Lifetimes of the Metastable Auto-Ionizing $(1s2s2p)\,^4P_{5/2}$ States of Lithiumlike F^{6+} and O^{5+} Ions

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Electrons emitted from foil-excited beams of F^{6+} and O^{5+} ions (2.5–20 MeV) have been energy analyzed and their number measured versus distance from the foil. Lines associated with the $(1s2s2p)\,^4P_{5/2}$ level and with higher quartet levels are observed to decay at various rates. Lifetimes for the $(1s2s2p)\,^4P_{5/2}$ state in F^{6+} and O^{5+} are found to be (1.5 ± 0.1) and $(2.5\pm0.3)\times10^{-8}$ sec, respectively. The latter disagrees with earlier experimental work and with theoretical estimates.

Useful information about simple ionic systems of high Z has been obtained recently by studying photon emission from beams of fast highly stripped ions.[1] Measurements of the radiative decay length and of the beam velocity yield a lifetime for the state which is the basic quantity normally compared with theory. It has proven highly desirable to spectrally analyze the emitted photons to discriminate against photons from other transitions.

Significant information may also be obtained by studying the *electrons* emitted from highly stripped beams. In this paper we report the first study of the lifetimes of metastable auto-ionizing states of excited three-electron ions in which the observed electrons are energy analyzed. Allowed auto-ionization processes typically have lifetimes several order of magnitudes too short to track over centimeter distances. Some metastable auto-ionizing states, however, have lifetimes $\sim 10^{-8}$–10^{-10} sec and are suitable for study in beams of velocity $\sim 10^9$ cm/sec ($\sim$ 1 MeV/amu). Examples are the metastable auto-ionizing quartet states in lithiumlike systems of higher Z. The lifetimes and energies of these quartet states in He^- and in Li have been extensively investigated both experimentally[2] and theoretically[3] because they are metastable against Coulomb auto-ionization [as well as against radiative decay in the case of the lowest quartet state $(1s2s2p)\,^4P^0_J$]. These states auto-ionize only through the spin-orbit and spin-spin interactions (for $J=\frac{5}{2}$, spin-orbit matrix elements also vanish) and hence their study has provided a sensitive test of the spin-orbit and spin-spin interactions in three-electron systems, including the effects of electron correlation. In particular, comparison of the extensive experiments of Feldman, Novick, and collaborators[2] with theoretical predictions (especially those of Manson, Holøien and Geltman, Estberg and LaBahn, and Laughlin and Stewart[3]) has shown that accuracy in wave functions for the three-electron system is extremely critical for predicting these level lifetimes and splittings.

Experimental and theoretical information concerning these states in three-electron systems of higher Z is minimal, in contrast to the cases $Z=2$ and 3. Measurements of the charge change in flight of the three-electron beam fraction in various cyclotron beams (beryllium through oxygen) have been made.[4] The observed change of the three-electron beam fractions was attributed to auto-ionization of the $(1s2s2p)\,^4P_J$ states of these ions; comparison values were deduced for the $^4P_{5/2}$ lifetime in C^{3+}, N^{4+}, and O^{5+}. A direct comparison with our present work is possible for O^{5+}. A discrepancy outside the combined error limits of the two experiments is found. Our result for O^{5+} is also different from the theoretical results of Manson[5] and of Balashov *et al.*,[6] but no precise estimate of the theoretical accuracy is available.

Beams of oxygen and fluorine ions from the Oak Ridge tandem accelerator (energy range 2.5–20 MeV) were stripped and excited by a movable carbon foil (10 $\mu g/cm^2$) and then passed axially into a cylindrical electrostatic electron spectrometer as shown in Fig. 1. The spectrometer is similar in design to that of Zashkvara *et al.*[7] Electrons emerging from the beams at angles near the spectrometer focusing angle of 42° were analyzed and counted with an electron multiplier. Foil position was adjustable over a range of about 15 cm parallel to the

