Lamb Shift in Heliumlike Uranium (U^{90+})

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We report a value of 70.4 ± 8.3 eV for the one-electron Lamb shift in uranium, in agreement with the theoretical value of 75.3 ± 0.4 eV. We extract our Lamb shift from a beam-foil time-of-flight measurement of the (54.4 ± 3.4)-ps lifetime of the $1s2p_{1/2}\,^3P_0$ state of heliumlike uranium.

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A possible failure of quantum electrodynamics (QED) to predict accurate radiative corrections to bound states at $Z = 92$ is not ruled out by its success at low Z. The largest contribution to the Lamb shift at $Z = 92$ comes from terms in the electron self-energy[1] which are high powers of $Z\alpha$ and which are invisible in experiments at low Z. Lamb-shift measurements on high-Z electronic and muonic atoms are complementary because muonic-atom measurements are sensitive to higher-order vacuum-polarization effects but not to self-energy effects.[2]

We report a value of 70.4 ± 8.3 eV for the one-electron Lamb shift in uranium. It is in agreement with the theoretical value[3,4] of 75.3 ± 0.4 eV based upon a calculation of the self-energy by Mohr.[3] We extract our Lamb shift from our beam-foil time-of-flight measurement of 54.4 ± 3.4 ps for the lifetime of the $1s2p_{1/2}\,^3P_0$ state of heliumlike uranium.

The $1s2p_{1/2}\,^3P_0$ state (Fig. 1) is the only low-lying excited state found in hydrogenlike uranium or heliumlike uranium whose long lifetime allows its decay to be observed in vacuum downstream from the target in which it is produced. In heliumlike uranium the $1s2p_{1/2}\,^3P_0$ state decays 70% of the time to the $1s2s\,^3S_1$ state by an electric-dipole ($E1$) transition. This makes the $1s2p_{1/2}\,^3P_0$ lifetime sensitive to the $1s2p_{1/2}\,^3P_0$–$1s2s\,^3S_1$ energy difference of 260.0 ± 7.9 eV (experimental value) and hence to the Lamb shift. At $Z = 92$ the major contributions to the calculated Lamb shift are the self-energy[3] of 56.7 eV, the leading-order term in the vacuum polarization[3,4] of -14.3 eV, and the finite-nuclear-size correction[4] of 32.5 eV. In heliumlike uranium there is also a small screening correction to the radiative corrections—expected to be of order $1/Z$ times the self-energy.[2,6] For zero Lamb shift the $1s2p_{1/2}\,^3P_0$ and $1s2s\,^3S_1$ states would be split by the difference in the $1s_{1/2}$-$2s_{1/2}$ and $1s_{1/2}$-$2p_{1/2}$ Coulomb interactions. This splitting at $Z = 92$ has been calculated by Mohr[7] to be 330.4 eV, which agrees (1 eV) with the calculations of Lin, Johnson, and Dalgarno[5] and of Drake.[8] The other significant decay of the $1s2p_{1/2}\,^3P_0$ state is to the $1s^2\,^1S_0$ ground state by a two-photon electric-dipole, magnetic-dipole ($E1M1$) transition.[8] To obtain the Lamb shift we combine our measured $1s2p_{1/2}\,^3P_0$ lifetime and the calculated values for the $E1M1$ decay rate,[8] the $1s2p_{1/2}\,^3P_0$–$1s2s\,^3S_1$ $E1$ matrix element,[9] and the $1s2p_{1/2}\,^3P_0$–$1s2s\,^3S_1$ Coulomb splitting.[7]

In our beam-foil time-of-flight measurement about 0.5% of a beam of 218-MeV/u hydrogenlike uranium is converted to the $1s2p_{1/2}\,^3P_0$ state of heliumlike uranium by electron capture in a 0.9-mg/cm^2 Pd foil. Hydrogenlike uranium[10] is obtained from the Lawrence Berkeley Laboratory's Bevalac.[11] Downstream from the Pd foil we observe, not the 260-eV photon from the $1s2p_{1/2}\,^3P_0 \rightarrow 1s2s\,^3S_1$ transition, but instead the 96.01-keV x ray[4,7] from the subsequent fast decay of the $1s2s\,^3S_1$ state to the $1s^2\,^1S_0$ ground state. The 96.01-keV x ray is much easier to detect than the 260-eV photon, and the $1s2s\,^3S_1$ lifetime[5] of 10^{-14} s has no effect on the measured $1s2p_{1/2}\,^3P_0$ lifetime, provided that sufficient time is allowed for the initial $1s2s\,^3S_1$ population to decay.

