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Measurement of the Lamb Shift in the $n = 2$ State of $^{12}C^{5+}$

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A beam of hydrogenic $^{12}C^{5+}$ atoms in the metastable $2S$ state has been produced. By quenching the state in a known motional electric field and measuring the decay length, an indirect measure of the Lamb shift $\mathcal{S}$ is obtained. A preliminary result of $\mathcal{S} = 744$ GHz, with a statistical uncertainty of less than 1%, is reported as compared with a theoretical prediction of $\mathcal{S} = 783$ GHz. Possible systematic effects which may reduce the discrepancy are considered.

Recent refinements in experimental and theoretical technique have removed several long-standing discrepancies in the predictions of quantum electrodynamics (QED). In particular, the hydrogen Lamb shift[1] ($\mathcal{S} = 2P_{1/2} - 2S_{1/2}$ splitting) and the anomalous magnetic moment of the electron,[2] the two quantities whose discovery stimulated the reformulation of the theory, now stand in excellent agreement with experiment. However, fundamental reasons exist for further tests of the validity of QED.[3] In particular, Lamb-shift measurements in high-Z hydrogenic atoms provide a basic test of our understanding of the virtual radiative processes associated with the electron and photon fields. These processes (e.g., the emission and reabsorption of virtual photons by the orbiting bound electron) which give rise to the Lamb shift are strongly affected by the external Coulomb potential. Experimental tests of the theory for systems in which the strength of this potential varies markedly from that of hydrogen thus provide a basic and worthwhile test of QED.

The Lamb shift is given as a strongly Z-dependent expansion[4] in α and $Z\alpha$,

$$\mathcal{S} = \sum_{i,j \geq 4} \alpha^i (Z\alpha)^j C_{ij},$$

where Z is the nuclear charge, α is the fine-structure constant, and the C_{ij} are term coefficients which are either independent or slowly varying functions of Z. The higher-order coefficients become increasingly more important as Z is increased and, unfortunately, significantly more difficult to calculate [terms of order $(Z\alpha)^6$ have been calculated to date]. It has been estimated[5] that departures as large as 1% between experimental and theoretical $\mathcal{S}$ values may be observed in a $Z = 10$ system if the theoretical value contains only the terms which have been presently calculated. Therefore, we conclude that even crude $\mathcal{S}$ measurements in high-Z systems are a significant test of present theory and may force modifications in calculational technique.

We report here the results of a preliminary measurement of the Lamb shift in the $n = 2$ state of $^{12}C^{5+}$, $Z = 6$. This work represents an initial step in our program to extend $\mathcal{S}$ measurements to high-Z hydrogenic systems. Our technique is similar to that employed by Fan, Garcia-Munoz, and Sellin[6] in their innovative work on the $Z = 3$ system but with important modifications. In essence, $\mathcal{S}$ is obtained indirectly by a measurement of the lifetime τ_{2S} of the metastable $2S$ state in the presence of a "quenching" electric field.

In the absence of external fields, τ_{2S} is equal to 2.61×10^{-6} sec as determined by the dominant two-photon decay process.[7] The $2P$ state, which can decay by a one-photon process to the ground $1S$ state, is short lived. A Z^{-4} scaling of the well-founded result in hydrogen[8,9] yields $\tau_{2P} = 1.232 \times 10^{-12}$ sec.[10] The presence of an external electric field mixes the $2S$ and $2P$ states, resulting in "quenching" of the $2S$ lifetime. The theory of this process has been given by Bethe and Lamb[11] and to lowest order yields the expression

$$\frac{1}{\tau_{2S}} = \frac{1}{\tau_{2P}} \frac{|V|^2}{\hbar^2(\mathcal{S}^2 + 1/4\tau_{2P}^2)}, \tag{1}$$

where $V = \sqrt{3}eEa_0Z^{-1}$ is the matrix element of the perturbation $e\vec{E}\cdot\vec{r}$ which couples the $2S$ and $2P$ states, $\hbar$ is the Planck constant, and $\mathcal{S}$ is the Lamb shift in circular frequency units. Clearly then, if we take the view that τ_{2P} is a known quantity, a measurement of τ_{2S} in a known electric field determines $\mathcal{S}$. Deviations of $\mathcal{S}_{exp}$ from QED perturbation-series expansions could be due to a breakdown in this assumption.