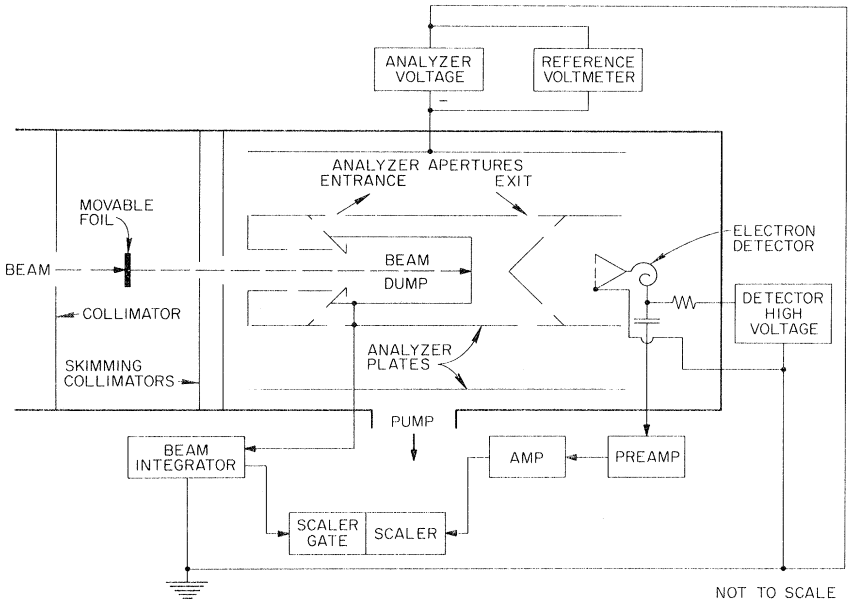

FIG. 1. Diagram of the apparatus. The cylindrical mirror electrostatic electron energy analyzer is shown schematically in a plane containing the beam axis.

beam direction. A drift space of about 2 cm beyond the extremal position of the foil accommodated a skimming collimator system shielding the region viewed by the analyzer annular entrance aperture. Some typical spectra of electrons emitted by the beam in the electrostatically and magnetically shielded viewing region (arising from long-lived states) are shown in Fig. 2. Two lines were observed with both fluorine and oxygen beams. For the higher-energy peak, line structure that changes shape with foil position has been observed (a considerable increase in point density and scale of Fig. 2 is needed to render these features apparent). This structure is being investigated. The corresponding laboratory energies of auto-ionization electrons from various long-lived quartet levels as calculated from the paper of Holøien and Geltman[8] are indicated in Fig. 2. Clearly we have observed electrons whose energy compares well, within experimental accuracy of about ± 4%, to those emitted from the various quartet states, especially since the laboratory electron energies scale correctly with beam velocity. There is little doubt that the large peak o of Fig. 2 arises from the decay of the $(1s2s2p)\,^4P_J$ states. The higher quartet levels, whose calculated energies match well the observed structured peak at higher laboratory energy, can decay to the lowest level allowed radiative transitions. The existence of small electron peaks in the spectrum corresponding to long-lived auto-ionizing transitions from these levels indicates that these radiative lifetimes are at least long enough to allow competition from these long-lived auto-ionizing transitions. We find experimentally that these small peaks decay away with lifetimes of roughly 1×10^{-9} sec. We are doing higher-resolution spectroscopy of these small peaks.

The principal aim of our work reported here was to obtain lifetime measurements. The advantages of our method are that we measure the ejected electrons directly and that we can spectrally select those electrons which came from particular identified auto-ionization transitions. Decay data for both lines in the spectrum were taken at 2.5, 4, 6, and 13 Mev for F^{6+} and 2.5, 5, 11.25, and 20 MeV for O^{5+}. Several decay curves were generated at each energy to test systematic consistency. Examples of the decay in flight of the $(1s2s2p)\,^4P_J$ electron emission line are shown in Fig. 3 for beams of F^{6+} and in Fig. 4 for O^{5+}. These curves are qualitatively similar to the decay curves for He^- obtained by Blau, Novick, and Weinflash.[9] The auto-ionization lifetimes of the $J=\frac{1}{2}$ and $\frac{3}{2}$ levels are much shorter than that of the $J=\frac{5}{2}$ level owing to admixture with ^2P_J states via the spin-orbit interaction. These short-lived decay components become relatively more prominent at higher beam energies, since they have not decayed away so much at a given point of observation.