Figure 2 shows a spectrum recorded by one of our Ge x-ray detectors collimated to view emission perpendicu-

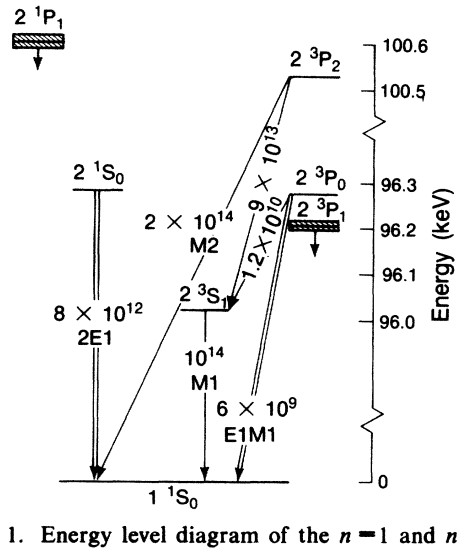

FIG. 1. Energy level diagram of the $n = 1$ and $n = 2$ states of heliumlike uranium. Decay rates, except for the $1s2p_{1/2}\,^3P_0$ state, are taken from Ref. 5. Energies are taken from Refs. 3–5. $M1$ and $M2$ decays are magnetic-dipole and magnetic-quadrupole decays, respectively, and decays without labels are electric-dipole decays. An approximate radiative width is indicated for the $^1P_1$ and $^3P_1$ states.

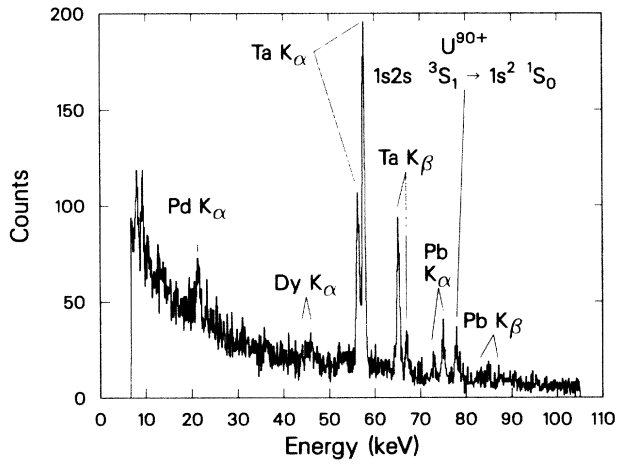

FIG. 2. Spectrum recorded by a Ge x-ray detector collimated to view emission perpendicular to the uranium beam at a point 0.67 cm downstream from the Pd foil. This spectrum represents 135 min of counting—about 10^8 uranium ions. The Doppler-shifted peak from the decay of $1s2p_{1/2}\,^3P_0 \rightarrow 1s2s\,^3S_1 \rightarrow 1s^2\,^1S_0$ is at 77.8 keV. Cascades from higher excited states would produce a peak at 81.4 keV. Peaks at 72.8 and 75.0 keV are Pb $K\alpha_2$ and Pb $K\alpha_1$ x rays, and those at 84.5–87.3 keV are Pb $K\beta_1$–$K\beta_3$ x rays. Peaks at 56.3 and 57.5 keV are Ta $K\alpha_2$ and Ta $K\alpha_1$ x rays, and those at 65.2 and 67.0 keV are Ta $K\beta_1$ and $K\beta_2$ x rays. Peaks at 45.2–46.0 keV are Dy $K\alpha_2$,$K\alpha_1$ x rays. Pb and Dy are used for shielding and Ta is used for x-ray detector collimators. The peak at 21.2 keV is scattered Pd $K\alpha_1$ radiation from the Pd foil. Background is caused by bremsstrahlung of the foil electrons in the field of the uranium projectile, by bremsstrahlung of electrons scattered in and ejected from the Pd foil, and by fast nuclear fragments colliding with the Ge in the x-ray detector. Other sources of background may also exist. To reduce background we restricted the scatter of x rays into the detector, held electrons ejected from the foil away from the detector with a magnetic field, and vetoed background from nuclear fragments by using scintillators.

