MEASUREMENT OF THE MUONIUM 1S-2S TRANSITION FREQUENCY

V.Meyer1, S.N.Bagayev5, P.E.G.Baird2, P.Bakule2, M.G.Boshier4, A.Breitric1, S.L.Cornish2, S.Dychkov5, G.H.Eaton3, A.Grossmann1, D.Huebl1, V.W.Hughes6, K.Jungmann1, I.C.Lane2, Yi-Wei Liu2, D.Lucas2, Y.Matynin5, J.Merkel1, G.ZuPutlitz1, I.Reinhard1, P.G.H.Sandars2, R.Santra1, P.Schmidt1, C.A.Scott3, W.T.Toner3, M.Towrie3, K.Traeger1, C.Wasser1, L.Willmann1 and V.Yakhontov1

1Physikalisches Institut, Universitat Heidelberg, Philosophenweg 12, D-69120 Heidelberg, D
2Clarendon Laboratory, University of Oxford, Oxford OX1 3PU, UK
3Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK
4University of Sussex, Physics Department, Brighton BN1 9QH, UK
5Institute of Laser Physics, Novosibirsk 630090, RU
6Gibbs Laboratory, Yale University, New Haven, Connecticut 06520-8121, USA

A new measurement of the 1S-2S energy splitting of muonium by Doppler-free two-photon spectroscopy has been performed at the Rutherford Appleton Laboratory in Chilton, Didcot, UK. Increased accuracy is expected compared to a previous experiment [1]. Spectroscopy of this transition promises an improvement of the muon mass value.

One-electron atoms, being the most fundamental atomic systems, provide excellent tests for bound state quantum electrodynamics (QED) and render the possibility of highly precise measurements of fundamental constants. As the energy levels of the natural hydrogen isotopes (hydrogen, deuterium and tritium) and hydrogen-like exotic systems with hadronic nuclei (e.g. muonic helium, pionium and many others) are influenced by the finite size and internal structure of the hadrons, the interpretation of highly precise measurements in such systems is limited by today’s insufficient knowledge of the nuclear size effects. The hydrogen-like muonium atom ($\mu^+e^-$) consists of two leptons from two different generations [2]. No internal structure is known for leptons down to dimensions of order $10^{-18}$ m; therefore muonium is free from nuclear structure effects. The level energies can be calculated to very high accuracy exclusively by the theory of bound state Quantum Electrodynamics (QED). The potential for high precision studies has been demonstrated in a long series of microwave measurements and theoretical calculations of the ground state hyperfine structure splitting [2], from which accurate values for fundamental constants (muon mass $m_\mu$ and fine structure constant $\alpha$) were obtained [2].

The optical 1S-2S transition offers a higher resolution than the ground state hyperfine structure splitting, because of the much higher transition frequencies (and QED contributions) and the same 144 kHz narrow natural linewidth, which is due to the muon lifetime $\tau_\mu \approx 2.2\mu$sec.

This experiment was performed at the world’s brightest pulsed surface muon source at the Rutherford Appleton Laboratory (RAL) in Chilton, UK. The $^1S_{1/2}(F=1) \rightarrow 2^2S_{1/2}(F=1)$ transition was induced by Doppler-free two-photon laser spectroscopy using two counter-propagating laser beams of wavelength $\lambda = 244$ nm [1]. The atoms were formed by electron capture after stopping positive muons close to the surface of a SiO$_2$ powder target. A fraction of these diffused to the surface and left...
the powder at thermal velocities (7.43(2) mm/µs) for the adjacent vacuum region.

The necessary high power UV laser light was generated by frequency tripling the output of an alexandrite ring laser amplifier in crystals of LBO and BBO. Typically UV light pulses of energy 3 mJ and 80 nsec (FWHM) duration were used. The alexandrite laser was seeded with light from a continuous wave Ti:sapphire laser at 732 nm which was pumped by an Ar ion laser. Fluctuations of the optical phase during the laser pulse were compensated with an electro-optic device in the resonator of the ring amplifier to give a frequency chirping of the laser light of less than about 5 MHz. The laser frequency was calibrated by frequency modulation saturation spectroscopy of a hyperfine component of the 5-13 R(26) line in thermally excited iodine vapour. The frequency of the reference line is about 700 MHz lower than 1/6 of the muonium transition frequency. The cw light was frequency up-shifted by passing through two acousto-optic modulators (AOM’s). The muonium reference line has been calibrated preliminarily to 3.4 MHz at the Institute of Laser Physics in Novosibirsk. An independent calibration at the National Physics Laboratory (NPL) at Teddington, UK is under way.

The 1S-2S transition was detected by the photoionization of the 2S state by a third photon from the same laser field. The slow muon set free in the ionization process is accelerated to 2 keV and guided through a momentum and energy selective path onto a microchannel plate particle detector (MCP). Background due to scattered photons and other ionized particles can be reduced by requiring that the MCP count falls into a 100 nsec wide window centered at the expected time of flight for muons and by additionally requiring the observation of the energetic positron from the muon decay. On resonance an event rate of 9 per hour was observed.

The line shape distortions due to frequency chirping were investigated theoretically [3,4] and experimentally by observing resonances in deuterium and hydrogen in the same experimental setup. A careful analysis is in progress.

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