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THE LAMB SHIFT IN HYDROGENLIKE ARGON

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ABSTRACT

The Lamb shift S in hydrogen like argon (Z=18) has been measured by a motional electric field quenching time-of-flight experiment. We find S = (38.0 ± 0.6 THz) where the error includes 1σ statistical error of 0.35 THz and an estimated systematic error of 0.48 THz.

The comparison between Lamb shift theory and experiment in hydrogenlike ions of high nuclear charge Z is a sensitive test of quantum electrodynamics (QED) in the region where higher order corrections to the binding energy are large.[1] To date, Lamb shift measurements on hydrogenlike ions through Z=9 have been reported.[2] In this letter we report a measurement of the $2S_{1/2} - 2P_{1/2}$ energy splitting (Lamb shift) of hydrogenlike argon (Z=18). We find S = (38.0 ± 0.6) THz which may be compared to values of S = (39.0 ± 0.16) THz calculated by Erickson[3] and S = (38.25 ± 0.025) THz calculated by Mohr.[4] This comparison constitutes the most rigorous test of QED at high field strengths.[1]

Our experiment is performed by measuring the electric field quenched lifetime of the metastable $2S_{1/2}$ state. At Z=18 the unperturbed state decays predominantly by the simultaneous emission of two electric dipole photons. A decay rate[5] of 2.76×10^{8} sec^{-1} is associated with this mode. There is also a relatively slow, single-photon magnetic dipole channel with a rate[5] $A = 9.08 \times 10^{6}$ sec^{-1}. The frequency distribution of the emitted photons therefore consists of a continuous spectrum centered about 1659 eV falling rapidly to zero at the end points plus a small peak at the $2S_{1/2} - 1S_{1/2}$ energy separation of 3318 eV.

The application of an external electric field mixes the wavefunctions of the $2S_{1/2}$ state with the nP states. Since P states decay by fully allowed electric dipole radiation, the $2S_{1/2}$ lifetime is shortened. To lowest order the decay rate R of the $2S_{1/2}$ state as a function of electric field is given by:[6] $R = R_s + R_p |V|^2/\hbar^2(S^2 + 1/4R_p^2)$ where R_s and R_p are the natural 2S and 2P decay rates, S is the Lamb shift in radians per second and V is the relativistic electric dipole matrix element: $V = 0.992 \sqrt{3}\ eEa_o/Z$ where e is the electric change, E the electric field in esu and a_o the Bohr radius. An electric field in the atom's rest frame is produced by passing atoms at a velocity of $v = 4 \times 10^9$ cm/sec through a homogeneous magnetic field. At a field of B = 16 kGauss, the 6.5×10^5 V/cm electric field produces a quench rate comparable to the natural $2S_{1/2}$ decay rate. The Lamb shift can thus be determined by measuring the velocity, magnetic field and quenched lifetime.

The magnetic field is measured with an integrating flux meter calibrated against a nuclear magnetic resonance Gauss meter. The velocity is determined to a few parts per thousand by measuring the beam energy (approximately 340 MeV) with surface barrier detectors which have been calibrated against a magnetically analyzed argon beam of 346 MeV. Errors from these velocity and magnetic field measurements make no significant contribution to the Lamb shift error.

Lifetimes of the $2S_{1/2}$ state are measured by beam-foil time-of-flight. Bare argon nuclei, at velocities of 4×10^9 cm/sec, obtained from the Lawrence Berkeley Laboratory SuperHILAC are passed through an 8 μg/cm^2 carbon foil located in a homogenous magnetic field (Fig. 1). Among the nuclei which capture electrons the ratio of hydrogenlike atoms to heliumlike atoms is 17:1. X-rays from decays in flight of the excited states are observed at a distance of approximately 0.6 meters from the beam by a pair of Si(Li) x-ray detectors. A typical pulse height spectra is shown in Fig. 2. The raw data for the $2S_{1/2}$

decay curves is the pulse-height spectra measured as a function of x-ray detector position downstream of the foil. The intensity is normalized to the integrated current obtained by stopping the beam in a Faraday cup. The comparable intensities in the quench peak and two-photon spectra enable us to construct decay curves from either portion of the spectra.

The raw data must be corrected for deflection of the beam in the magnetic field. In addition to the change in solid angle and change in length of the beam viewed, there is a large change in brightness due to the motion of the deflected beam toward (or away from) the detectors.[7] Our model was tested by deflecting beams of heliumlike argon in the long lived 2^3S_1 state, so that changes in count rate were primarily due to deflection effects rather than population depletion. At current levels of accuracy the uncertainities in the geometrical corrections make a negligible contribution to the experimental error.