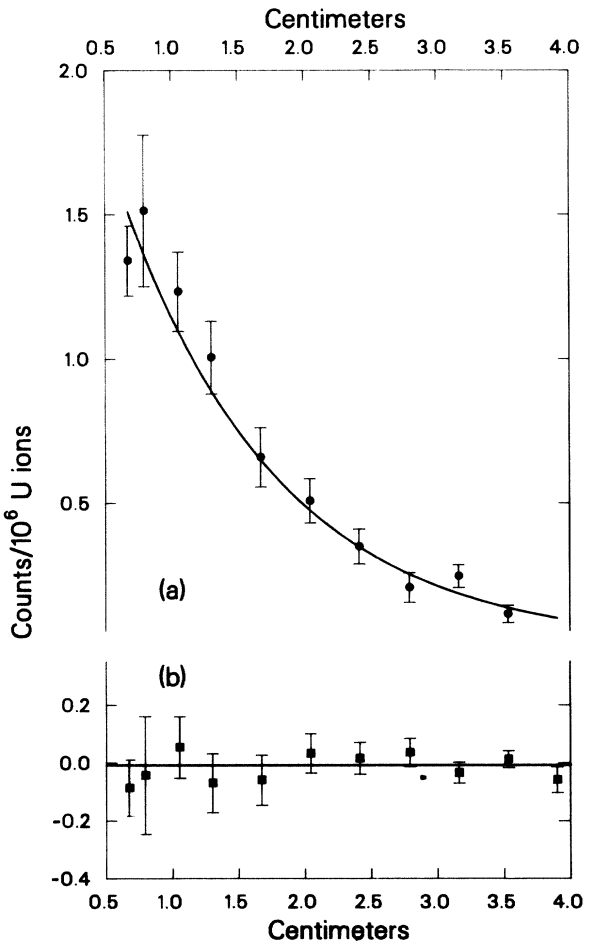

FIG. 3. Linear plots of the intensity of x rays from the transitions (a) $1s2s\,^3S_1 \rightarrow 1s^2\,^2S_0$ and (b) $1s2p_{3/2}\,^3P_2 \rightarrow 1s^2\,^1S_0$, as functions of distance downstream from the Pd foil. Each point is the sum of the spectra from two x-ray detectors. Error bars are one-standard-deviation statistical errors. The horizontal line in (b) is the fit of a hypothetical constant counting rate to the data. The counting rate is consistent with zero and sets a limit to the contamination of our signal by cascade feeding.

lar to the uranium beam at a point 0.67 cm downstream from the Pd foil. The 96.01-keV x ray from the $1s2p_{1/2}\,^3P_0$-fed $1s2s\,^3S_1 \rightarrow 1s^2\,^1S_0$ decay is Doppler shifted and appears as a peak at 77.76 ± 0.18 keV. We identified this peak by its correct time dilation (transverse Doppler shift) and exponential decay at two different beam energies, 218 and 175 MeV/u (here determined from the operating conditions of the Bevalac and corrected for energy loss in the foils), by the dependence of the Doppler-broadened peak width on the angular acceptance of the detector, by the yield[12] from foils of different Z and thickness, by the peak's absence when the foil is removed, and by the lack of any other long-lived, low-lying states of heliumlike uranium or hydrogenlike uranium besides the $1s2p_{1/2}\,^3P_0$ state.

The height of the peak above background was found by a maximum-likelihood fit of a quadratic to the background. The decay curve (Fig. 3), which spans 2.7 decay lengths, is a maximum-likelihood fit of a single exponential to the data. The reduced χ^2 for the fit is 0.89. The spectrum shown in Fig. 2 contributes to the first point at 0.67 cm in Fig. 3. The $1/e$ decay length is 1.182 ± 0.069 cm, and the 5.8% statistical error dominates our final error in the $1s2p_{1/2}\,^3P_0$ lifetime. We determine the beam velocity to be $(0.5866 \pm 0.0044)c$ from the Doppler shift of the x ray from the $1s2s\,^3S_1 \rightarrow 1s^2\,^1S_0$ transition. This velocity agrees with the value of $(0.583 \pm 0.002)c$ determined from the operating conditions of the Bevatron and corrected for energy loss in the foils. (We choose to use the Doppler-shift-determined value of the velocity which, although less accurate, is more direct.) Our value for the $1s2p_{1/2}\,^3P_0$ lifetime is 54.4 ± 3.4 ps. Other contributions to our 6.3% total lifetime error are 1.2% in the determination of the beam velocity and time dilation from the transverse Doppler shift of the $1s2s\,^3S_1 \rightarrow 1s^2\,^1S_0$ transi-

tion and 2.3% from the experimental upper limit to contamination of our signal by cascade feeding.

