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Measurement of the Lamb shift in muonium

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Abstract

The Lamb shift in muonium has been measured for the first time by a beam foil spectroscopy radio-frequency technique. The value obtained is 1070 +12/-15 MHz, with a systematic uncertainty of 2 MHz, compared with the present theoretical value of 1047.03 MHz.

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Recent measurements of the Lamb shift in hydrogen show a possible discrepancy with theory at the level of 40 ppm,[1,2] which may be explained by the difficulty in estimating proton structure effects.[3] The Lamb shift has been calculated[4] to the few ppm level for the hydrogen-like muonium (μ^+e^-) atom, where finite nuclear size effects are absent. A muonium experiment with comparable precision could thus test quantum electrodynamics without the ambiguity present for hydrogen. We report here the first radio-frequency (RF) measurement of the muonium Lamb shift.

Experiments at TRIUMF and LAMPF have established the flux and estimated the velocity distribution of 1S (Ref. 5) and 2S (Ref. 6) muonium from foils bombarded with muons. The fraction emerging in the 2S muonium state[7] is comparable to that for hydrogen[8] in the velocity range of c/50 to c/200. These rates are confirmed in the present measurement, where the resonant de-excitation of the 2S state provided a distinctive signature of 2S muonium.

A 15.4 MeV/c positive muon beam with 7% momentum acceptance (FWHM) was transported by the TRIUMF M13 beam line[9] into the evacuated apparatus shown in Fig. 1 through a 50 μm mylar window. A 63 μm plastic scintillator (X) detected particles incident on a 0.75 μm aluminum foil. Muons and muonium emerging from the foil passed through an RF transmission line into a static electric Stark quench field (~300 V/cm) and were detected by a rectangular (92 × 75 mm) microchannel plate (MCPB). Transitions from 2S to 2P states induced in the 3.4 cm long RF transmission line region depopulate the n=2 state. At resonance with 12.5 W of RF power, approximately $1/3^{rd}$ of the 2S muonium moving at c/70 would survive the RF region. The lifetime of the surviving 2S muonium in the quench region was reduced to about 8 ns due to Stark mixing. The resulting Lyman α radiation was detected by two (40 mm diameter) CsI coated micro-channel plates (MCP1 and MCP2). Positrons in the beam or from muon decay were detected by a rectangular box of thick plastic scintillators (BOX). Quartz halogen light bulbs were mounted near the MCP's but outside the beam path to facilitate baking of the MCP's and testing of their photon efficiency and pulse height response.

After adjusting beam parameters for optimum flux between X and MCPB of particles with velocity near c/70, data were accumulated in runs of approximately eight hours over an eight day period. RF power was maintained at either 2, 12.5 or 25 W during a run, and the frequency was changed every few minutes. An event was defined by a count in either MCP1 or MCP2 as well as in MCPB within 450 ns of detection of an incident muon in the X scintillator. Events were vetoed for which any MCP fired in fast coincidence with a BOX scintillator.

The apparatus was tested in a similar configuration with the beam line tuned to produce an optimum flux of c/70 protons between X and MCPB. This allowed estimation of the efficiencies of MCP1 and MCP2 for Lyman α detection, using measured neutral fractions for hydrogen[8] and assuming 10% were in the 2S state. An efficiency of about 11% was obtained, in reasonable agreement with a quoted value of 14% for similar detectors.[10]

Off-line analysis started by requiring the following criteria for the time relationship between X, MCP1 or MCP2, and MCPB:

1) The time of flight between X and MCPB corresponded to a velocity between c/55 and c/200.

2) MCP1 or MCP2 fired after the particle entered the quench region, but more than 5 ns prior to striking MCPB.

3) The interval between entry into the quench region and detection of a Lyman α photon was less than 20 ns.

4) No muon arrived in X before the preceding muon had reached MCPB.

These requirements removed 99.98% of the recorded events. Restrictions on the MCP pulse heights removed less than 20% of the remaining events. The time distribution of the remaining events displayed a signal with a quench lifetime of about 8 ns, plus a background consistent with the random coincidence rates.