A monoenergetic beam of bare carbon nuclei, $^{12}C^{6+}$, is obtained by poststripping the dominant 4+ component of the output carbon beam from the Rutgers University–Bell Telephone Laboratories tandem electrostatic accelerator. The 6+ beam energy is determined by the tandem 90° analyzing magnet to an accuracy of ±10 keV. Thus far, measurements have been made at 20, 25, and 30 MeV. The analyzed beam is collimated and passed through a baffled, windowless gas cell containing argon at a pressure of about 0.1 Torr (see Fig. 1). The dominant charge-transfer process occurring in the gas cell is the pickup of one electron by the carbon nucleus.[12] A few-nanoampere emergent beam containing roughly equal fractions of 6+ and 5+ ions and negligible fractions of the remaining charge states is observed, in agreement with equilibrium charge measurements of Martin.[13] The charge states were studied on a highly collimated beam (less than 1 pA) with a position-sensitive detector inserted into the beam beyond a homogeneous magnetic field. For the full beam, charge-state separation could be observed with a removable quartz viewer situated within the Faraday cup at the end of our beam line. Following the gas cell, the beam, which contains some $2S$ ions, passes through two additional collimators and gas baffles into a differentially pumped quenching region maintained at a pressure of about 10^{-7} Torr. Other relevant excited $^{12}C^{5+}$ atomic states should have lifetimes appreciably less than the transit time to the quenching region. Metastable ions, which are moving with a velocity of about 2×10^9 cm/sec, would easily survive transit to and across our quenching region in the absence of external fields.

For high-Z metastable atoms moving at relativistic velocities, the large uniform electric fields required to produce measurable decay lengths are difficult to generate in the laboratory. A solution to this problem is afforded by employing the motional electric field $\vec{E}_m = (\gamma/c)\vec{v}\times\vec{H}$, where $\gamma = (1 - v^2/c^2)^{-1/2}$. In the quenching region a transverse magnetic field is applied to the ions. A magnetic field of 3.1 kG produces an electric field effective on the ions sufficient to reduce the $^{12}C^{5+}$ metastable decay length to 2.8 cm at 25 MeV.

The decaying atoms emit 33.8-Å Lyman-α quanta which are detected with two counters, one

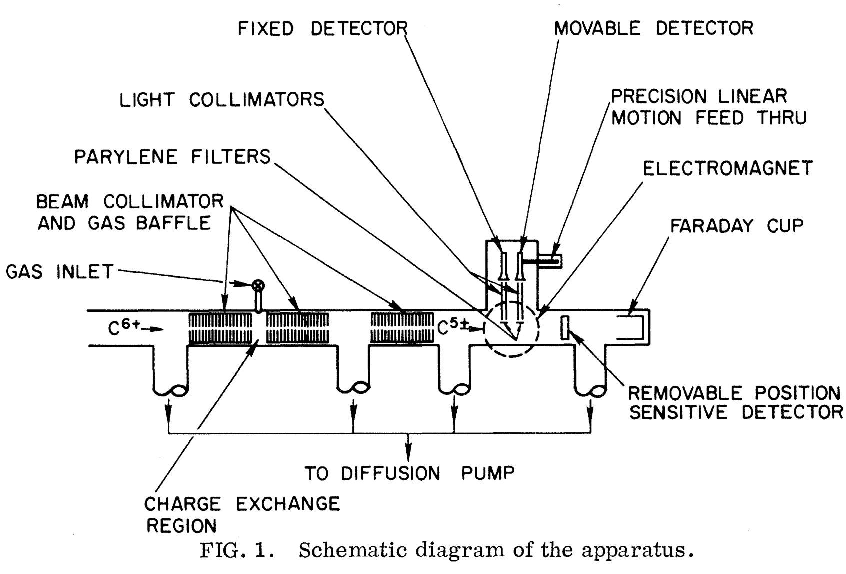

FIG. 1. Schematic diagram of the apparatus.

stationary and one movable parallel to the beam direction. The detectors employed in this initial work were windowless, Spiraltron electron multipliers produced by the Bendix Corporation. Finally, the beam is collected in a Faraday cup beyond the quenching magnet and integrated, providing a monitor of beam-current intensity.

Light reaching the detectors has been collimated and passed through a 1000-Å-thick parylene C filter. The filter provides a barrier against low-energy charged particles and affords appreciable narrow-banding of the detector sensitivity. As a check on the energy of the detected photons, the Spiraltrons were replaced with calibrated avalanche diode detectors.[14] These indicated that radiation of the order of a few hundred eV was being detected.

The lifetime τ_{2S} is determined from the known ion velocity and a careful measurement of the decay length and quenching magnetic field. The magnetic field is measured with an NMR gaussmeter. Theoretical decay curves are fitted to eleven data points obtained by counting with the movable detector at different precisely set points along the decay path. Integrated beam current and stationary detector counts are simultaneously collected. Several normalized decay curves obtained at different quenching fields are shown in Fig. 2. Typically, 20 min is spent collecting a single data point.

