and the outer radii.

Initially we searched for the $2S_{1/2}$, $F=1\rightarrow 2P_{1/2}$, $F=1$ transition at 1140 MHz with the maximum available microwave input power of 100 W (70 W transmitted power) where large microwave power broadening of the line is expected. The microwave power was modulated between on and off with a frequency of 1 Hz. The static electric field in the quenching grids was held constant at 600 V/cm. With microwave power on, M(2S) atoms should be quenched in the rf region, while with power off, quenching will take place only in the region of the static field quenching grids which is viewed by the phototubes. Event counts were defined as above and our signal should be the reduction in event counts due to the microwave power. The signal S is defined as the normalized difference between rf power on and power off. A large signal of the expected sign was found: $S=(-40\pm 10)\%$.

Our six data points are shown in Fig. 4 and were obtained in six days of data taking in two runs. After obtaining a second point with 100 W at 1000 MHz which is off the center of the resonance, we took the four data points shown with 25 W input power, which is calculated to be approximately the optimum power for studying the resonance line. Again no signals were observed with delayed coincidences outside the expected times of flight of muonium atoms. The solid curve shows the theoretical non-power-broadened resonance line shape with its height normalized to the data point at 1140 MHz with a microwave input power of 25 W. The four data points are clearly consistent with the theoretical curve and indicate that a more correct theoretical curve would include some power broadening. The magnitude of the signal at the peak of 1140 MHz, $(-28\pm 6)\%$, agrees well with that expected from the measured static electric field signal, namely $S_{\rm rf}=-(0.6)S_{\rm static}=-25\%$. We note that the large S value observed at 1000 MHz with 100 W input power is expected due to power broadening and provides further evidence of our observation of the $2S(F=1)\rightarrow 2P(F=1)$ transition. Our resonance curve with 25 W input power is in agreement with the predicted value of the Lamb shift.

We conclude from our data that we have formed muonium in the 2S state with the expected rate and that we have observed the Lamb shift transition. We are proceeding to make measurements of the $2S_{1/2}\rightarrow 2P_{1/2}$ transitions to determine the Lamb shift and hfs intervals.

This work was supported in part by Department of Energy Contract No. DE-AC02-76ER03075, by NATO Research Grant 1589, German Ministry for Science and Technology (BMFT), and National Science Foundation Grant No. PHY8215754. We are happy to acknowledge the helpful support of Dr. L. Rosen, Dr. L. Agnew, Dr. R. Werbeck, and the LAMPF staff. We thank R. Amittay for his effective work on the microwave system.

[1]V. W. Hughes and T. Kinoshita, in *Muon Physics I*, edited by V. W. Hughes and C. S. Wu (Academic, New York, 1977), p. 12.

[2]F. G. Mariam *et al.*, Phys. Rev. Lett. 49, 993 (1982).

[3]J. R. Sapirstein *et al.*, Phys. Rev. Lett. 51, 982 (1983); J. R. Sapirstein, Phys. Rev. Lett. 51, 985 (1983).

[4]S. R. Lundeen and F. M. Pipkin, Phys. Rev. Lett. 46, 232 (1981).

[5]H. G. Berry, Rep. Prog. Phys. 40, 155 (1977).

[6]P. R. Bolton *et al.*, Phys. Rev. Lett. 47, 1441 (1981).

[7]G. Gabrielse, Phys. Rev. A 23, 775 (1981).

[8]H.-W. Reist *et al.*, Nucl. Instrum. Methods 153, 61 (1978).

[9]H. Tawara and A. Russek, Rev. Mod. Phys. 45, 178 (1973).

[10]A. Chateau-Thierry *et al.*, Nucl. Instrum. Methods 132, 553 (1976).

[11]D. A. Owen, Phys. Lett. 44B, 199 (1973).

[12]W. E. Lamb, Jr., and R. C. Retherford, Phys. Rev. 79, 549 (1950).

[13]C. J. Oram *et al.*, J. Phys. B 14, L789 (1981).