Most of the hydrogenlike argon forms in the $1S_{1/2}$ ground state or low lying excited states. Among the atoms formed in highly excited states, few cascade through the $2S_{1/2}$ state, because decay chains which populate the $2S_{1/2}$ state are far more likely to decay to the $1S_{1/2}$ state due to a much larger energy separation. Furthermore, atoms undergoing transitions in which the principle quantum number n decreases more rapidly than the orbital angular momentum ℓ have a high probability of reaching states of maximum ℓ = n-1 which are long-lived and decay through the chain .... 4F, 3D, 2P, 1S. An upper limit to the cascading to the

$2S_{1/2}$ state can be made from examination of the spectra (Fig. 2) as follows. Assume that all of the counts in the (240 eV Gaussian width) region 4000 eV - 4700 eV are from (Doppler shifted) decays $nP \rightarrow 1S$ ($n > 2$). The branching ratio[8] $nP \rightarrow 1S:nP \rightarrow 2S$ ($n > 2$) is about 7.5:1. By comparing the number of counts in the two-photon continuum with the ($n > 2$)$P \rightarrow 1S$ rate we find an upper limit of 0.2% of the observed two-photon counts orginating from cascades to the $2S_{1/2}$ state, an insignificant contribution. At larger foil-detector separations the upper limit is much smaller. We emphasize that this upper limit is derived from purely experimental quantities and is model independent. The large energy gap between the series limit of the Balmer series at 1100 eV and the beginning of the Lyman series at 3318 eV assures the absence of intefering lines in this region of the two-photon spectra.

In the observation of single photon decay of the $2S_{1/2}$ state interference between the unresolved spectra lines $2S_{1/2} \rightarrow 1S_{1/2}$ and the cascade fed $2P_{3/2,1/2} \rightarrow 1S_{1/2}$ result in a large systematic error in determining the $2S_{1/2}$ decay rate. In measurements of unquenched $2S_{1/2}$ lifetimes in hydrogenlike argon and hydrogenlike iron ($Z=26$) we observe a significant number of counts arising from cascades through the 2P state. In the absence of information about the populations of the different $n\ell$ states this cascade data is not directly applicable to quenching experiments as the electric field cuases appreciable mixing of states of different parity. For the present, we base our Lamb shift determination only upon $2S_{1/2}$ decay rates obtained by observing the two-photon decay channel.

Heliumlike argon, present in the beam in small quanitites has metastable states 2^3P_2 and 2^3S_1 whose decay produces x-rays at 3126 eV and 3104 eV respectively.[9] (Counts from these lines can be separated from the 3318 eV line from hydrogenlike argon by a careful computer fit to the spectra using the measured x-ray detector response function.) However, the two-photon decay (2E1) of the 2^1S_0 state in the argon is a continuum and can not be distinguished from the two-photon decay spectra of the $2S_{1/2}$ state of hydrogenlike argon. From observed population ratios $2S_{1/2}:2^3P_2$ in this experiment and population ratios $2^3P_2:2^1S_0$ in experiments on heliumlike argon performed by Marrus and Schmeider,[9] we find the initial population of 2^1S_0 to be 0.03 ± 0.01 of the initial $2S_{1/2}$ population. The uncertainty in the 2^1S_0 fraction is the largest source of systematic error in this Lamb shift measurement.

Lifetimes were measured over an average of 2.5 decay lengths in electric fields of $\pm(5.93, 7.14, 8.06, 8.60) \times 10^5$ V/cm with two detectors for a total of 16 decay curves. Position dependent background (which appears to be the result of gamma rays, Compton scattered in the detector) was measured as a function of detector position (see Fig. 1) with the foil 0.75 meters upstream to allow the $2S_{1/2}$ state to depopulate before reaching the detectors. The data was sorted to yield Lamb shift values as a function of field strength and polarity, direction of beam bending, direction of detector travel and count rate. No systematic differences were observed.

The result for the Lamb shift is 38.0 ± 0.6 THz. Contributions to the error are statistics, 0.35 THz which is mostly due to variation in the background; 0.45 THz, from uncertainty in the 2^1S_0 fraction, and 0.15 THz miscellaneous.

Many people made contributions both large and small to this experiment. We thank them all, but most especially we thank our engineer, Douglas MacDonald, who contributed to all aspects of the technical design. This work was supported by the Division of Chemical Sciences, Office of Basic Energy Sciences, U.S. Department of Energy.