Since the accelerator output may vary substantially over the course of a run, a reliable normalization scheme is required. Both normalization to a fixed number of counts in the stationary detector and to a fixed amount of integrated ion beam have been tried. No statistically significant difference in results has been obtained with either scheme. However, a reduction in scatter is observed with the beam normalization scheme, and hence it has been used in the final analysis. One explanation for this improvement is the much better statistics inherent in the integrated beam counts.

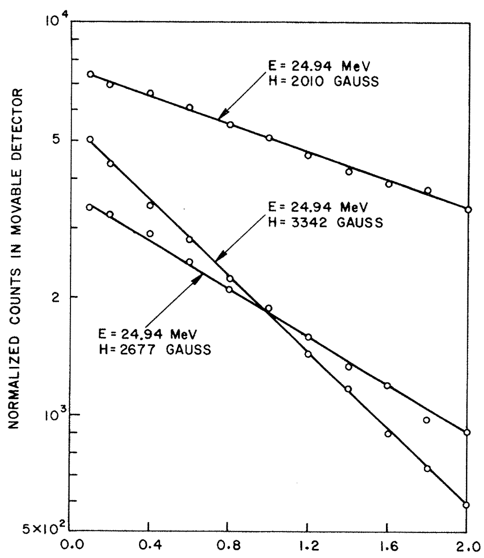

FIG. 2. Semilog plot of normalized decay curves obtained with different values of the quenching field.

Lamb-shift values are obtained by making least-squares computer fits to data of the type shown in Fig. 2. A function of the form

$$S(x) = A e^{-(x/v\tau_{2S})}, \qquad (2)$$

where $S(x)$ is the signal at detector position x, is employed in the fitting.[15] Two variable parameters are fitted to the data, A, an amplitude factor, and τ_{2S}, which determines $\mathcal{S}$. Prior to fitting, a small background has been subtracted from the data. In zero magnetic field, a small position-independent signal has been detected. Typically, the background signal was 5% of the field-on counting rate at the midpoint of a decay curve with the 1000-Å parylene C filter present. The background-to-signal ratio was significantly greater without the parylene C filter. This signal has been carefully measured and eliminated from the analysis. All data shown in Fig. 2 are with this background subtracted. The source of this background has not yet been determined.

Corrections to Eq. (2) have been included in the analysis to allow for several additional effects. These are the Zeeman effect of the $n = 2$ levels, prequenching of the metastables in the fringing field of the electromagnet, coupling of the $S_{1/2}$ level to the $P_{3/2}$ level, special relativity, and the physical deflection of the beam which changes slightly the effective solid angle subtended by the detectors. The details of these corrections will be presented in a future publication, but is is important to point out that each one of them is small (~0.1%) and their net effect on the final result is <1%.

The results of our initial investigation, consisting of ten runs at different energies and magnetic fields, are presented in Table I. The statistical uncertainty in each value is about ±1%. Runs were taken in pairs with the magnetic field first left (L) then right (R). An average value of $\mathcal{S}$ = 744 GHz was obtained as compared with a theoretical prediction[1,16] of $\mathcal{S}$ = 783 GHz. The deviation of our preliminary result from the QED prediction is significantly greater than our statisti-

Table I. Summary of experimental results.

Energy (MeV)	Magnetic field (G)	$\mathcal{S}$ (GHz)
24.94	2677 L	748
24.94	2677 R	750
24.94	2010 L	736
24.94	2010 R	739
24.94	3342 L	748
24.94	3328 R	745
20.00	2632 L	740
20.00	2632 R	743
29.95	2632 L	743
29.95	2632 R	749
	Average	744

cal uncertainty. This result was unexpected and remains presently unexplained. The fact that consistent results were obtained at several values of quenching field and beam velocity reduces the probability of systematic error. However, we are currently engaged in an extensive search for possible systematic errors in both the experiment and the analysis. Our initial investigation of many such effects has not yet yielded the source of the discrepancy. Experimental effects which have been given initial study include magnetic field gradients, magnetic field effect upon the detector, NMR probe position correction, misalignment of ion beam with the movable detector and the magnetic field, stray electric fields, residual-gas quenching of metastables, error in beam energy determination, and contamination of the C^{6+} beam with other components of the same rigidity. Effects in the analysis being considered are higher order corrections to the Bethe-Lamb theory; magnetic-field, relativistic, and reduced-mass corrections to the matrix element V; Stark shift of the energy levels; and higher-order corrections to the $^2P_{1/2}$ state lifetime.

The possibility that some new and interesting effect underlies the discrepancy should not be ruled out. While a 5% error in the QED calculation of $\mathcal{S}$ seems untenable, a search for other effects in the atomic physics, e.g., radiative corrections to the relevant lifetimes and relativistic effects on the atom, must also be made.

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