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Lamb shift in heliumlike uranium (U^{90+})

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We report a preliminary value of the Lamb shift in two-electron heliumlike U^{90+} of 69.1 (8.0) eV which is in agreement with the theoretical value^{1,2} of 75 eV for the one-electron Lamb shift at $Z=92$.

The measurement of the Lamb shift in a very high- Z atom is a test of quantum electrodynamics (QED) in a strong Coulomb field. QED is well tested for free particles and in the weak fields of low- Z atoms. But just as Newton's laws work well in weak gravitational fields but fail in strong gravitational fields, experiments in low- Z atoms do not rule out a possible failure of QED in the strong Coulomb field of a very high- Z atom.

We choose heliumlike uranium over hydrogenlike uranium for this measurement because both the $2^2S_{1/2}$ and $2^2P_{1/2}$ states of hydrogenlike uranium decay very rapidly making it very difficult to observe the decays outside of the target where the hydrogenlike uranium is formed. Consequently there is the risk that interactions with the target will perturb the energy levels of the atom. In heliumlike uranium the $1s2p\ ^3P_0$ state is metastable (55 ps lifetime) because angular momentum conservation forbids single photon decays to the $1s^2\ ^1S_0$ ground state.

Our value for the Lamb shift in heliumlike uranium was obtained from a measurement of the lifetime of the $1s2p\ ^3P_0$ state (see Fig. 1). In heliumlike uranium about 70% of the $1s2p\ ^3P_0$ state decays by an allowed electric-dipole (E1) transition to the $1s2s\ ^3S_1$ state, making the $1s2p\ ^3P_0$ lifetime sensitive to the $1s2p\ ^3P_0 - 1s2s\ ^3S_1$ energy splitting. The remainder decays to the ground state by a two-photon electric-dipole magnetic-dipole (E1M1) transition³. The $1s2p\ ^3P_0 - 1s2s\ ^3S_1$ splitting arises from the Lamb shift and from the Coulomb interaction between the two electrons in the $1s2p\ ^3P_0$ and in the $1s2s\ ^3S_1$ states. The latter is calculated to be 329 eV (Ref. 4,5) and 326 eV (Ref. 3). The measured $1s2p\ ^3P_0$ lifetime, the calculated E1M1 decay rate³ and the calculated E1 matrix element⁶ and

the non-QED contributions to the $1s2p\ ^3P_0 - 1s2s\ ^3S_1$ splitting are combined to determine the Lamb shift. The E1M1 decay rate and the E1 matrix element are insensitive to QED effects. The effect of the second electron on the Lamb shift⁷ is to decrease it by a term of order $1/Z$ which we neglect for $Z=92$ in the present experiment.

The indirect method of measuring the $1s2p\ ^3P_0$ lifetime rather than a direct measurement of the $1s2p\ ^3P_0 - 1s2s\ ^3S_1$ transition energy was chosen because it is experimentally much easier than measuring the 0.25 keV photon from this transition. In particular, 0.25 keV photon followed rapidly by emission of a 96 keV x ray from the $1s2s\ ^3S_1 - 1s^2\ ^1S_0$ decay. The 96 keV x ray is easy to detect. The 10^{-14} sec lifetime of the $1s2s\ ^3S_1$ state has no effect on the measurement of the 6×10^{-11} sec $1s2p\ ^3P_0$ lifetime provided sufficient distance is allowed for the initial $1s2s\ ^3S_1$ population to decay. A spectra taken 0.5 cm downstream from the target is shown in Fig. 2. The $1s2p\ ^3P_0$ lifetime is measured by the beam-foil time-of-flight technique. In this technique a beam containing the excited state whose lifetime is to be measured is prepared by passing a beam of ions of known velocity through a thin target. Down stream from the target, photons from the decay-in-flight of excited states are counted as a function of distance downstream from the target and normalized to the beam intensity.

Heliumlike uranium in the $1s2p\ ^3P_0$ state is prepared by stripping a beam of 220 MeV/amu uranium $39+$ which is obtained from the Lawrence Berkeley Laboratory's Bevalac. An aluminum target produces an equilibrium charge state distribution of roughly 5% U92+, 30% U91+, 60% U90+, 5% U89+. The hydrogen-like U91+ fraction is magnetically selected and transported to a 1 mg/cm² Pd target. About half of the U91+ ions are converted to heliumlike U90+, with about 1% of these being formed in the $1s2p\ ^3P_0$ state or in states which rapidly decay to the $1s2p\ ^3P_0$ state.

The price for using the $1s2s\ ^3S_1$ decay is to make the measurement more sensitive to possible cascade feeding from long-lived states of high principle quantum number (n) and angular momentum (J). Decays of high n, J states cascade down the yrast chain and reach the $1s2p\ ^3P_2$ state which has a branching ratio of $1/3$ to the $1s2s\ ^3S_1$ state by E1 decay and $2/3$ to the ground state by electric quadrupole decay. It is the branch to the $1s2s\ ^3S_1$ state which is a potential source of systematic error. In heliumlike uranium, however it takes a state of about $n=30$ and high angular momentum before the cascade time is comparable to the lifetime of the $1s2p\ ^3P_0$ state. The populations of excited states fall rapidly with increasing n and we estimate⁸ that less than 1% of the population lies above $n=30$ and with only a small fraction of these in high J states. We therefore expect no observable effect from cascades on our measured $1s2p\ ^3P_0$ lifetime with our present statistical accuracy of 6%. Furthermore, because the difference in transition energy to the ground state from the $1s2s\ ^3S_1$ and $1s2p\ ^3P_2$ states is resolved by our germanium x-ray detector, cascades through the $1s2p\ ^3P_2$ state will show up in our spectra as a resolved peak lying just above the decay peak. Figure 2 shows no evidence of a cascade peak nor does any of our data to within

background statistics.

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Figures

1. Energy level diagram of the $n=1$ and $n=2$ states of heliumlike uranium. Decays without labels are E1 decays. The cross hatching on the $1s2p\ ^1P_1$ and $3P_1$ states indicates the approximate radiative width. Singlet-triplet classification (and LS coupling) is used for the convenience of the authors. At $Z=92$ singlet-triplet mixing is close to 100%.

2. X-ray spectra 0.5 cm downstream from the target. The Doppler-shifted peak from the decay of $1s2p\ ^3P_0 \rightarrow 1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$ is near 78 keV. Peaks at 73 keV, 75, keV and 82 - 86 keV are from fluorescence of Pb. and at those near 57 keV and 65 keV from Ta. Pb and Ta are used for shielding the x-ray detector and for Soller and slits respectively. Cascades from higher excited states would produce a peak at 81 keV. This spectra represents 135 minutes of counting, or about 10^8 uranium ions. Background is caused by bremsstrahlung of electrons in the target off of the uranium projectile, elastic scattering of the electrons in the target followed by bremsstrahlung of the electrons either in the target, or, if the electrons leave the target, in the walls of the vacuum chamber, and by fragments from nuclear disintegrations in the target.

Heliumlike Uranium

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