The remaining number of events was normalized by the X•MCPB coincidences at each frequency and power. To check for the effect of stray RF fields on the efficiencies of MCP1 and MCP2 and to check the normalization of the data, the total (i.e. before imposing time requirements) number of events at each frequency and power was normalized in the same way. The data are shown in Fig. 2. Also shown are fits consisting of a power independent flat background plus the resonance curve determined from the 2S muonium velocity distribution and the total transition rate to the 2P states. The total transition rate at each frequency and power was the sum of the individual transition rates between the 2S and 2P hyperfine levels. The individual rates are proportional to the applied RF power and are functions of the Lamb shift because they depend upon the energy differences between the initial and final levels.[11] The velocity distribution of 2S muonium was taken to be the product of the observed velocity distribution between X and MCPB and the fraction of the beam in the 2S state as calculated from hydrogen data.[8] The Lamb shift obtained from the fit was found to be quite insensitive to the exact velocity distribution. Consistent values were obtained when the data for MCP1 and MCP2 were analyzed separately. The results of the fitting process under a variety of conditions are summarized in Table I.

The sensitivity of the measurement to systematic effects is shown in Table II. These are believed to be uncorrelated and so are added in quadrature giving a total systematic error of 2 MHz.

It is useful to estimate the yield of 2S muonium from the aluminum foil in order to aid in the design of future experiments. However, the detection efficiency of MCPB for muonium is unknown and extrapolation from electron and ion data[10] is difficult. Assuming an average efficiency of 25% we find that about 31 2S muonium emerge from the foil for an incident μ^+ flux of 4×10^4 per second, in agreement with the 1S data of Bolton et al.[5] (after correcting for our reduced stopping rate at the surface of the foil and assuming $1/10^{th}$ of the neutrals were in 2S state), and slightly less than Oram et al.[6]

In conclusion, we have measured the Lamb shift of the 2S state of muonium to be 1070 (+12/−15) (±2) MHz within two standard deviations of the calculation by Owen[4] of 1047.03 MHz. The main limitation in this type of experiment is the low stopping density of available muon beams. Using present beams, the statistical uncertainty in future experiments could in principle be reduced for instance by a larger angular acceptance from the foil; however it appears that such improvements result in larger systematic uncertainties.

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Table I. RF spectrum fitted parameters.

Signal amplitude	Background amplitude	Lamb shift (MHz)	Hyper-fine $2P_{1/2}$ level (MHz)	$2P_{1/2}$ Mean life (ns)	χ^2 2 W	χ^2 12 W	χ^2 25 W
Fixed 0	51.1±1.7	-	-	-	5.8	6.3	20.0
40.7±8.1	19.8±6.0	1047.0[a]	187[b]	1.6[c]	4.5	2.3	3.0
43.3±8.3	17.2±6.3	1069.8 ±13.3	187[b]	1.6[c]	4.4	1.3	2.7
43.7±8.3	17.2±6.3	1068.0 ±13.6	205 ±35	1.6[c]	4.4	1.2	1.6
41.2±11.6	19.4±10.1	1069.6 ±13.6	203 ±36	1.8 ±0.8	4.5	1.1	1.4

[a]Theoretical Lamb shift of muonium.

[b]Theoretical hyperfine splitting of the $2P_{1/2}$ level.

[c]Theoretical $2P_{1/2}$ mean life.

Table II. Estimated magnitudes of effects caused by systematic uncertainties.

Source of systematic error	Resulting error (MHz)
25% Uncertainty in RF power	1.4
1% RF power variations between data points at same nominal power	0.3
5° uncertainty in alignment of RF cavity with beam direction	1.3
Uncertainty in velocity distribution	0.1
1 G uncertainty in magnetic field	0.1
2% Non-linearity in normalization	1.0

Figure captions

1. A schematic of the apparatus, showing a good event in which a Lyman α photon is detected in microchannel plate (MCP1) from de-excitation of $\mu^+e^-(2S)$ in the quench region.