A disadvantage in using the $1s2p_{1/2}\,^3P_0$-fed $1s2s\,^3S_1 \rightarrow 1s^2\,^1S_0$ decay as a signal is that it makes the measured $1s2p_{1/2}\,^3P_0$ lifetime sensitive to repopulation of the $1s2p_{1/2}\,^3P_1$, $1s2s\,^3S_1$, and $1s2p_{1/2}\,^3P_1$ states by cascade feeding from states of high principal quantum number n. States of heliumlike uranium with $n < 22$ will cascade to the $1s^2\,^1S_0$ ground state before we begin our measurement of the $1s2p_{1/2}\,^3P_0$ lifetime. But the population of states with $n \geq 22$ and high orbital angular momentum (l) can perturb our measurement by cascadeing down the chain of $l = n - 1$ yrast states. The population of these states, however, is very small and we are able to set an upper limit of 2.3% for their contribution to the measured decay length.

In heliumlike uranium there are four $J = j_1 + j_2$ (jj coupled) states of a $1s_{1/2}$ electron coupled to an nl electron: They are $J = l - 1$ and $J = l$ for a $1s_{1/2}$ electron coupled to a $nj = nl - \frac{1}{2}$ electron, and $J = l$ and $J = l + 1$ for a $1s_{1/2}$ electron coupled to a $nj = nl + \frac{1}{2}$ electron. We assume that the populations of the $nj = nl + \frac{1}{2}$ and the $nj = nl - \frac{1}{2}$ states are equal. This assumption is consistent with our observation of the intensities of the $N = 2$ state fine-structure components of heliumlike and hydrogenlike uranium when we view the target directly and by the population of the $1s2p_{1/2}\,^3P_0$ state. (If the $nj = l + \frac{1}{2}$ states have greater population, our analysis overestimates the uncertainty due to cascades.) We also assume that for each nj electron the populations of the two states of different J are equal. Surprisingly, the populations of the four different jj coupled states are only slightly redistributed in the cascade because the probability for making $\Delta J = 0$ or $\Delta j = 0$ transitions scales roughly as $0.5l^{-2}$ and therefore is very small at high l.

Cascades which have the potential to affect the measured decay length, besides those reaching the $1s2p_{1/2}\,^3P_0$, are those reaching the $1s2p_{1/2}\,^3P_1$ and $1s2p_{3/2}\,^3P_2$ states: the $1s2p_{3/2}\,^3P_2$ state because it decays 30% of the time to the $1s2s\,^3S_1$ state, and the $1s2p_{1/2}\,^3P_1$ state because its decay is not resolved from the $1s2s\,^3S_1$ decay. We set a limit to the presence of these cascades by searching for the x ray which results[4,5] both from $1s2p_{3/2}\,^1P_1$ decay (100.6 keV) and from the 70% of the $1s2p_{3/2}\,^3P_2$ state which decays directly to the ground state (100.5 keV). The rates at which cascades enter the $1s2p_{1/2}\,^3P_0$, $1s2s\,^3S_1$, and $1s2p_{1/2}\,^3P_1$ states are proportional to the intensity of this x-ray line. In Fig. 2 this x-ray line would appear as an isolated peak, Doppler shifted to 81.4 keV. The counting rate from this supposed peak, after subtraction of the background, is plotted in Fig. 3 and is consistent with zero.

As both feeding of the $1s^2p_{1/2}\,^3P_0$ state and blends from the $1s2s\,^3S_1$ and $1s2p_{1/2}\,^3P_1$ states would be present from cascades, the effect upon the measured $1s2p_{1/2}\,^3P_0$ decay length would be positive for a constant or slowly decreasing cascade rate and negative for a rapidly decreasing cascade rate. The bounds set by the data on the respective shifts are +3.2% and −1.4%, respectively. These are smaller than the statistical error in the $1s2p_{1/2}\,^3P_0$ lifetime of 5.8% and we combine cascade uncertainties into a single error of 2.3%.