Analysis of the decay curves in the first few centimeters is very complex because of contributions from both of the short-lived $(1s2s2p)\,^4P_{1/2}$ and $(1s2s2p)\,^4P_{3/2}$ states and because the higher quartet states (which we observe to decay in a few centimeters) may also be decaying radiatively to the lower quartet states. Cascading states which might complicate the downstream $J=\frac{5}{2}$ lifetime measurement would either have appeared on our electron spectrum or else have decayed so rapidly (by radiation or auto-ionization) that they would not influence the measurement. To avoid the ambiguities in in-

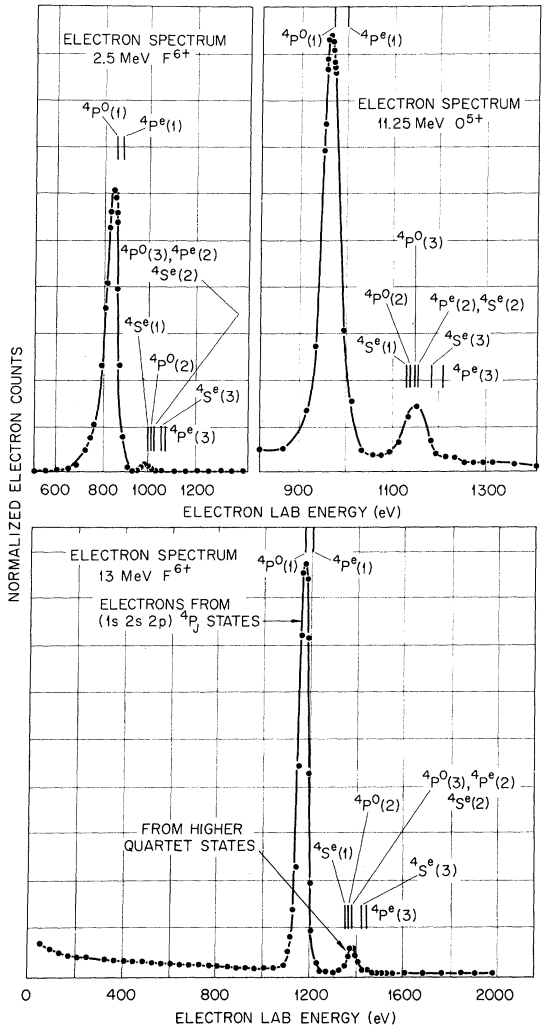

FIG. 2. Representative electron spectra (laboratory system) for metastable auto-ionizing states of F^{6+} (2.5- and 13-MeV beams) and O^{5+} (11.25-MeV beam), all taken at $\theta_{lab} \sim 42°$. The laboratory energies of the electrons are considerably higher than the center-of-mass energies because of the high ion beam velocity. Emitted electron energies for the lowest-lying S and P metastable auto-ionizing states are shown, as calculated from the term values in Ref. 8 (notation corresponds to this reference). One would not expect to see electrons arising from the lowest $^4P^e$ state since an allowed electric dipole transition to the $^4P^0(1)$ state is probably the dominant decay mode.

terpreting the first part of the decay curve we use only data taken far enough downstream from the foil that the $J=\frac{1}{2}$, $J=\frac{3}{2}$, and higher quartet states have decayed, leaving only the $(1s2s2p)\,^4P_{5/2}$ state. For the same reason, data obtained at low beam velocities were used in the final lifetime determinations.

Least-squares fits to downstream data give $^4P_{5/2}$ lifetimes of (1.5 ± 0.1) and $(2.5 \pm 0.3) \times 10^{-8}$ sec for F^{6+} and O^{5+}, respectively. Data-point scatter came