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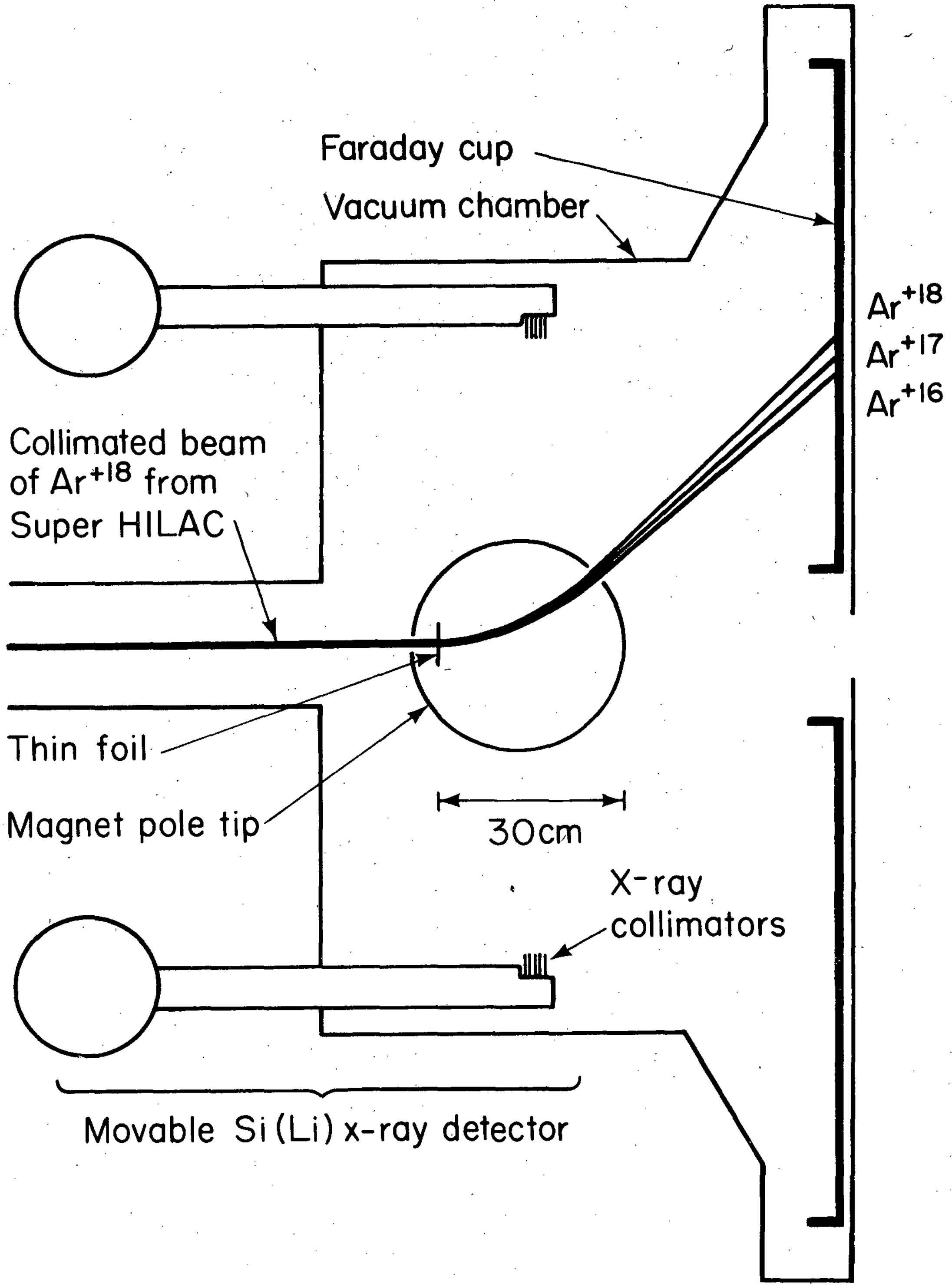
FIGURE CAPTIONS

Fig. 1. Schematic diagram of the apparatus. Sideways looking x-ray detectors are collimated to view approximately a 2 cm long segment of beam.

Fig. 2. Pulse height spectra from decays in flight of the $2S_{1/2}$ state of hydogenlike Ar in a motional electric field of 7.8×10^5 V/cm at a foil-detector separation of 9 cm. The detector has a F.W.H.M. resolution of 280 eV and the spectra is Doppler shifted 4% due to the deflection of the beam in the magnetic field. Below 1500 eV the sensitivity of the detector drops rapidly to zero. In addition to the 3318 eV line from 1γ decay of hydrogenlike Ar there are weaker lines at 3126 eV and 3104 eV from decays of 2^3P_2 and 2^3S_1 states of heliumlike Ar. The hydrogenlike line can be separated from the helium-like lines by a computer fit.


