

Excitation of the 1S-2S Transition in Muonium

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Muonium, the bound state of a positive muon and an electron, is one of the simplest systems for testing QED. Spectroscopic measurements in muonium are particularly attractive since the atom does not possess the proton structure effects present in hydrogen. Positronium is free of nuclear structure offsets, but the relativistic two-body problem presents formidable calculational difficulties. The ultimate precision of a measurement of the muonium energy levels will be limited by the 2.2 μsec lifetime (72kHz line width) of the muon.

Our experiment was performed at the booster meson facility of the National Laboratory for High Energy Physics (KEK), in Tsukuba, Japan. 500 MeV protons incident on a Be target create a pion shower that was used to produce a low energy μ^+ beam ($\sim 100 \mu^+$ /pulse at 27 MeV/c). The 20 Hz pulsed beam was directed onto a SiO₂ powder target where approximately one muonium per pulse was generated in vacuum at a density of $\sim 4 \times 10^{-2}$ atoms/cm³.

The excitation of the 1S-2S transition in muonium follows from previous pulsed spectroscopy of positronium [2] and hydrogen [3]. The atoms were excited and ionized by counterpropagating light beams at 244nm placed $\sim 4\text{mm}$ in front of the SiO₂ target. The light was produced by amplifying 50 mW of cw dye laser light at 488nm in an XeCl excimer pumped dye laser amplifier chain, and then doubling the frequency in a $\beta\text{-Ba}_2\text{B}_4\text{O}_{14}$ crystal. $\sim 80\text{mj/pulse}$ at 488nm in a bandwidth of 35 MHz were converted into $\sim 15\text{mj/pulse}$ at 244nm. A laser fluence of 0.25 joules/cm² in a fourier transform limited pulse is necessary to obtain an excitation probability of 0.5. Muons produced by the ionization of muonium were collected by an immersion lens and guided electrostatically to a microchannel plate detector. The frequency of the muonium resonance was measured relative to Te₂ line recently calibrated [4] to be at 613 881 150.89 (45) MHz. A 74.5 MHz frequency marker was used to measure the frequency interval between the reference line and the 1S-2S, F=1 \rightarrow 1 muonium resonance.

Figure 1 is a plot of our best data as a function of laser frequency and time after the laser pulse. A time histogram of the counts for a laser frequency between 10 and 11.5 fringes to the blue of the Te₂ line is shown on the right. The peak at 1.4 μsec can be identified as muon counts caused by the laser pulse. This timing is consistent with the arrival of hydrogen ions produced in the target region by laser light. Muons created by the same light pulse should arrive $\sqrt{m_\mu/m_p}$ sooner than the protons. In figure 2 we present a plot of counts from all the data detected within 50 nsec of the expected arrival time as a function of laser frequency. Also shown in figure 2 is a fit to the data, and the expected position of the resonance after accounting for the QED prediction [5], the frequency shift of the cw dye laser with respect to the amplified pulse, the acousto-optic modulator shift used in the Te₂ spectroscopy and our best estimate of the ac Stark shift. The ac Stark shift was estimated by using the data of figure 2 to give an estimate of the

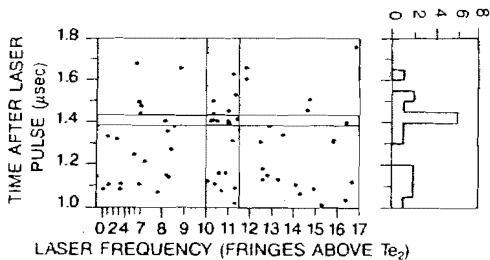


Fig. 1 A time-frequency plot of the CEMA during our best run. The scan between -2 to +7 fringes relative to the Te_2 line was a factor of five faster than the scan between +7 and 17 fringes.

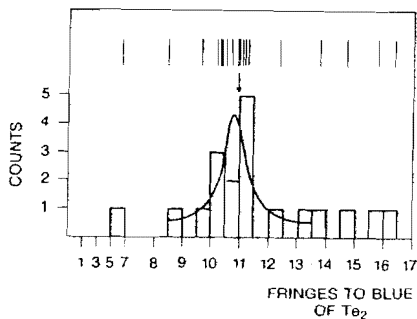


Fig. 2 Sum of all data taken in the time - laser frequency counting mode. The fit to the actual data (before binning into 0.5 fringe bins) gives a line center at 10.8 ± 0.4 fringes with a fwhm of 0.9 ± 0.3 fringes. Peak amplitude = 0.77 ± 0.55 counts per 0.1 fringe and a background of 0.087 ± 0.055 counts. 1 fringe = 74.5 MHz.

width of the resonance line. By scaling the results from the positronium 1S-2S measurement where the Stark broadening to shift ratio is $\sim 2.5[2]$, we estimate that the ac Stark shift is $30 \left(\begin{smallmatrix} +35 \\ -15 \end{smallmatrix} \right)$ MHz. All other uncertainties are less than 10 MHz.

We have shown the feasibility of laser spectroscopy experiments on muonium. Clearly a more intense source of thermal muonium is desirable. Active work on muon moderators, improved muon-to-muonium conversion targets, and brighter pulsed meson sources are underway in several laboratories. We anticipate a 3 order of magnitude improvement in thermal muon sources in the near future. Coupled with improvements in uv sources and detection efficiency, a high resolution measurement of the 1S-2S transition should be possible.

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