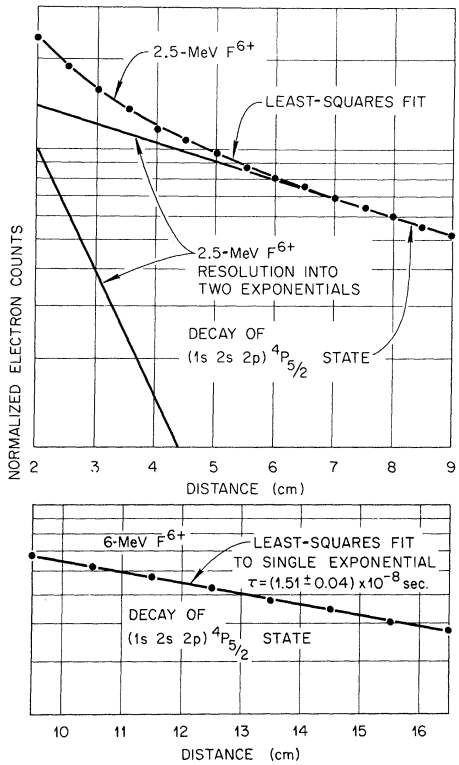

FIG. 3. Decay curves for the $(1s2s2p)\,^4P_J$ states of lithiumlike F^{6+} at 2.5- and 6-MeV beam energies. Solid lines represent the least-squares fit to the data points. The uncertainty in lifetime quoted in the text is larger than the statistical error shown in this diagram to take into account possible systematic errors.

predominantly from variation of counted electron flux with slight changes in beam shape and steering rather than from counting statistics. Errors given take into account the consistency from run to run at a variety of beam energies. The average lifetime of the states contributing to the first few centimeters

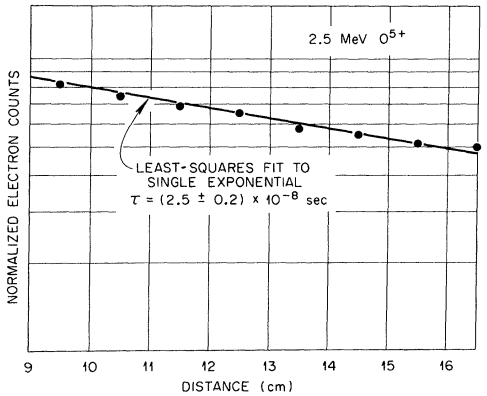

FIG. 4. Decay curve for the $(1s2s2p)\,^4P_{5/2}$ states of lithiumlike O^{5+} at 2.5-MeV beam energy. The indicated uncertainty in the lifetime is due to statistics alone.

of the decay curve [the $J=\frac{1}{2}$ and $\frac{3}{2}$ components of the $(1s2s2p)\,^4P_J$ multiplet] is less than about 2×10^{-9} sec, so that a good separation of the long-lived $J=\frac{5}{2}$ component is possible. With the precision at hand, it was not possible to extract unique lifetime or population information about the $J=\frac{1}{2}$ and $\frac{3}{2}$ states in the beam. The analysis is complicated by the possibility of cascades and by the unknown variation of the relative populations of the $J=\frac{1}{2}$ and $\frac{3}{2}$ states with beam energy.

Our lifetime value for the $(1s2s2p)\,^4P_{5/2}$ state of O^{5+} is somewhat lower than the experimental value of Dmitriev *et al.*[4] of $(4.4\pm0.8)\times10^{-8}$ sec, measured by the charge-change method. Our value is only slightly lower than the value of 3.1×10^{-8} sec calculated by Manson[5] using single-configuration Hartree-Fock wave functions but it is distinctly lower than the value 7.5×10^{-8} sec calculated by Balashov *et al.*,[6] who used screened Coulomb functions for the bound electron.

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Electron-Impact Excitation of Auto-Ionizing Levels in Cesium*

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Auto-ionizing states in Cs between 12 and 20 eV have been studied by electron impact. The retarding-potential-difference method was used to obtain an electron beam with energy spread of about 0.1 eV. To determine the threshold energies, inelastically scattered electrons were analyzed by the trapped-electron method. We have been able to identify about 20 levels, and the agreement with spectroscopic data is excellent. A peak appearing at 12.80 eV is probably due to the quartet states observed by Feldman and Novick.

I. INTRODUCTION

The structure that is sometimes seen in electron-impact ionization curves, as well as certain anomalies in vacuum ultraviolet absorption experiments, can in many cases be attributed to the process of auto-ionization. Series of auto-ionizing levels in atoms and molecules result from the excitation of an inner-core electron or from the simultaneous excitation of two electrons. The levels are located above the first ionization potential and can, in principle, decay via one of the following two channels: (i) by a radiative transition to a bound state of the atom below the ionization poten-