Faraday cup
Vacuum chamber
Ar+18
Ar+17
Ar+16
Collimated beam of Ar+18 from Super HILAC
Thin foil
Magnet pole tip
30cm
X-ray collimators
Movable Si(Li) x-ray detector

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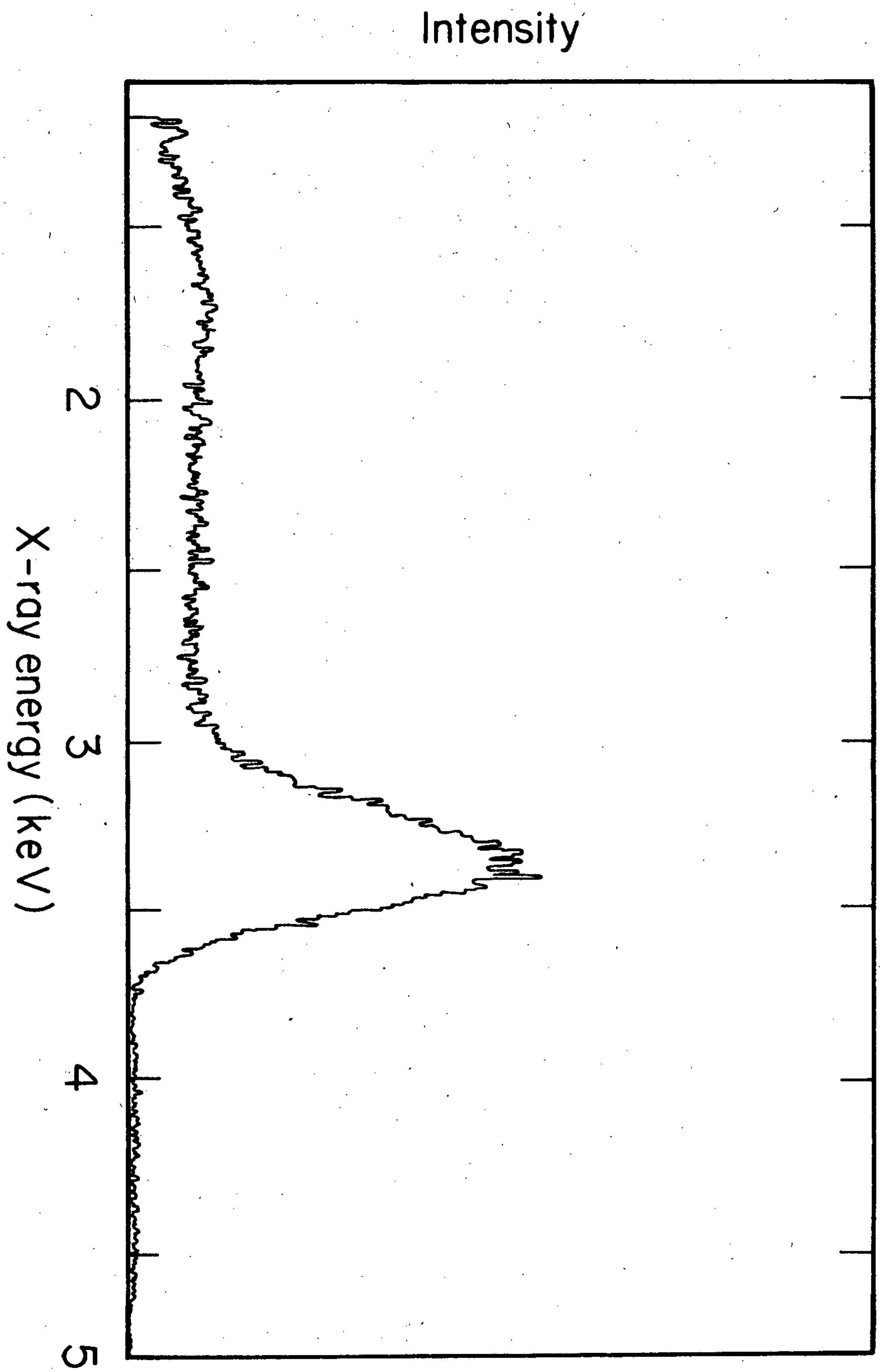

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