Possible cascades in the hydrogenlike fraction of our beam would feed the $2^2P_{3/2}$ and $2^2P_{1/2}$ states which are unresolved from the corresponding states in the heliumlike fraction. We find that if part of the cascades came from hydrogenlike uranium instead of heliumlike uranium, the net effect of cascades on the measured $1s2p_{1/2}\,^3P_0$ lifetime would decrease. We have found it difficult to produce excited states of heliumlike uranium by direct excitation in a target, and therefore we expect to produce only a negligible number of excited states of hydrogenlike uranium in our target.

From our $1s2p_{1/2}\,^3P_0$ lifetime of 54.4 ± 3.4 ps and Drake's calculated $E1M1$ decay rate[8] of $0.564(5) \times 10^{10}$ s^{-1} we obtain a $1s2p_{1/2}\,^3P_0$–$1s2s\,^3S_1$ $E1$ decay rate of $(1.273 \pm 0.116) \times 10^{10}$ s^{-1}. Using the dipole length formula for the $E1$ decay rate,[9] $A = 12ak^3(Z\alpha)^{-2}(0.792 + 0.795/Z)^2$ ($\hbar = m = c = 1$), we find for k, the $1s2p_{1/2}\,^3P_0$–$1s2s\,^3S_1$ splitting, a value of 260.0 ± 7.9 eV. Subtracting the calculated Coulomb contribution[6] of 330.4 eV yields a Lamb shift of 70.4 ± 7.9 eV.

So far we have accounted only for experimental uncertainty; theoretical uncertainty comes from the effect of small terms omitted from the calculations. We estimate that a $Z^{-1}(Z\alpha)^2$ correction to the $1s2p_{1/2}\,^3P_0$–$1s2s\,^3S_1$ $E1$ matrix element and a $1/Z$ correction to the $E1M1$ decay rate contribute a total of ≈ 1 eV to our inferred $1s2p_{1/2}\,^3P_0$–$1s2s\,^3S_1$ splitting; that a term of $Z^{-2}(Z\alpha)^5$ or $Z^{-2}(Z\alpha)^6$ contributes ≈ 2 eV to the 330.4-eV Coulomb splitting of the $1s2p_{1/2}\,^3P_0$–$1s2s\,^3S_1$ states; and that a $1/Z$ screening correction to the self-energy, vacuum polarization, and finite nuclear size contributes ≈ 1 eV to the Lamb shift. These combine to give a separate theoretical error of 2.4 eV in our extracted value of the Lamb shift.

In conclusion, we have used the following steps to measure the Lamb shift in uranium: (i) measured the decay length for the heliumlike uranium $1s2p_{1/2}\,^3P_0$ state using the beam-foil time-of-flight technique by observing the $1s2s\,^3S_1 \rightarrow 1s^2\,^1S_0$ x-ray transition; (ii) determined the $1s2p_{1/2}\,^3P_0$ lifetime by combining the measured $1s2p_{1/2}\,^3P_0$ decay length with the beam velocity; (iii) found the $1s2p_{1/2}\,^3P_0 \rightarrow 1s2s\,^3S_1$ $E1$ decay rate by combining the $1s2p_{1/2}\,^3P_0$ lifetime with the calculated $E1M1$ decay rate[8] for $1s2p_{1/2}\,^3P_0 \rightarrow 1s^2\,^1S_0$; (iv) found the $1s2p_{1/2}\,^3P_0$–$1s2s\,^3S_1$ energy splitting from the $1s2p_{1/2}\,^3P_0 \rightarrow 1s2s\,^3S_1$ $E1$ decay rate and the calculated $E1$ matrix element[9]; (v) found the uranium Lamb shift from the $1s2p_{1/2}\,^3P_0$–$1s2s\,^3S_1$ splitting and the calculated Coulomb interaction between the electrons.[7] Our final value of the uranium Lamb shift of 70.4 ± 8.3 eV is

in agreement with the theoretical value[3,4] of 75.3 ± 0.4 eV.

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