2. The intensity of the muonium 2P-1S signal is plotted (triangles) for the measured RF frequencies and powers. The circles, representing the background intensities (before imposing timing criteria), give an independent test of the normalization (error bars are smaller than the circles). The smooth curve is a fit with three free parameters: signal amplitude, background amplitude, and the Lamb shift. The two resonances correspond to the transitions $2S_{1/2}(F=1) \rightarrow 2P_{1/2}(F=1)$ at 1140 MHz and $2S_{1/2}(F=1) \rightarrow 2P_{1/2}(F=0)$ at 1327 MHz.

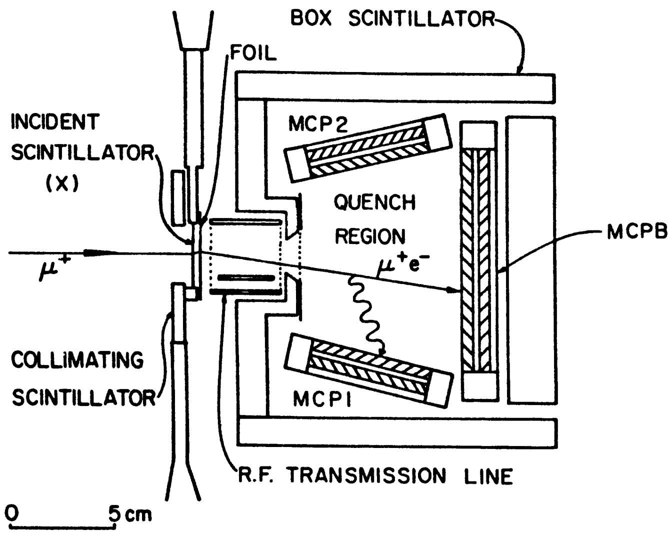

Fig. 1

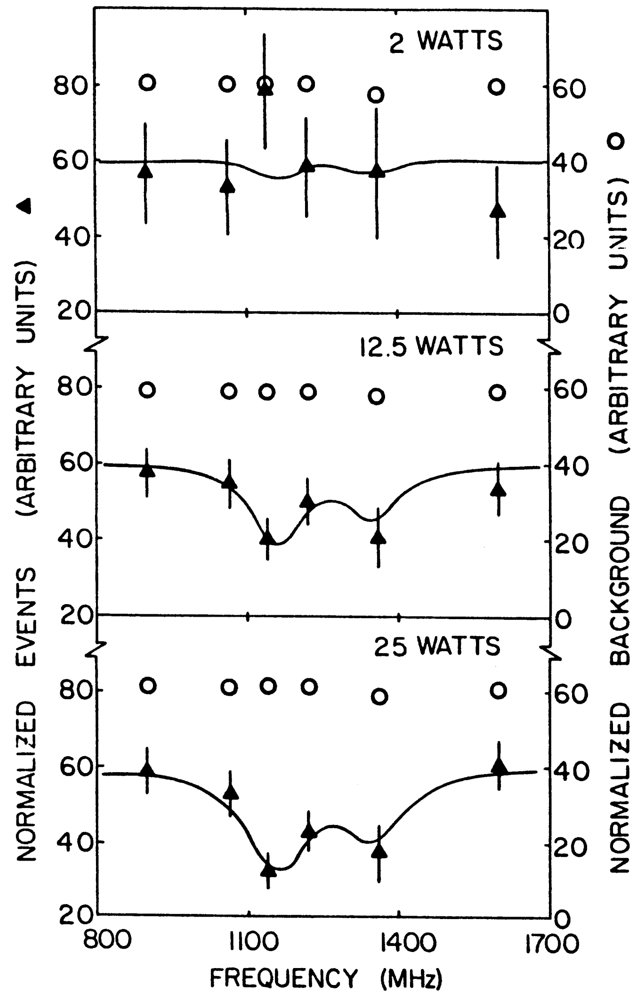

Fig. 2